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TECTONIC CONTROL ON THE ARCHITECTURE OF SEDIMENTARY BASINS: BETWEEN SIMPLE MODELS AND REALITY

Giovanni Bertotti

Numerical models are often considered as having some kind of miraculous properties or, alternatively, to be of limited value. Little room seems to be present between these two extremes. There is also a tendency to think that, more complex models (both in terms of software and input parameters) are more reliable and provide better predictions than simple ones. For the same token, simple even merely semi-quantitative models are neglected and first-order features misinterpreted. These assumptions are not always correct.

In fact, simple models can provide very interesting and often neglected tools and predictions. More complex models become very useful only when the scientific question has been exhaustively understood and defined. These topics are discussed on the basis of two examples relevant to the Alpine setting

The first example concerns relations between geochronological data and rock exhumation in a contractional context. A simple qualitative model, constructed assuming stable isotherms, leads to the disturbing conclusion that most of the samples measured for geochronology will yield ages basically unrelated to the thrusting (or contractional) event under scrutiny. This is the truer the more unrealistic is the assumption of constant geotherm. Particularly tricky is the interpretation of ages from mylonites which formed above the closing temperature of a specific mineral system. The presence of fundamental problems in the interpretation of the ages reported in the literature is demonstrated by the apparent contradiction between the very precise ages produced on such rocks and the well known long-lived character of most crustal faults.

A sophisticated modeling, able to consider the relative rates of exhumation and thermal relaxation can provide indirectly a measure of the quantities looked for, namely the ages of thrusting and exhumation.

The second example is that of foredeep basins, which, according to the general knowledge are quite simple and "boring" systems. Similarly to what seen for exhumation, a first simple analysis provides interesting observations. Indeed, simple models provide quite stringent predictions on the internal geometry of foredeep basins. The main predictions are: a) a stratigraphic gap is observed at the base of the foredeep which should increase moving towards the bulge; b) the pinch-out position of basin fill formations should migrate towatds the bulge; c) deeper beds should display an increasing dip towards the mountain chain. Furthermore, assuming an elastic rheology, subsidence should be contemporaneous with thrusting.

It is surprising how often these predictions are not verified in nature. Examples are observed in the Po Plain, the foredeep of Southern Alps and Apennines) and in the Adriatic domain between Dinarides and Apennines. In all these cases the mechanics of the lithosphere plays a significant role in influencing the simple behaviors. Most important are softening processes which tend to localize the deformation and, thereby prevent the migration of the system predicted by simple models.

A further, commonly observed, phenomenon is the increased coupling between upper and lower plate in the convergence zone and the consequent onset of lithospheric folding. This produces patterns very different than those of simple models. For instance, areas previously uplifted such as the orogen itself can experience subsidence and become (partly) covered by marine sediments These topics can be adequately described only with more developed numerical models, especially those able to include the mechanics of the system.

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NEOGENE LANDSCAPE EVOLUTION OF THE EASTERN ALPS

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The modern geomorphological evolution of the Eastern Alps started with the termination of the Eo-/Oligocene collision. A first uplift impulse in Early Oligocene times is reflected by a sudden increase in sediment discharge and the production of coarse clastic material. Only the central and eastern Northern Calcareous Alps (NCA) remained lowlands and were covered by sediments which were not removed until early Miocene times. The shape of the Eastern Alps and their geomorphological evolution were sustainedly influenced by Early to Middle Miocene lateral tectonic extrusion, which stretched the Eastern Alps for more than 50 per cent in E-W direction. Tectonic extrusion was combined with an abrupt lowering of relief and sediment discharge. Middle Miocene sedimentation covered large areas along the eastern margin of the Eastern Alps so that the Pannonian basin extended further to the west than today for several tens of kilometers. In Late Miocene to Pliocene time elevations and relief increased, and the sediments of the eastern margin were removed. Late Pliocene to Pleistocene glaciation led to a fundamental morphological recast of the higher parts of the Eastern Alps and substantial peak uplift.

Provenance analysis of marker pebbles indicate that the large NE-directed catchment of the Paleo-Inn river originally extended much further to the S than today and even crossed the Periadriatic lineament. This river system persists since Early Oligocene times until present with relatively limited change. In the eastern part of the Eastern Alps, N-directed rivers dominated most of the Oligocene and the earliest Miocene time discharging their load on top of the central and eastern NCA. In Early Miocene times, a pattern of large-scale, ENE- and SE-trending faults was established in the course of lateral tectonic extrusion, which led to a complete reorganization of the river network and the overall geomorphological evolution in the eastern Eastern Alps.

In Neogene times, cannibalism of S-directed catchments on the expense of the N-directed rivers prograded from W to E, according to the maturity of S-directed river profiles. Marker pebbles record the first exposure of the Tauern core complex in Middle Miocene time, and fast relief increase in that area.

The gross structure of the modern macrorelief of the Eastern Alps was established during Early to Middle Miocene lateral tectonic extrusion. The modern mesorelief is strongly influenced by glacial erosion dynamics. The microrelief reflects the activity of post-glacial processes. The different temporal and spatial scales of relief-forming processes require quite different tools for a holistic quantitative reconstruction of the geomorphological evolution. Our work focuses on the evolution of the meso- and macrorelief, and thus on processes in the time-scale of millions of years.

For an analysis of the mesorelief, numerical DEM analysis, neotectonic movements, fault plane solutions, geodetic uplift data and sediment budgets of open and semi-enclosed catchments have been considered. The macrorelief of the past was reconstructed by considering differential exhumation in the orogen, precise provenance analysis of clastic material, lithospecific

thermochronology on pebble material, sediment discharge rates, and structural data. The combination of apatite and zircon fission track data and sediment budget calculations of circum-Alpine basins enables to estimate long-term denudation rates with a temporal resolution of 1 Ma. Regional climate change in the eastern Alps during the Oligo-Miocene period appears to follow the global changes only in a very damped manner. Therefore, denudation rates rather reflect changes of relief in response to vertical movements, than climatic changes. Estimated changes in relief, combined with palinspastic restorations and reconstructions of paleogeology and river network led to the presentation of paleogeograhic 3D models of the post-collisional evolution of the Eastern Alps.

DEM analysis enables to distinguish several geomorphological domains defined by geometric characteristics. The most rugged domain with high relief encounters the crystalline region west of the Brenner line, the western NCA, the Tauern window and the area to its south, and the Niedere Tauern. This region matches with Miocene apatite fission track ages, maximum Pleistocene glaciation and maximum recent uplift. Typically, it shows U-shaped valleys and a local relief up to 3000 m. Elevations above the regional and local average are more frequent than below (negative skewness of elevation frequency curves).

A region of high to intermediate relief and relics of the early Oligocene Dachstein paleosurface characterizes the central and eastern NCA. After sediment coverage and removal, this area experienced episodic surface uplift since ca. 10 Ma. Preservation of the paleosurface was only possible in areas, where thick Triassic limestones enabled subsurface erosion by karstification.

Intermediate to low relief with relics of the early Miocene Nock paleosurface is found in the Gurktal Alps east of the Tauern window and neighbouring regions. Here, glacial landscape overprint is of minor importance. The preservation of modified paleosurface remnants is due to only late and moderate uplift (not before Pliocene time) and, probably, sediment burial before that time. Apatite fission track ages are Paleogene. Elevation frequency curves show positive skewness.

In conclusion, the relief evolution was mainly governed by Neogene geodynamics and, only in the second place, by the exposed lithologies. Presently, there is an excellent match between measured surface uplift, elevation, and Pleistocene ice thickness, which may suggest that isostatic rebound after ice melting is responsible for the recent vertical movements. However, subsidence (in the eastern part of the Eastern Alps) and uplift (in the western part) relative to a reference point in the Bohemian massif also match positive resp. negative isostatic anomalies indicating deep-seated causes for vertical movements. In our opinion, recent movements are governed by isostatic response to crustal (and lithospheric) thickness, to ice load and release, as well as to tectonic pressure as evidenced from neotectonic analysis.

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TRANSALP: CONCEPT AND MAIN RESULTS OF THE PROJECT

Helmut Gebrande and TRANSALP Working Group

The Alps as the youngest and highest mountain range in Europe have always been a challenge for geoscientists and have played a key role in the development of new concepts and theories of mountain building. Recently, remarkable progress has been achieved by applying the modern technology of deep seismic reflection profiling to the Western Alps. The combination of the seismic reflectivity pattern with depth extrapolated surface geology resulted in a new concept, in which a wedge-shaped Adriatic indenter splitting the European crust forms the dominant tectonic element in the late stage of continent-continent collision. This model has been readily adopted to the Eastern Alps although the existence of the Austroalpine mega-nappe and the north-ward offset of the Periadriatic Lineament (PL) indicate the necessity of modifications or even basically different processes in the east. TRANSALP is aimed at providing new data and constraints for a better understanding of these processes.

More generally speaking, TRANSALP is conceived as a multidisciplinary research programme for investigating orogenic processes by continent-continent collision, focusing on the Eastern Alps. It consists of several seismic and seismological sub-projects within a 300 km long and 40 km wide north-south transect (approx. between Munich and Venice) and is accompanied by complementary geophysical, geological and petrological research projects.

The backbone of TRANSALP, jointly financed by Italian, Austrian and German partners, is a near-vertical seismic reflection profile designed for high resolution as well as deep penetration into the lithosphere by combining Vibroseis with high energy explosion seismics. The transect has been located at the longitude of the (according to surface geology) most northerly advanced indentation of the Adriatic into the European plate. The 300 km long main line is supplemented by seven 20 km long cross-lines for the control of 3D-effects. Additionally, a large number (up to 128) of continuously recording seismological 3-component stations was installed along the transect for active and passive tomography, for seismotectonic studies, and for imaging lithospheric discontinuities by the receiver-function technique.

Although the acquisition of the reflection data was splitted up in three different campaigns between autumn 1998 and winter 1999, it provided for the first time a coherent, homogeneously measured, and thereby fully migratable section through the complete orogene and parts of its molasse foredeeps. In the meantime the main line has been processed in considerable extent and detail. The velocity model, originally taken from older deep refraction seismic results, was refined by stacking and pre-stack migration velocity analysis as well as by tomographic inversion of TRANSALP travel-time data. State-of-the-art CMP stack sections and post-stack migrated sections of the Vibroseis and dynamite data have been distributed to the international TRANSALP Working Group in two releases in July and November 2000, and provide the basis for interdisciplinary and partially controversial interpretations being presented at this workshop.

The results leave no doubts that the 30 km thick European crust, marked by the top of basement and the Moho, plunges with about 7° more or less undeformed from the northern foreland up to the Inn valley fault. On its top the northern Molasse basin is imaged with unprecedented clearness. Surprisingly, the thickness of the post-Jurassic sediments increases suddenly at the orogenic front from about 6 to 9 km. The thickness of the Northern Calcareous Alps (NCA) is similar, but less well displayed. No evidence for thick Molasse sediments underlying the NCA has been found. The internal seismic structures of the NCA match well with prominent tectonic features known from surface geology. South dipping reflections may indicate a continuation of the Northern Calcareous Alps beneath the "Grauwacken Zone" south of the Inn valley. They seem to be related to a 40 to 50° south-dipping transcrustal reflective zone, which terminates the undeformed European crust and may be interpreted as a shear zone, along which the Tauern window was upthrusted by a lower crustal Adriatic indenter. This shear zone would then represent the actual boundary between the European and the Adriatic Plates at depth. The European Moho can be traced (with increased dip south of the Inn valley) down to 55 km depth below the main crest of the Eastern Alps. Further to the south it disappears in the reflection seismic image, but low frequency receiver functions derived from teleseismic recordings indicate its continuation to south of the PL. It will be attempted to confirm this findings with higher resolution by a supplementary seismic experiment this year.

The Adriatic Moho is displayed by explosion seismics in the south at 45 km depth, but again disappears when approaching the actual collision zone beneath the central Eastern Alps giving room for different tectonic models. The Periadriatic Lineament, supposed to be a key structure for the reconstruction of Alpine mountain building, separates segments of poor (in the north) and excellent reflectivity (in the south) at higher crustal levels. Looking at the sections with seismic eyes only, it can be argued for north-dipping as well as for south-dipping PL, implying quite different collision scenarios. Some of them will be presented at this workshop. They reflect our continuing task to resolve ambiguities and to find compatible and conclusive solutions by bringing data and arguments from different fields of geoscience together.

Another important future task will be the extension of the models to greater depth. To understand the dynamics of Alpine orogeny the entire lithosphere-asthenosphere system has to be considered. TRANSALP has provided excellent teleseismic observations proving that the travel-time delays through the thickened Alpine crust are overcompensated by a body (a slab?) of high seismic velocity (and most likely low temperature) in the upper mantle.

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ENGINEERING GEOLOGY OF THE GOTTHARD BASE TUNNEL AND INTERRELATIONSHIPS WITH ALPINE TECTONICS

Simon Löw

The Swiss AlpTransit System (also called NEAT) is an important element of the new European high speed railway network. This system, which is currently under construction, consists of two railway axes - the Gotthard and Lötschberg Axes - which will pass through the western and eastern parts of Switzerland (Figure 1). Each of these axes consists of 2 to 3 base tunnels, the longest being the two-tube Gotthard base tunnel (57 kms in length), which is currently the world's longest tunnel under construction. Within this system, an existing base tunnel will be used (the Simplon base tunnel), a second is to be located in the pre-alpine foreland (the Zimmerberg tunnel), and the remaining three are to be built within the Alpine region (the Gotthard, Lötschberg and Ceneri base tunnels). These final three tunnels are of notable concern since the rugged topography in this young mountain belt reaches altitudes of up to 3000 m near the tunnel axes, resulting in an overburden of up to 2500 m. Here the new base tunnels will intersect many of the tectonically deep units of the alpine mountain chain: mesozoic to tertiary sediments and the crystalline basement of the helvetic and penninic domain.

The Gotthard (GBT) and Lötschberg (LBT) base tunnels run more or less perpendicular to the main geological structures of the Alps (Figure 2). Crossing from north to south these include 1) The Helvetic autochthonous sediments and nappes, 2) The Aar, Tavetsch and Gotthard basement "massifs", and 3) The Penninic units of the Lepontine area. Together these units form the "core" of the Central Alps, which in turn was primarily shaped during tertiary (Eocene to Miocene) crustal subduction, thrusting, folding and updoming. Even today the Alpine mountain chain is still active. This is reflected, for example, in regional uplift rates derived from selected first order levelling benchmarks and GPS measurements performed along several cross-section through the Swiss Alps. These show maximum values of 1.4 mm/year in the region of the southern LBT and the southern GBT. In addition, neotectonic movements along selected fault zones of steep inclination are postulated based on observed "fault scarps" in young glacial tills and erosion surfaces with glacial polish, and from new geodetic measurements performed across fault zones in the southern Aar Massif (Frei and Löw 2001). These movements would correspond to

Fig. 1: Geographical and geomorphological situation of the AlpTransit railway system

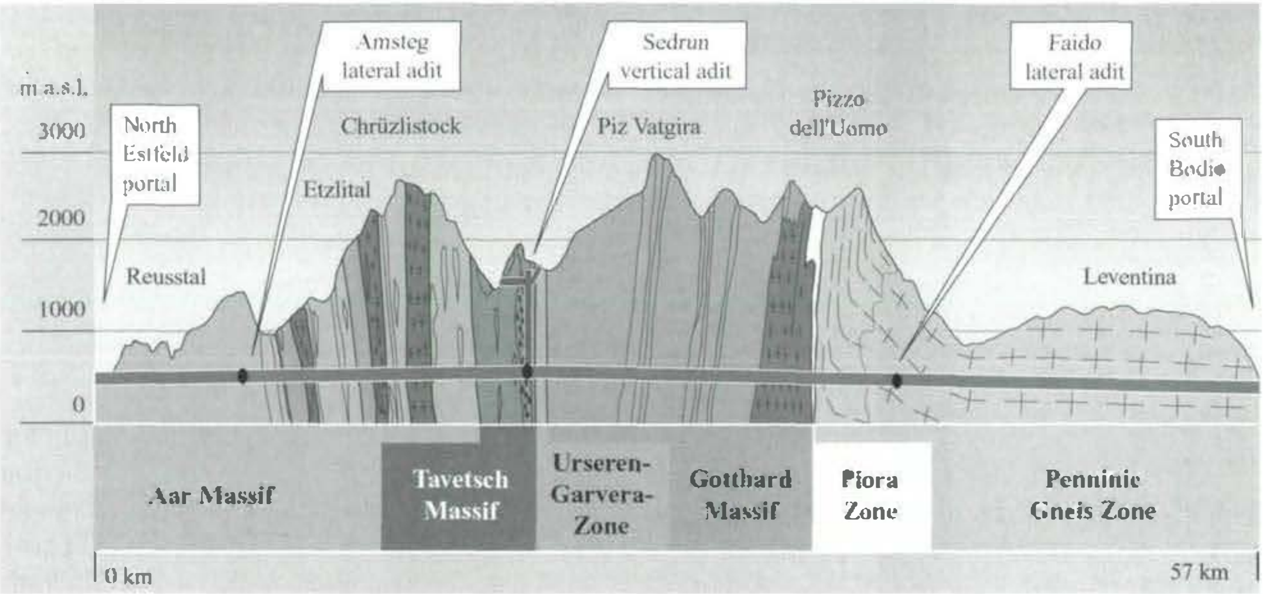

Fig. 2: Simplified longitudinal section of the Gotthard base tunnel

continued reactivations of old shear structures. Unfortunately the active stress field in this aseismic area is not well understood and paleostress analyses give uncertain results.

While the longest sections of the Gotthard base tunnel will be drilled in fairly stable ground, this project will also be confronted with a large variety of geologically controlled hazards, most of them being interrelated with Alpine tectonics. The most important hazards include: high water inflows along faults, inflows of rock debris (e.g. sugar-grained dolomites) under high fluid pressures, strongly squeezing ground in schists and phyllites, stress-controlled instabilities (i.e. rock bursting), and surficial disturbances (settlements) through drainage effects (Loew et al. 2000). Within the framework of the AlpTransit project these hazards have been investigated during the past 10 years by means of a long exploration tunnel (the Polmengo Tunnel in the Penninic Domain, from which 4 intermediate size boreholes have been drilled into the Piora Zone), 5 deep boreholes drilled from surface into the Tavetsch Massif, several geophysical and geodetical surveys, and geological field mapping and data compilation at the scales of 1:10'000 and 1:50'000 (Löw and Wyss 1999). In addition to these works, several Swiss research groups have been working in related fields mainly focussing on the structural, petrological and rock-mechanical aspects of fault zones and sugar-grained dolomites. In the lecture we will present new results from field and laboratory studies related to the dense fault and fracture patterns occurring in the Aar- and Gotthard massifs (Laws 2001, Laws et al. 2001, Zangerl et al. 2001) and demonstrate some important relationships between engineering geological problems and Alpine tectonics. Among these relationships special weight will be given to the impact of late- to post-alpine brittle and fracturing and rock mass stability, deformability and permeability.

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POST-COLLISIONAL OVERPRINT OF THE ALPINE NAPPES: HOW MUCH OROGEN-PERPENDICULAR SHORTENING, HOW MUCH OROGEN-PARALLEL EXTENSION?

Stefan M. Schmid

Within the roughly E-W-striking part of the Alps (Eastern Alps and Swiss-Italian part of the Western Alps) post-collisional deformation follows Tertiary collision in the Alps (50-35 Ma). This deformation is characterised by post-nappe folding by ongoing N-S compression and contemporaneous orogen-parallel normal faulting (SCHMID et al. 1996). Orogen-perpendicular faults, such as the Simplon or Brenner normal faults, undoubtedly accommodate orogen-parallel stretching and contribute to the exhumation of neighbouring domes such as the Lepontine and Tauern dome, respectively. The ratio of this E-W extension over contemporaneous N-S-shortening, however, is a matter of dispute. This ratio largely influences the relative importance of tectonic unroofing versus denudation by erosion. On the basis of a sediment budget method it has recently been proposed that tectonic unroofing may contribute as much as 70% and 80% to total exhumation in the Lepontine and Tauern domes, respectively (KUHLEMANN et al. 2000).

Subduction retreat and associated extension in the Pannonian basin provide boundary conditions which are favourable for substantial orogen-parallel stretch in the Tauern window and further to the east. Regarding the Alpine transect across the Tauern window, the total amount of post-35 Ma N-S shortening between Adria and Europe may amount to a total of about 120 km based on an extrapolation of the data given for a transect across Eastern Switzerland (SCHMID et al. 1996). A slightly lower value for N-S shortening (86-113 km) results from a retro-deformation of post-30 Ma deformation within the Austroalpine units overlying the Tauern window, which yielded 170 km of orogen-parallel stretch (FRISCH et al. 1998). Hence, it appears that N-S-shortening and orogen-parallel stretch have similar magnitudes during post-collisional deformation. However, the activity of the Brenner normal fault did not start before about 20 Ma ago (FÜGENSCHUH et al. 1997). Hence, tectonic unroofing started to play a dominant role only after 20 Ma ago.

The situation is totally different in case of the Lepontine dome. Firstly, orogen-parallel stretching started as early as 35-30 Ma ago, i.e. during the so-called Niemet-Beverin phase (SCHMID et al. 1996) and lasted until the final stages of normal faulting across the Simplon normal fault at around 15 Ma ago. The estimated 60 km of orogen-parallel stretch (SCHMID & KISSLING 2000) are a consequence of diverging thrust directions in the Swiss Alps (top-N) and in the French-Italian Western Alps (top-WNW). These diverging thrust directions are kinematically related to a corridor of dextral shearing along the Tonale and Simplon shear zones. It is proposed that the Simplon normal fault represents a local tensile bridge which formed during a late stage within this zone of dextral shearing. The estimated 120 km of N-S shortening after 35 Ma exceeded the orogen-parallel stretch of about 60 km during the entire post-collisional deformation history. Hence, from a tectonic point of view, exhumation of the Lepontine dome must have been dominated by erosional denudation, induced by backthrusting along the Insubric line; this dome definitely does not represent a core complex in the footwall of a low angle detachment.

The N-S striking French-Italian Alps undergo a major change in thrusting direction from top-N to top-WNW after the Priabonian and at around 35 Ma ago (CERIANI et al. 2001) and coeval with orogen-parallel stretching in the Lepontine dome and dextral movements along the Tonale line. Orogen-parallel extension has not been described in case of the French-Italian Alps.

On the scale of the entire Alps post-collisional deformation is dominated by orogen-perpendicular shortening rather than by orogen-parallel extension, except for post-20 Ma deformation of the Eastern Alps east of the western margin of the Tauern window. In the latter case it is suggested that subduction roll-back in the Carpathians, rather than indentation by the Southern Alps and lateral extrusion due to an overthickened crust (FRISCH et al. 1998), represents the primary cause for very substantial orogen-parallel extension.

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TECTONIC INFORMATION OF METAMORPHIC DISEQUILIBRIA: EXAMPLES FROM THE HIGH GRADE EOALPINE OF THE KORALPE

Kurt Stüwe

Metamorphic rocks contain valuable information about the pressure (*P*) and temperature (*T*) evolution of mountain belts, which is commonly extracted using the tools of *equilibrium* thermodynamics. Because diffusion processes are strong exponential functions of temperature, this information is largely that of the metamorphic *temperature peak*. In fact, even *P* sensitive mineral equilibria will record the metamorphic *temperature* peak because activation volumes in the Arrhenius relationship are much smaller than activation energies. While non-equilibrium thermodynamics has been a fully-developed tool in metamorphic petrology since the seventies (FISHER, 1973; JOESTEN, 1977), its methods have not found their way into the list of widely used tools in modern interpretations of metamorphic rocks (FOSTER, 1986). It remains common practice to use the methods of *equilibrium* thermodynamics to interpret *non-equilibrium* information, for example when interpreting reaction textures to infer metamorphic *PT* paths.

In the past years we have been involved in the development and application of petrological tools that can be used beyond the interpretation of *PT* paths. We do so by using *equilibrium* thermodynamics to interpret textural observations on metamorphic *disequilibria.* In particular, we have been involved with investigations of (i) cooling rate, (ii) tectonic stresses and even (iii) strain rate. While the investigation of these parameters has typically been the realm of geochronologists and structural geologists, petrological tools for their investigation are rapidly advancing. This contribution gives an overview over new developments in the field of such *petrological* tools.

Many of our investigations were applied to the Koralm crystalline complex of the eastern Alps, in part because its heterogeneous equilibration lends itself to the interpretation of metamorphic disequilibria (e.g. STÜWE & POWELL, 1995; TENCZER & STÜWE, 2001a); and in part because some burning questions on the heat sources and tectonic interpretation of the metamorphic field gradient exposed in the Koralps require the determination of functions like cooling rate or tectonic stresses (STÜWE, 1998; STÜWE & TENCZER, 2001).

Cooling Rate: The determination of cooling rates of rocks is typically performed using a series of geochronological systems with different closure temperatures. However, DODSON (1973) formalized the relationship between *grain size*, *cooling rate* and *closure temperature* for both geochronological and major element exchange systems. Thus, it is possible - in principle - to use zoning profiles of garnets to infer the cooling rate of rocks. Using statistical approach we have shown that the cooling rates of the highest temperature evolution of the Plattengneiss shear zone was extremely rapid (EHLERS et al., 1994). We believe that it was too rapid as that it could be explained by exhumation processes alone (STÜWE & EHLERS, 1998).

Stress Information: Metamorphic parageneses record only a single quantity of the stress tensor: pressure. However, by comparing pressure variations on a small scale (where lithostatic stress variations are negligible) it is possible to infer also non-lithostatic stress fluctuations in metamorphic rocks. In the Koralpe, syndeformational decompression textures within the Plattengneiss shear zone have been interpreted to indicate that the Plattengneiss deformation was an *exhuming* deformation phase. However, we have shown recently that pressure variations up to about 1 kbar are reasonable within the scale of a thin section (TENCZER & STÜWE, 2001b). Modal shifts between minerals in trivariant parageneses of the Plattengneiss shear zone are consistent with pressure variations of about 1 kbar.

Strain Rate Information: In principle, it is possible to infer strain rates from inclusion trails in garnets, if two parameters are known: 1. The relationship between strain rate and rotation rate of the crystal and 2. The growth rate of the crystal. Interestingly, garnet crystals in coarse grained rocks from the Koralpe show a wide variety of inclusion trails, even within a single thin sections. Such variations in inclusion trails may indicate that neighboring porphyroblasts may hinder or accelerate each others rotation rate for a given shear strain rate in the far field (BIERMEIER & STÜWE, 2001). We are currently in the process to measure growth rates of garnet crystals from the Koralm complex.

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VERTICAL MOVEMENTS OF DIFFERENT TECTONIC BLOCKS ALONG THE CENTRAL PART OF THE TRANSALP – TRAVERSE. CONSTRAINTS FROM THERMOCHRONOLOGICAL DATA

Petra Angelmaier, István Dunkl & Wolfgang Frisch

The aim of the project is to reconstruct the exhumation history of the metamorphic units between Inntal (Austria) and Gadertal (Italy) and to model the vertical motion paths. Therefore we collected 65 samples for geochronological investigations, mainly zircon and apatite fission track dating. At the time of writing 36 zircon ages and 22 apatite ages have been obtained. First track length measurements are in progress.

Penninic units

The Zentralgneisses yield zircon fission track ages between 16 and 11 Ma and apatite fission track ages between 10 and 5 Ma. An increasing fission track age with altitude is visible. Because of the high relief in the Zillertal mountains it is possible to estimate an exhumation rate with the altitude dependence method using the same dating methode in two rock samples from different hights. With this method we calculated for the Ahornspitze profile (Fig. 1) exhumation rates of 1mm/a for the time between 14 and 12 Ma and 0,5 mm/a for the time between 9 und 5 Ma. To the north, the fission track ages increase. The zircon fission track ages of the Bündnerschiefer are around 20 Ma and the apatite ages are around 14 Ma.

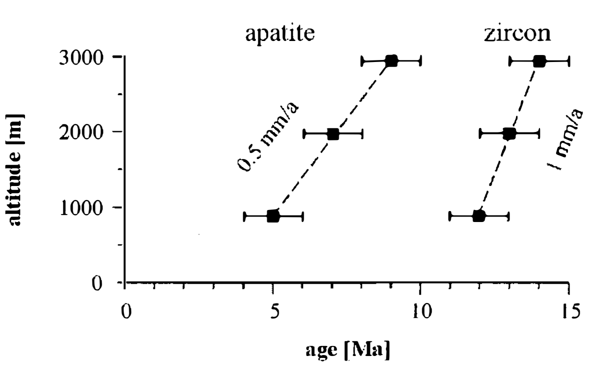

Fig. 1: Exhumation rates, calculated with the altitude dependence method.

Austroalpine units

First zircon fission track dating of the Kellerjoch gneisses yield ages around 60 Ma. This age is also represented in the Innsbrucker quartzphyllit. The apatite fission track ages are around 13 Ma. A zircon fission track age of 116 Ma and an apatite fission track age of 38 is obtained in the Greywacke zone. In the so called "Altkristallin" between the southern border of the Tauern Window and the Pustertal Line, the zircon fission track ages increase from 20 Ma to 122 Ma towards the south with clear jumps of the ages by crossing the DAV and KV Lines (see also STÖCKHERT et al. 1999). In contrast to the zircon fission track ages the apatite fission track ages shows a uniform age pattern of 9–10 Ma. Fig. 2 and Fig. 3 show the different exhumation history of the metamorphic unit between Tauern Window and DAV Line (northern block) and the metamorphic unit between KV Line and Pustertal Line (southern block).

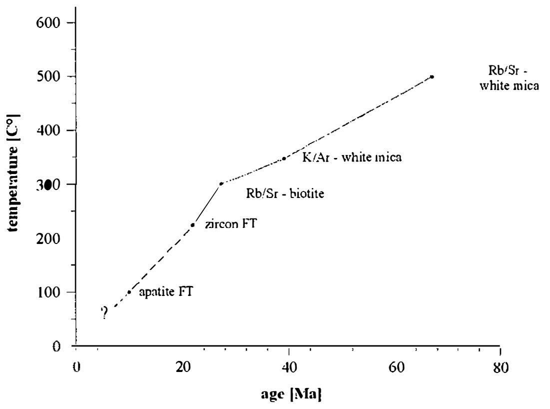

Fig. 2: Tt-path for the northern block, all data except apatite FT, zircon FT and K/Ar-white mica are from BORSI et al. (1973).

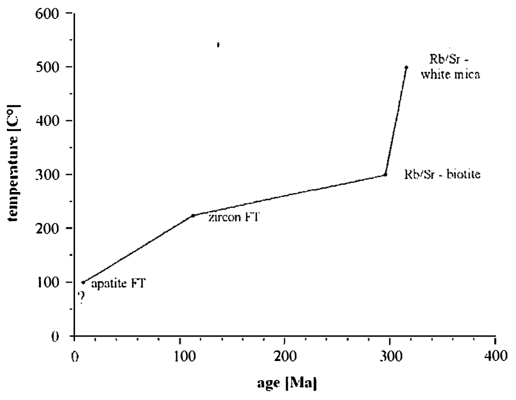

Fig. 3: Tt-path for the southern block, all data except apatite FT and zircon FT are from BORSI et al. (1973).

Southalpine units

First zircon fission track ages of the Brixen Quartzphyllite are around 210 Ma.

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STRUCTURE AND KINEMATICS OF THE NORTHERN CALCAREOUS ALPS ALONG THE TRANSALP-PROFILE

Matthias Auer & Gerhard H. Eisbacher

In order to better understand the structural and kinematic development of the frontal Upper Austroalpine Thrust Complex a strip roughly 30 km wide of the Northern Calcareous Alps (NCA) was investigated between the rivers Isar and Inn. The main aim was the construction of a depth-extrapolated geological cross section along the TRANSALP seismic profile and a semiquantitative retrodeformation of the section. In addition to depth-extrapolated surface structures, reflection seismic lines and well data from Vorderriss 1 (located about 35 km to the west) yielded useful information on a possible model for the deep structures.

In the cross section area the NCA consist of 4 major structural units: the NCA-Borderzone, the Allgäu Sheet, the Basal-Lechtal-Imbricates and the Lechtal Sheet. The **NCA-Borderzone** is made up of two internally folded and imbricated tectonic units separated by a major thrust. The **Allgäu Sheet** is characterized by tight, N-verging fold structures which are modified in the west by bivergent thrusting. The overlying **Basal-Lechtal-Imbricates** are restricted to the central and eastern areas. They consist of incomplete Triassic-Jurassic successions and indicate that this tectonic unit was part of a horst in Early to Middle Jurassic time. The structural geometry of the frontal **Lechtal Sheet** was clearly influenced by major pre-existing Jurassic extensional faults. Development of these faults controlled rapid thinning of Triassic platform carbonates in the east and caused a down-section shift of the Lechtal Thrust in the west. The internal structure of the Lechtal Sheet is dominated by N-verging first-order folds with wavelengths of approximately 8km. Conspicuous NNE-SSW- to NE-SW-trending structures in the Achensee area probably resulted from anticlockwise rotations between high-angle transverse faults. The continuity of the fold trains in the Lechtal Sheet is modified by a major out-of-sequence fault (Achental Thrust). In the southsoutheast all structures are truncated by the steep sinistral Inntal fault zone.

Geological mapping, TRANSALP- and OMV-seismograms and well data from the borehole Vorderriss 1 constrain the extrapolated cross section along the TRANSALP-Traverse between the NCA-front and the Inntal fault zone. According to seismic data the top of the autochthonous European crust is located between 7.5 and 9 km below sea-level. Allochthonous units below the NCA taper southward and their cumulative thickness decreases to about 1km in the central and southern part of the profile. The lower unit of the NCA-Borderzone was intersected in the borehole Vorderriss 1; its trailing edge therefore is assumed to be located about 15 km south of the NCA frontal thrust. Field observations in the western area suggest limited displacement of the Allgäu Sheet over the upper unit of the NCA-Borderzone which therefore is expected to taper out only 2 km below the surface. According to reflection seismic data and tectonic half windows in the Vilstal/Lechtal Alps to the west and in the Weyerer Bögen to the east, the trailing edge of the Allgäu Sheet is located about 25 km south of the NCA-front. Its trailing part has been displaced 4 to 5km by the Achental Thrust the hangingwall of which displays a complex pop-up-structure. The Basal-Lechtal-Imbricates taper out

only 5 km west of the section, so a maximum continuation to depth of 2km is suggested. As the internal shortening of the Lechtal Sheet was transferred from folds onto thrusts the basal geometry of the Lechtal Sheet is considered to be rather even. **NCA-Basement** is expected at the base of the Lechtal Sheet somewhere south of the Achental Thrust trace. Semiquantitative retrodeformation of the profile yields a minimum shortening of the NCA along the TRANSALP-Traverse of 85km, corresponding to a relative shortening of approximately 75%. Internal shortening of the Lechtal Sheet amounts to about 13 km or 34%.

The timing of deformation in this part of the NCA can be unravelled by means of an analysis of the stratigraphic thicknesses, the occurrences of breccias, the basal contacts of synorogenic sediments, and their deformation. Between the Triassic and Early Cretaceous the region was dominated by extensional tectonics and differential subsidence. A Middle to Late Jurassic contractional event apparently did not significantly influence structures in the area investigated. Lower to Middle Jurassic coarse grained breccias in the southwest (Rofan Mountains) are thought to be linked to this contractional event and were probably shed from a scarp created along a foreland thrust belt located somewhere to the south. The first major contractional deformation occurred in late Early Cretaceous, leading to shortening along approximately NNW-directed thrusts. The distribution and basal unconformities of early Upper Cretaceous synorogenic sediments suggest contemporaneous E-W-folding at higher levels. The deformation was partitioned into folds and ESE-WNW-oriented dextral strike-slip faults which partly controlled the deposition of the Upper Cretaceous synorogenic Gosau clastics. Although folds in Gosau deposits show larger interlimb angles these structures correspond roughly to those observed in the subjacent strata and indicate that folding continued in post-Cretaceous time. Continuous sedimentation in the frontal NCA until Paleocene-Eocene time and the complete closure of the Penninic ocean not earlier than Eocene time constrain this second major contractional period. Late Eocene to Miocene deformation produced a tightening of folds, the creation of N-/NNW- and S-directed thrusts and strike-slip faults which cut across earlier developed fold-thrust structures, but did not displace the structures of the cross section area significantly.

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HIGH P METAMORPHISM AND TECTONICS IN THE NORTHEASTERN PART OF THE SESIA-LANZO ZONE (WESTERN ALPS)

J. Babist, M.R. Handy & M. Konrad

The Sesia-Lanzo Zone (SLZ) overlies the Liguro-Piemontese ophiolites and is separated from the Ivrea-Verbano Zone (IVZ) to the east by the Canavese Line (CL), part of the Insubric fault system. Several workers have proposed a Late Cretaceous metamorphic field gradient across the SLZ comprising subduction-related eclogitic and blueschist facies assemblages south and southwest of the Val Sesia transitional to lower pressure greenschist facies assemblages northeast of Val Sesia (e.g. COMPAGNONI et.al. 1977). The Mesozoic Canavese metasediments along the CL were thought to contain only Late Cretaceous and Tertiary greenschist facies assemblages (ZINGG & HUNZIKER 1990). So far, no convincing mechanism has been proposed for exhuming the HP rocks of the SLZ; the 45 Ma Gressoney Shear Zone (WHEELER & BUTLER 1993, REDDY et al. 1999) formed in the footwall of the SZ and therefore only exhumed structurally deeper units like the Middle Penninic basement units (e.g., Monte Rosa nappe) and the Liguro-Piemontese ophiolites.

Detailed mapping in the Canavese mylonites and the easternmost SLZ in the lower Val Sermenza revealed four Alpine deformational phases: The oldest visible structures are relicts of an older foliation within the regional composite main foliation. Microprobe analysis of blue amphibole clasts within these relicts reveal glaucophanes (gln) without any internal zonation. The gln coexisted stably with paragonitic white mica (wm) and albite (ab), an assemblage diagnostic of blueschist facies. Low-Fe gln also occurs in Canavese-derived calc-silicate mylonites along the CL at Scopello. As there is no evidence for eclogitic assemblages within these relicts, these early structures may be correlated regionally with the retrograde blueschist facies D2 deformation in the central SLZ (e.g. GOSSO et al., 1979).

D3 deformation involved isoclinal folding and the development of a composite S2/S3 foliation parallel to moderately SE- to E-dipping F3 axial planes. Shear bands indicate that this main foliation accommodated WNW- to NW-directed extensional exhumation of the footwall parallel to a gently ESE- to SE-plunging stretching lineation (Ls). Kinematic indicators are best preserved near the CL. Away from the CL within the SLZ, the D3 microstructures are partly annealed. D3 was associated with a marked decompression, as evidenced by the partial replacement of D2-gln by tremolite (tr) or actinolite (act), and by the synkinematic growth of act+ab+wm+-bt in the pressure shadows of gln microboudins. White micas that are dynamically recrystallized or newly formed have a muscovitic chemistry, and both qtz and fsp underwent syn-D3 dynamic recrystallization. Taken together, these observations indicate lower amphibolite to upper greenschist facies conditions for D3.

D4 deformation within the bulk of the SLZ involved subhorizontal, NE-SW extension along conjugate sinistral, NE-SW-trending and dextral, ENE-WSW-trending oblique-slip shear zones. These shear zones are several hundred meters wide and were active under retrograde amphibolite- to greenschist facies conditions. The dextral shear zone probably merges with the Canavese mylonites near Fobello, whereas the sinistral zone forms the steep northern margin of the SLZ from the Val Macugnaga to the Val Sesia. In the Val Sesia, it truncates the dextral shear zone and continues to the SW as an internal dislocation of the SLZ. Along the CL in the lower Val Sermenza, D4 is characterized by steep F4 folds and a steeply WNW-dipping mylonitic foliation that overprints the SLZ-IVZ contact. The Ls plunges variably within this foliation, although most shear bands indicate ESE-backthrusting of the SLZ onto the IVZ. These movements occurred under retrograde conditions, as evidenced by the brittle behaviour of fsp and the syn-D4 growth of chl, tr, ep and ab. The celadonite component of syn-D4 white micas is similar to that of D3 muscovites. D5 involved the development of open to tight folds (100 m scale) with moderately dipping axial planes. These folds refolded steeply dipping S4 in the D4 shear zones under greenschist facies metamorphism.

We propose the following tectonic history for the NE part of the SLZ: **D1** involved stacking of the SLZ and parts of the IVZ (the seconda zona dioritica-kinzigitica, IIZDK) as nappes during Late Cretaceous subduction (e.g. RUBATTO et al. 1998) and HP metamorphism. The kinematics of **D2** blueschist facies deformation are unknown, but similar conditions are found in other parts of the SLZ (see KONRAD et al., this volume) and are clearly retrograde with respect to the thermal and baric peak during D1. **D3** top-to-SE extensional mylonitic shear in the internal part of the SLZ (near the CL) appears to be responsible for early (pre-Insubric) juxtaposition of the SLZ with the Alpine-unmetamorphosed IVZ. However, we suspect that most exhumation of HP metamorphic rocks was accommodated elsewhere, perhaps by thrusts at the base of the SLZ and/or at within the Penninic nappe pile. Unfortunately, these units are overprinted by the Gressoney Shear Zone. We are currently dating white micas to constrain the age of D3 (Early Tertiary or Late Cretaceous?) and its possible temporal relationship to thrusting in deeper units of the nappe pile. **D4** accommodated Mid-Tertiary transpressional tectonics in front of the Apulian indenter. This intense greenschist facies D4 overprint obliterated most HP assemblages. D4 strain was strongly partitioned, such that Sesia-internal steep belts accommodated NE-SW subhorizontal extension while mylonites of the CL accommodated backthrusting of the SLZ onto the IVZ. Dating of D2-D4 fabrics is in progress. **D5** accomodated minor shortening of the locally D4-steepened main foliation.

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COMPUTER-AIDED 3D RETRO-DEFORMATION OF THE NORTHERN CALCAREOUS ALPS AROUND THE TRANSALP PROFILE

Jan H. Behrmann & David C. Tanner

To determine the amount of shortening, the depth of detachment and the style of deformation for the Northern Calcareous Alps (NCA) in the TRANSALP sector, we retro-deformed three-dimensionally an approximately 40 x 40 km area comprising the Lechtal and Allgäu Nappes. For the Lechtal Nappe, the largest coherent thrust sheet within the NCA, a three-dimensional model was constructed by splining lines from eight N-S cross sections, spaced E-W at about 4 km intervals. The data base consisted of all published and available geological surface and drillhole information, and preliminarily processed sections of the TRANSALP reflection seismic experiment. The model defines faults and seven stratigraphic layers of laterally variable thickness comprising the Permo-Triassic to Cretaceous stratigraphy.

Nearly all the structural features of the Lechtal Nappe are controlled by the Triassic Hauptdolomit (HD) layer. Where it is less than 500 m thick, imbricate thrusts develop. Sections where the the HD is more than 1 km thick are not faulted. Where the HD is thicker than 2.5 km, the whole thrust system is jammed. The consequence of jamming is folding of earlier detachments, development of backthrusts and fault-bend folding of the HD and the other layers.

The modelled area has four main thrusts which link to a detachment at 2-5 km depth below sea level. 3D fault displacements and heaves were determined using Allen Maps. Algorithms for fault-parallel flow and flexural slip unfolding were used to restore northwards movement on the thrusts and folding of beds over thrust planes, respectively. Minimum shortening estimates vary, from east to west, from 25% to 42% (with a typical error of 6%). Additional shortening in the west of the area is mainly accomodated by folding.

The Allgäu Nappe, subjacent to the Lechtal Nappe, is composed of a much thinner sequence of sediments. Its subsurface structure in the western part is markedly different to the structure in the eastern part. In the east the Allgäu Nappe can be traced about 10 km down-plunge, and can be restored to an initial width of approximately 20 km. In the western part the downplunge width is at least 15 to 20 km, with a restorable shortening of 32%.

As a consequence this means that the triple (Inntal, Lechtal, Allgäu Nappes) NCA nappe system was moved fairly uniformly to produce laterally heterogeneus shortening within the individual units. Therefore the clockwise rotation of the nappes by 30-40°, as shown by paleomagnetic data is likely a product of post-nappe block rotations. The best kinematic constraint for a predominantly northward movement of the nappes comes from the Thiersee Synform-Achental Thrust- Karwendel Synform structural assemblage, which can only be properly retro-deformed in 3D using a N-S kinematic vector.

The following results of our study are potentially valuable to TRANSALP interpretation:

The position of the basal datachment to the NCA can be estimated by depth extrapolation in the deformed crustal volume.

The downplunge extension of the Allgäu Nappe could be determined.

The internal stucture of the Lechtal Nappe, not clearly visible in the TRANSALP seismic data, could be constrained.

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PRESSURE TEMPERARTURE TIME PATH OF THE COL DEI BOVI METAMORPHIC UNIT (EASTERN SOUTHALPINE BASEMENT, SOUTH TYROL)

Luca Benciolini, M. Eliana Poli, Dario Visonà & Adriano Zanferrari

The Sarentino/Sarnthein – Bressanone/Brixen metamorphic basement (SBMB) in the eastern Southern Alps belongs to the southern flank of the European Variscides and is characterized by a polyphase tectono-metamorphic evolution. Up to day low- to intermediate pressure greenschists facies metamorphism as well as contact metamorphism at the Brixen Granodiorite border has been described in this region (SCOLARI & ZIRPOLI, 1971; MORGANTE, 1974; HAMMERSCHMIDT & STÖCKHERT, 1987; MAZZOLI & SASSI, 1988; SASSI & SPIESS, 1993; RING & RICHTER, 1994). In the Col dei Bovi/Ochsenbichl area close to Bressanone/Brixen, a relatively small rock volume records a high temperature metamorphic imprint.

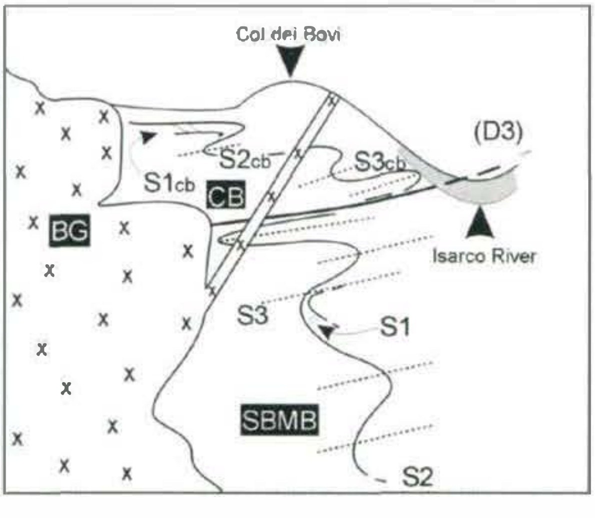

Fig. 1: Schematic relationships among the Sarentino/Sarnthein – Bressanone/Brixen metamorphic Basement (SBMB), Col dei Bovi metapelites (CB) and Brixen Granodiorite (BG). S1, S2, and S3: foliations within the SBMB; S1cb, S2cb and S3cb: foliations within the CB; grey: quaternay deposits.

Detailed structural and microstructural analisys has been carried out in the Col dei Bovi area on the relationships between High Temperature Col dei Bovi metapelites, greenschists facies SBMB basement and Bressanone granodiorite (fig. 1).

The structural and metamorphic evolution compounds four main phases: a) high temperature - intermediate pressure D1 phase: Quartz, Plagioclase, Biotite, K-feldspar and Garnet assemblage preserved within D1 microlithons; b) high temperature - low pressure D2 phase (Quartz, Plagioclase, K-feldspar, Biotite, Sillimanite, Andalusite, Cordierite and Corundum assemblage developed within the differentiated S2 layering; c) D3 retrogression phase (Sericite, Quartz, Chlorite and Albite) commonly developed in the whole eastern Southalpine basement; d) intrusion of the Bressanone granodiorite pluton at 282 ± 14 Ma, generating in the surrounding rocks the static growth of reddish-brown Biotite, Andalusite and Cordierite. D3 reveals the same structural and metamorphic features in the eastern Southalpine basement (e.g. SASSI & SPIESS, 1993) where 320 Ma cooling ages have been detected (HAMMERSCHMIDT & STÖCKHERT, 1987). On the contrary D1 and D2 events appear to be unconsistents with the metamorphic evolution of the surrounding basement (fig. 2). As a consequence, as also supported from structural relationships with the Bressanone Granodiorite intrusion at 282 Ma, D1 and D2 events in the Col dei Bovi area may represent pre-320 Ma events and may compared with coeval similar events in the European Variscan chain. We suggest that the

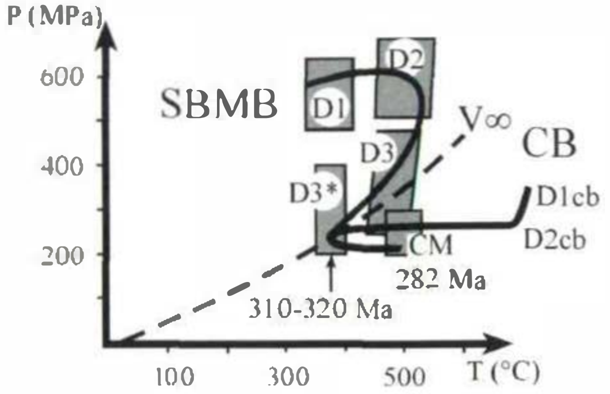

Fig. 2: P-T-t path of SBMB and CB units. D1, D2 and D3 (SBMB) as after Ring and Richter (1994); D3* after HAMMERSCHMIDT & STÖCKHERT, (1987); D1cb, D2cb and CM (= contact metamorphism): Col dei Bovi metapelites, this paper; V∞ geotherm as after THOMPSON & ENGLAND (1984).

thermal evolution of the Col dei Bovi unit accounts for the post-collisional setting of the European Variscan chain and probably for the late orogenic collapse.

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HOW TO DELIMIT CRYSTALLINE NAPPES? AN EXAMPLE FROM THE CIMA LUNGA AND ASSOCIATED UNITS IN THE CENTRAL ALPS (SWITZERLAND)

Alfons Berger, Martin Engi, Astrid Gruskovnjak, Tom Burri

In the crystalline nappe stack of the internal part of the Alps, metasedimentary rocks have long been used as nappe separators. In areas where such metasedimentary nappe separators are missing, tracing a nappe boundary may be ambiguous and may lead to different interpretations of the nappe stack. We are trying to reexamine and delimit general tectonic units on the basis of their lithological content and their metamorphic and kinematic evolution. In the Central Alps we distinguish two groups of units: (1) coherent continental basement units, some of them still containing prealpine features; (2) fragmented units including Alpine HP-rocks and oceanic parts. We propose that the second group includes slices of the subduction channel that underwent intense deformation during subduction. For example, a representative element of Type 2 is the Cima Lunga unit, which is defined here by its rock association (marble, calcsilicates, ultramafic rocks and eclogitic amphibolites) and by the evidence of HP-metamorphism. In the remapped southern part, the Cima Lunga unit is only some 100 meters thick. It separates the underlying Simano nappe from the clearly overlying Maggia nappe. The thickness and differences in metamorphic evolution, as compared to surrounding units, characterize the Cima Lunga unit as nappe-divider rather than a proper nappe. The Maggia and the Simano nappes are both Type 1 units, as they include a basement with prealpine structures and leucocratic metagranitoids. Further west, the corresponding European basement units (Maggia and Antigorio nappes) are separated by the Someo zone, which includes mesozoic metasediments. Newer findings even indicate eclogitic relics inside this zone. Those data in combination with structure of the Someo zone may indicate also between Maggia and Antigorio nappes relicts of a Type 2 unit.

In terms of metamorphic evolution and lithological contents, the Cima Lunga unit can be compared with other units of the Central Alps (i.e. parts of the Southern Steep Belt; Adula), but those units show different sizes and different final tectonic positions. Type 2 units have a similar early history, but they are tectonically transported into continental basement at different levels. Tectonic transport may also include „out of sequence“ thrusting. We recognize different pieces of oceanic fragments in the Central Alps (i.e. Cima Lunga unit; Adula nappe; Southern Steep Belt; Antrona unit), but we emphasize that their role during nappe stacking may differ. Some oceanic- and mantle fragments are welded to the continental basement early (e.g. Adula and Monte Rosa nappes), other pieces (Cima Lunga unit) may act as a nappe separators. The different history of oceanic fragments puts a question mark behind the use of such units as paleogeographic markers.

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THE ROLE OF STRATIGRAPHICALLY-CONTROLLED DETACHMENT SURFACES IN THE TECTONIC SETTING OF THE SOUTHERN ALPS OF LOMBARDY

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The stratigraphic succession developed on the Southern Alps passive margin in Lombardy is preserved within a thrust and fold belt, produced by the Alpine north-south compression. The older rocks outcrop toward the north (immediately south of the Insubric Line) and the younger toward the south, where they are covered by the deposits of the Po Plain. The Alpine tectonics is responsible for the development of different tectonic units, controlled by two main detachment horizons: the lower Triassic dolostones and pelites of the Carniola di Bovegno and the Carnian sabkha facies of the San Giovanni Bianco Formation. These detachment surfaces acted as important structural boundaries, separating three huge portions of the stratigraphic succession with different age, lithology and rheology: 1) a lower portion, represented by basement rocks capped by Permian volcanites and siliciclastics; 2) a middle portion represented by Anisian subtidal limestones and Ladinian carbonate platforms capped by shallow water mixed sediments; 3) an upper portion, represented by a thick Norian dolomitized carbonate platform covered by deeper sediments. Tectonic units belonging to each of these portions are never overthrust by units belonging to the underlying portions, with the only exception of the Bruco Klippe (western Val Brembana), where Anisian and Ladinian rocks overthrust Norian dolostones.

The lower detachment surface (controlled by the rheological characteristics of the Early Triassic pelites, sabkha dolostones and evaporites of the Carniola di Bovegno) is represented by the fault system known as Valtorta-Valcanale Fault (VVF). Previous works interpreted the VVF as a system of minor faults acting in different ways or as a system of steep transcurrent faults dividing rigid blocks with different kinematic behavior. New detailed geological mapping of the Southern Alps of Lombardy (scale 1:10.000, Carg Project, Regione Lombardia) allowed to identify the VVF system as a major tectonic element, separating the basement and the Permian-Early Triassic succession from the younger sediments. Actually, the tectonic units below the VVF (Orobic Anticlines) are interpreted as antiformal stacks that developed below the Triassic cover, detached at the Carniola di Bovegno level. Similarly, the Middle Triassic overthrust units are interpreted as antiformal stacks between the VVF and the upper detachment surface at the top of the Carnian succession (Clusone-Antea Fault, CAF), previously interpreted as a wedging fault in its eastern portion or, locally, as a normal fault. The Middle Triassic rocks are covered, above the CAF, by tectonic units consisting exclusively of Norian and younger sediments.

The strong control of the two detachment surfaces on the tectonic setting has an important stratigraphic implication: the sedimentary succession of the Southern Alps of Lombardy is never preserved as a continuous succession.

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NEW BIOSTRATIGRAPHIC RESULTS FROM THE BÜNDNERSCHIEFER – IMPLICATIONS ON PALEOGEOGRAPHY

Rufus J. Bertle

New biostratigraphic data from the Bündnerschiefer (schistes lustrés) of the Lower Engadine Window (LEW) are presented from the two major tectonic units of the LEW, the tectonically highest Fimber-unit (OBERHAUSER 1983) and the tectonically deepest Zone of Pfunds (BERTLE 1999). The whole sedimentary sequence has undergone HP-LT metamorphism during Tertiary times as indicated by the occurrence of index minerals like carpolithe and blue amphibols (BOUSQUET 1998) or phengites (STÖCKHERT et al. 1990). Therefore it was only possible to establish a lithostratigraphic sequence missing biostratigraphic data (UCIK 1993). Despite of the HP-LT metamorphism and high grade of deformation of the rocks microfossils can be found with success as demonstrated by CADISCH et al. (1941), RUDOLPH (1982) and OBERHAUSER (1983) for the western Fimber-unit.

Until now biostratigraphic data from the core of the window (Zone of Pfunds) and the eastern part of the Fimber-unit (E of the Fimber valley south of Ischgl) were missing. Based on micropaleontological investigations combined with investigation of lithofacies a first detailed stratigraphic sequence for the schistes lustrés could be established. The oldest sediments of the blueschist-facies metasedimentary rocks of the Zone of Pfunds are of uppermost Jurassic (?) to lower Cretaceous age. This pure calcschists are succeded by the mid-Cretaceous Tristel formation with e.g. *Orbitolina* (SCHWIZER 1983), which is overlain by the Gault-formation (age indication by reworked *Calpionella*) (HESSE 1972). At the top of the sequence a turbiditic sequence ("Bunte Bündnerschiefer") of upper Cretaceous to lower Tertiary (?) age is exposed. Based on micropaleontological investigations two nappes within the Zone of Pfunds can be distinguished, both showing HP-LT metamorphism (BOUSQUET 1998 and references therein) of Tertiary age (THÖNI 1981, BERTLE 2000).

In the Zone of Pfunds *Orbitolina* and stratigraphically useful dasycladales indicating the mid-Cretaceous period and an *Orbitoides-Globotruncana* assemblage were found. Rocks of South Penninic position revealed Globotruncanids, orbitolinids, algae and cf. *Nummulites.*

Reconstruction of the pre-Tertiary paleogeographic situation leads to a similar picture as it was first discussed in detail by OBERHAUSER (1983):

1) Ending of the Brianconnais swell in the region of the LEW as indicated by ending of cristalline basement with its characteristic upper Cretaceous sedimentary rocks (couches rouges),
2) sediment transport of Tristel Formation and Gault Formation in southern, eastern and northern direction as indicated by regional distribution of the formations mentioned above.

Basic lithoclasts found in the middle Cretaceous Tristel Formation are interpreted as intraformational clast whereas basics found as clasts in uppermost Cretaceous (?) to lower Tertiary rocks (Bunte Bündnerschiefer of the Fimber unit) are interpreted as derived from the accretionary wedge of the South-Penninic-Austroalpine boundary.

The new biostratigraphic data from the Engadine window enable intrabasinal correlation of highly metamorphosed metasedimentary sequences of the Western and Central Alps with the schistes lustrés of the Tauern Window where Cretaceous age constraints are still scarce.

Based on the new biostratigraphic data, in combination with sedimentological, geochemical, petrological data from the literature a new correlation of the Penninic units of the Engadine Window with those of the Tauern Window is presented.

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QUATERNARY MORPHODYNAMICS AND NEOTECTONICS OF THE LOWER ENGADINE (SWITZERLAND/AUSTRIA)

Rufus J. Bertle & Peter Schlusche (1937–1981)

The results of the investigations of P. Schlusche, who died in 1981 are presented in this abstract for the first time. The investigations took place from 1959 to 1980 in the area of the Lower Engadine valley and included detailed mapping and C-14 dating. Schlusche was the pioneer of neotectonic investigations in Austria (TOLLMANN 1987, p. 135).

The Engadine valley, located in the western part of the Eastern Alps, is striking in W-E direction from the Maloja-Paß in the West to Landeck in the East. The main structural features along the Engadine valley are the W-E trending Engadine Line (TRÜMPY 1972, SCHMID & FROITZHEIM 1993) and the Lower Engadine window (BERTLE in prep.), which is located at the Austrian-Swiss border region.

In the western part of the Engadine valley, in the region of St. Moritz, Quaternary evolution is well known, whereas the region between Zernez and Landeck is still a missing gap from recent investigations except the excellent, but unpublished work of Schlusche (data collected from 1959-1981). The results of Schlusche are presented for the first time here.

Morphodynamics of the Lower Engadine is dominated by adaption of glacial erosion and filling on the neotectonic movements along prominent tectonic structures. During and after glacial regression (post-Gschnitz) fluvial processes like filling of lakes, which were dammed by rock falls and later floods caused by the break down of the dams. Three different stages of lake evolution in the main valley between Scuol and Pfunds are documented and two other stages of lake evolution are known from the S-charl valley. The age of the different lakes is pre-Daun, around Egesen and around 2000 B.C. (last age is indicated by carbon dating – Probenanalysen B-996, B-976, B-2027, B-2028, B-977, B-978, B-2029, all data measured in Bern). Increased fluvial sedimentation around 1500 B.C. can be correlated with the Santorin-event.

The main morphological features of the Lower Engadine valley are the so called "Dorfterrassen" which show a complex sedimentological structure due to polyphase development and the confluent valleys which reach the main valley several hundred meters above the recent river bed resulting in deep gorges of the confluents in the direction of the main river En (Inn).

The neotectonic activity is dominated by two main systems – one striking E-W (Engadine Line, see also SCHMID & FROITZHEIM 1993 for the part above/west of Scuol) and the other one striking N-S (Reschen Line and parallel faults, SCHLUSCHE & BERTLE in prep., BERTLE in prep.). Slope movements in the valleys are controlled by these two fault systems resulting in rock slides in areas where Bündnerschiefer crop out.

Recent geothermal activity (mineralised springs of Scuol, Val Sinestra, Prutz) along the Engadine valley correlates with major fault systems.

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IMAGING THE DEPOSITS THAT FILL VALTELLINA (NW ITALY) BY SEISMIC REFLECTION INVESTIGATION

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Alfredo Bini, Mauro Guglielmin, Stefano Carbonara & Michele Terenzoni

In the frame of a contract with regione Lombardia, in November 2000 and April 2001 the National Research Council (CNR) shot three seismic reflection profiles across the Valtellina valley in order to identify the sediment layering and the rock basement depth. The acquisition parameters were as follows: group interval 5 m; shot interval 10 m; CDP fold 12; number of groups 48; geophone frequency 30 Hz; sample rate 1 ms; record length 1024 ms, energy source dynamite, acquisition geometry off end.

The Valgella profiles were also acquired simultaneously with a 24 channels instrument and a 25 m group interval, reaching a maximum offset of 850m. All reflection shots were acquired from the refraction cable in order to better control the velocity of the upper part of the valley with refraction first arrivals and to have wide offset reflection phases In this way we were able to record clear deep reflections, where the bedrock shows the maximum depth. For this line the reflection and refraction data were merged in the reflection data processing.

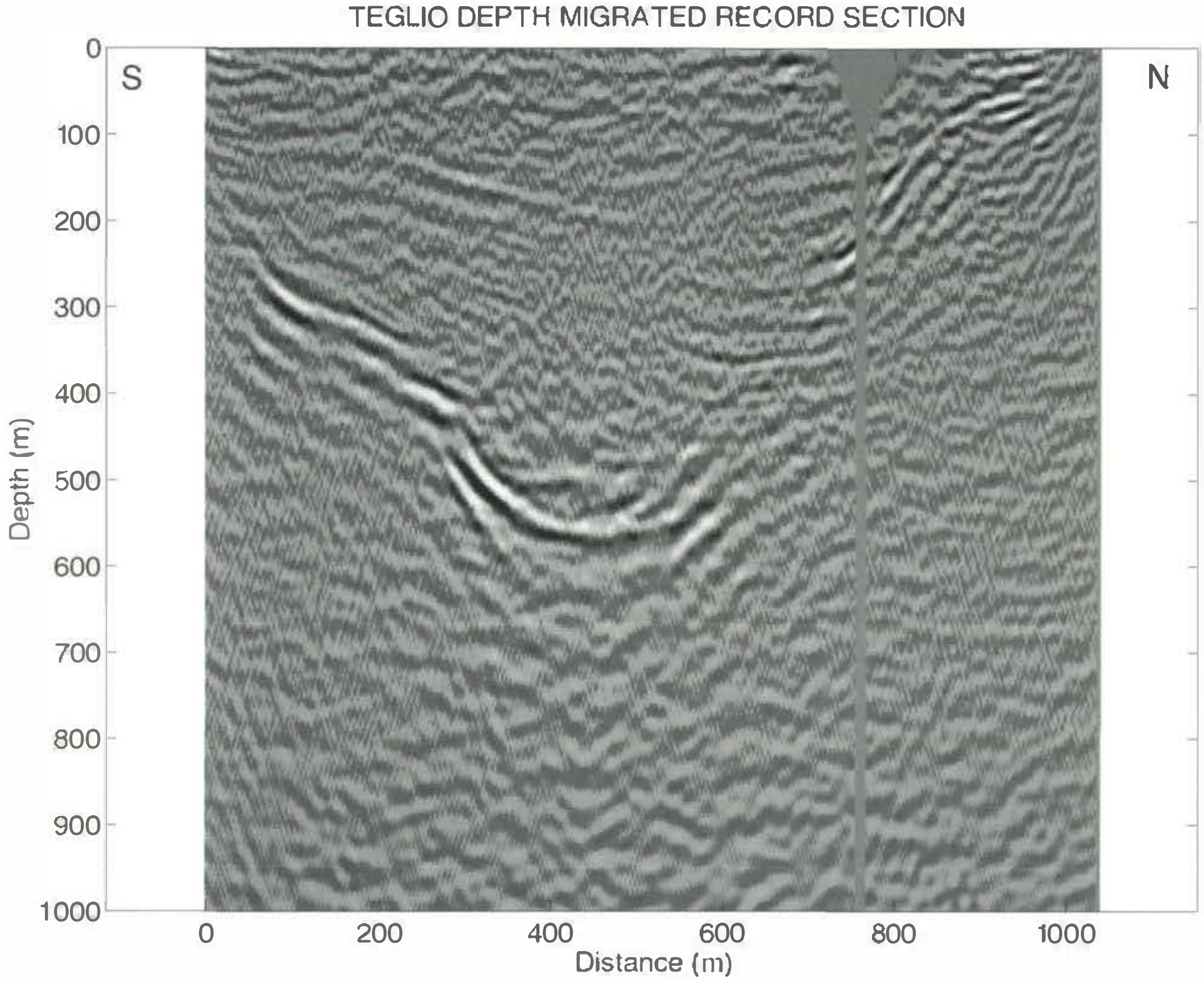
Bormio profiles were shot by using as energy source both dynamite and hydropulse, in order to compare their efficiency and resolution.

The data were processed by a standard procedure using PROMAX and SUNT5 processing codes.

The statics were calculated starting from the refracted first arrivals using a two layer inversion based on least square optimisation. Single CDP was filtered, after a spectral analysis, with a band pass working between 20 hz and 210 hz with 100% band pass between 30 hz and 200 hz. We attenuated the air blast pulses and ground roll using the FK filter defining for each CDP a mute function in the FK domain. The manual mute of refracted arrivals and an AGC with 50 ms window length were applied. A time variant spectral whitening was also applied to balance the spectra of the reflected signals. The sorted CDP were corrected of Normal Move Out (NMO) using the velocity profile obtained in the velocity analysis step. In order to enhance the lateral correlation a DIP scan filter was applied to the shot point panel corrected of NMO. The time migration was obtained using a finite difference algorithm using the interval velocity obtained from RMS velocity deduced from the previous velocity analysis; a reduction of 30% and 40% of the original velocity values was applied. In order to choose the better migration a test of migration with constant velocity was performed. The migrated section were calculated using a step of 250 m/s, from 1500 m/s to 3000 m/s, and obtaining the best result for a mean velocity of 2000 m/s.

The depth migrated record section of the profile shot in Valgella is shown in Figure (datum 300 m, mean surface elevation 363 m).

The bedrock features are clearly identified, with a maximum depth of about 550 m, which means about 180 m below the sea level. The sediments that fills the valley are characterised by a well defined layering, with a clear reflection, below about 150 m depth. These deposits are interpreted as lacustrine deposits (Bini et al.,



this issue) and they have been confirmed by the visual observation of the cores collected in a bore-hole drilled at 300 m distance (Figure). In this core have been observed for the depth ranging between 192 and 209 m lacustrine deposits overlaid by a succession of till until the depth of 40 m when starts a fluvial sequence.

Along both the buried slopes the basement, seems to suffer some deformations related to a deep-seated gravitational slope deformation (DGSD) as more described in detail in Bini et al. (this issue).

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DEEP-SEATED GRAVITATIONAL SLOPE DEFORMATION UNDER THE SEDIMENT FILL OF INSUBRIC VALLEYS (ITALY – SWITZERLAND)

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Within some valleys located along the Linea Insubrica, some seismic investigations (using the reflection method) along profiles transversally orientated respect to the direction of the valley have been carried out in the frameworks of different projects. Two profiles are in the Magadino Plane, northward to the Maggiore Lake in Switzerland (FELBER et al., 1994; FELBER & BINI, 1997) and another profile is in the eastern part of Valtellina near Valgella (BINI et al., this issue; BIELLA et al., this issue).

The first (carried out in the project PNR20) of the two profiles reveals a buried valley bottom at 750 m below the topographic surface reaching the depth of 510 m below the actual sea level. The second profile carried out by Ferrovie Federali Svizzere 1 km eastward from the previous one not reach the rock basement investigating only the upper 400 m of the sediments. The Valgella profile shows a buried valley bottom at 550 m ca. below the surface that reaches the depth 180 m below the actual sea level.

All the profiles show the same structural assessment characterised by the upper part until 200 m of depth with chaotic and irregular reflectors and the lower one with a series of sub horizontal and parallel reflectors that pinching out on the rock sides of the valley.

The deposits of the upper part have been attributed to the glacial deposition during the Last Glacial Maximum (LGM) (FELBER et al., 1994; FELBER & BINI, 1997) while the sub horizontal reflectors can be interpreted as fluvial and/or lacustrine deposits earlier than LGM. The occurrence of terraces constituted by LGM fluvial and fluvioglacial deposits at the outflows of Como and Maggiore lakes at an altitude much higher than the top of the buried deposits found in the seismic prospections confirms that the last one are older than LGM.

In all the profiles are clearly visible deep-seated slope gravitational deformations (DGSD) along almost the entire buried slopes, not genetically linked with the glacial evolution in the valleys (BINI et al., this issue).

In correspondence of the DGSD the sub horizontal reflectors are deformed and folded according a compressive stress due to the sliding or creeping of the bedrock. The absence of evidences of inverse faults or "flower structure" within the bedrock, confirm that deformations both in the rock and in the overlying sediments is not due to a transpressive tectonic style.

The DGSD continued their downward movement and deformation even after the filling of the valley without any constraints by the deposits.

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DEEP-SEATED GRAVITATIONAL SLOPE DEFORMATIONS AS ORIGIN OF THE TERRACES ON THE NORTHERN SLOPE OF VALTELLINA (ITALIAN CENTRAL ALPS)

Alfredo Bini, Giancarlo Biella, Roberto de Franco, Mauro Guglielmin & Paola Tognini

The Valtellina is one of the main valleys of the Italian Central Alps, E-W oriented along the Linea Insubrica, a transcurrent fault that divides the Austroalpine domain to the North from the South Alpine domain to the South .

The landscape of the northern slope of Valtellina is characterized by the occurrence of a succession of several terraces placed at different altitudes ranging between 1000 and 450 m a.s.l. The lower terraces are several kilometers in length, while the upper ones are less than 4–5 km. The terraces in general are joined at the foot of the slope in a zone up to two kilometres in width.

All the terraces are carved on the metamorphic or intrusive outcropping bedrock and covered by glacial and fluvioglacial deposits. Almost all the terraces show some elongated rock hills, mainly along the downward edge while the flat surface area upward is built by till and/or fluvioglacial deposits. Sometimes there are other minor reversed slopes carved on the bedrock upward. The till that fill these terraces, related to the Last Glacial Maximum (LGM) are continuous also on the upslope. Moreover the occurrence of many evidences of the glacial erosion on the rock hill (roches moutonnées and striae) suggests that the formation of the terraces was earlier, at least, than the LGM.

These terraces were interpreted by previous authors (VENZO, 1971; BELTRAMI et al., 1971, NANGERONI & GIACOMINI, 1961) as glacial terraces carved by the Valtellina Glacier. In some cases VENZO (1971) explained the reversed slopes at the outer edge of the terraces as morainic ridges deposited after the LGM .

To investigate the evolution of the slopes along Valtellina a 1 km high resolution seismic reflection profile was shot, perpendicular to the direction of the valley close to Valgella, together with a seismic refraction profile meant to better control the velocity of the upper part of the valley (see more details in Biella et al, this issue) The Valgella site was chosen because the slope is characterized by 6 terraces located between 900 and 500 m a.s.l. and many other reversed slopes occur up to the mountain-top.

The profile shows a main deep reflector, interpreted as the bedrock at the bottom of the valley. This bedrock appears undisturbed in the central part while in the northern sector another slight convex reflector can be recognized, showing upward an irregular and undulated morphology.

A similar but less important phenomenon occurs also on the other side of the valley.

The slight convex reflector could be interpreted as the lower part of the failure surface of a huge deep-seated gravitational slope deformation (DGSD). This interpretation of the reflector together with the surface morphology allow us to assume that the entire slope is interested by a DGSD or creep mass rock.

It is reasonable to extrapolate our interpretation of the Valgella slope to all the terraces that occurs along the northern slope of Valtellina because the surface morphology and the geological assessment are the same.

The origin of these terraces is related to the gravitational evolution of the slopes and to the weakness of the rocks due to the Linea Insubrica that should run along this part of the slope.

The terraces can be considered completely independent by the glacial action except for the local and minor morphological details post-dated with respect to the formation of the terraces.

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ENDOKARST EVOLUTION RELATED TO GEOLOGICAL, TOPOGRAGRAPHIC AND CLIMATIC EVOLUTION IN THE LOMBARD SOUTHERN ALPS

Alfredo Bini & Paola Tognini

The longest and deepest cave systems in Lombardy (Northern Italy) are found in the Southern Alps, where the most karstifiable formations crop out, with the highest karst potential. The structural setting is very favourable to deep karst systems (km-scaled syncline folds), together with favourable palaeoclimatic, morphologic and topographic factors.

The idea of the evolution of a region, and of its related endokarst, as a sequence of distinct-in-time phases (as by Davis at the end of the 18th century) is hard to die, but after the modern concept of speleogenesis and karst evolution, early endokarst began to form as the area was raised above sea level and kept on developing during Alpine orogenesis: morphogenesis does not follow tectogenesis, but it is contemporary to it, and in the meanwhile the regional topographic and climatic evolution strongly controls the genesis, evolution and characteristics of endokarst.

Some Lombard endokarst systems have been the object of detailed studies, the most interesting of them being the systems of Campo dei Fiori (over 25 km caves, maximum depth -640 m), of Mt. Bisbino, of Pian del Tivano (over 30 km caves, maximum depth -560 m) and of Northern Mt. Grigna (with the highest cave density in Lombardy, and the deepest Lombard cave, -1170 m deep).

A global analysis taking into consideration caves geometry and morphology, their tectonic and structural setting, the position, facies and characteristics of cave deposits and speleothemes, enriched with U-Th dating, allowed the endokarst evolution to be reconstructed and compared with the regional tectonic, palaeogeographic and palaeoclimatic history, from the moment the area was raised above sea level, when the main karstification phase began: caves are considered to be an integral part of a region and must therefore be studied together with it.

After geological studies, the emersion of the Lombard Southern Alps is estimated to be early Miocene, or late Oligocene, in age by dating of valleys filling and by the occurrence of palaeovalleys which fed the sub-marine canyons where the Southern Molasse was laid down.

Older valleys networks are cut by Messinian valleys (dated on the basis of their sediment content in the Varese district). The main evidence of old valleys is given by seismic profiles showing deeply embanked palaeovalleys often continuing under the Po Plain sediment cover, several km southward: dating of their sediment filling proves ages from Messinian on, so that valleys should predate both sediment deposition and the Messinian Entrechment.

Analysis of soils and weathering products prove that during Alpine orogenesis climate was tropical humid: under such conditions, rock weathering was intense and karstification sped up. Alpine uplifting played an active role in creating an increasing relief energy, which controlled the topographic and morphologic evolution of the region, promoting the entrenchment of the long, deep Southalpine valleys: this was a very favourable condition to the development of deep caves systems, too. Valleys and endokarst features are therefore inferred to develop before Messinian Entrenchment and when glaciations began (late Pliocene) they were obviously preexisting, so that glacial modelling on endokarst was minimal and restricted to high mountain regions.

Lombard Southern Alps endokarst exhibits several examples of caves systems not in equilibrium with the present topography: this proves endokarst is old and formed and evolved under topographic and climatic conditions quite different from present ones. Evidences of a non-equilibrium situation are corroborated by field data, such as:

1 – endokarst systems cut by younger erosion surfaces (i.e.: by glacial scouring) and valleys, causing a fragmentation of the endokarst systems, originally continuos, into smaller sub-systems. Caves systems cut by younger valleys can be observed at different scales, from the valley presently filled with the Como Lake, to its tributary gorges, to small lateral vallets at higher altitudes.

2 – syngenetic galleries are observed at different altitudes, much higher than the present base level (1.200-1.400 m above the p.b.l. in the Pian del Tivano system, 1.800-2.000 m in the Grigna system, 900 m in the Campo dei Fiori system): they are different in age and related to different base levels, which were continuously evolving while karst was evolving.

3 – cave passages are often too large with respect to the present catchment: the hydrogeologic basins in the past should have been much larger (i.e.: Pian del Tivano, Grigna, Campo dei Fiori);

4 – most endokarst in the Como Lake surroundings have their main springs below the present lake level (Pian del Tivano, Grigna), karst features have been observed below lake level and some caves exhibit a complex network of drowned galleries, some tenths of m deep;

5 – some springs are burden under sedimentary cover post-dating springs formation (i.e.: Campo dei Fiori main springs, covered with late Pliocene- Quaternary deposits);

6 – some caves contain sediments brought into caves by rivers, which are not consistent with any river possibly flowing into caves in the present topographic situation and contain grains of rocks which at present have been completely eroded away in the surroundings (i.e.: Campo dei Fiori).

7 – caves passages and concretions are deformed by late-Alpine tectonics correlated with deformation phases dated at surface by dating sediments they affect (early Pliocene, early Pleistocene) (Campo dei Fiori, Bisbino).

8 – speleothem radiometric dating often shows ages older than the method limit (350 ka), even older than 1.5 Ma (on the basis of their $^{234}U/^{238}U$ ratio). A very old age for the oldest speleothemes is inferred on the basis of the relations with cave deposits and on their weathering state. Some speleothemes are engulfed into sediments related with climate changing and glacial advance phases, so that caves must predate.

As for the evolution of karst, a global analysis of caves morphologies and minerals points out:

1 – one palaeokarstic phase during episodic raising above sea level of the Esino Formation carbonate platform during Ladinian (i.e.: Northern Grigna);

2 – one hydrothermal karst phase, probably affecting just small areas close to intensely tectonised areas (i.e: Northern Grigna, Mt. Tremezzo), related to the eo-Alpine and neo-Alpine thrusting;

3 – one “pseudoendokarstic” phase, due to very deep pedogenetic processes under a hot humid tropical climate (i.e.: Mt. Bisbino) giving rise to peculiar morphologies; soil formation under tropical hot humid climate is detectable over large areas in Lombardy, not only on carbonate parent material, and the process is likely to be continuos from the uplifting above sea level (early Miocene) till late Pliocene climate worsening pre-dating the beginning of Plio-Quaternary Ice Age;

4 – one deep “classical” karst phase: the evolution of this phase is related to topographic evolution and is controlled by base level changing (due to neo- and late-Alpine tectonic uplift, to Messinian Entrenchment and to Pliocene marine transgression).

Furthermore, analysis of facies, lithology and grain weathering in caves deposits point out dramatic changes in climate, with a changing from biostatic (alloctonous caves deposits very scarce or absent) to rhesistatic situation (mobilisation of tropical soils brought into caves from surface) and a progressive cooling, with suffering and final disappearing of the vegetation cover, related to late Pliocene climate worsening, the precursor of the first glacial advances (recorded by deposition of alloctonous materials into caves). Analysis of caves deposits and U-Th speleotheme dating allowed reconstructing the alternating warm and cold climate related to Plio-Quaternary glaciations (in the studied area, at least 13 glacial advance phases have been detected during the last 2.6 Ma).

As a synthesis of field data interpretation, integrated analysis of endokarst points out:

1 - caves origin is old, and due to a long period with a hot humid climate and a contemporary intense tectonic uplifting, while the Plio-Quaternary glaciations do not played any role in endokarst morphogenesis, their influence being on the contrary basic in controlling caves deposits;

2 - karstification is a continuos-in-time process (although it undergoes phases of rapid morphogenesis and phases of predominant cave sedimentation and concretioning);

3 - karstification is contemporary to geological and geographical evolution, being controlled by the tectonic, topographical and climatic history of the region.

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STRUCTURAL SETTING AND LARGE LANDSLIDES IN UPPER ISARCO VALLEY (ITALIAN EASTERN ALPS)

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Matteo Massironi, Bruno Monopoli & Alessio Schiavo

During the geological survey for the Brenner Basis Tunnel project (BBT), a close relationship between brittle regional tectonic setting and large surface slope deformations was found in Isarco, Vizze and Mules valleys (Italian Eastern Alps). This roughly triangular area is bounded by the Pustertal fault system (tectonic boundary between Austroalpine-Penninic nappe-stack and Southern-Alps) and the Brenner line (extensional detachment between western Tauern window and Austroalpine). From south to north the tectonic units are: i) the Austroalpine polymetamorphic basement (mainly retrogade paragneisses and amphibolites) and related Permian-Triassic cover; ii) the overlying Glockner nappe (Mesozoic calcschists and minor metabasalts and serpentinites). The geomorphology of this area is the product of a complex history started during the Pleistocene Alpine glaciations and continuing with post-glacial gravity-dominated slope processes.

Integration of systematic field survey and image interpretation of aerial-photographs, satellite scene and shaded relief products shows that the main "deep-seated gravity slope deformations" (DGSD) and some large rock-fall landslides are strictly related to the major fault systems. Even if the triggering factors of these processes are generally the post-glacial slope release and the energy of relief, lithological and structural features are always important controlling factors.

In this case the tectonic factor is dominant for the following evidences:

i) Location of major landslides is not influenced by lithology (large landslides both in Austroalpine paragneiss and Glockner calcschists).

ii) DGSD location is closely controlled by major fault systems, i.e. the Pustertal fault system and Brenner-related brittle structures.

iii) Numerous trenches and up-hill facing scarps are located in sector of relatively low topographic stress. These features may also be influenced by deep karst dissolution along faults and fractures.

The best example of fault-related DGSD in the study area is at the confluence between the Vizze and Isarco valleys (Giogo di Trens DGSD). This is a pluri-kilometric area characterised by a poligenic landslide complex with several shallow landslides and rock-falls debris which are closely related to the DGSD itself. The main mass movement is controlled by the interference between a major Pustertal-related tectonic line (Sprecken-stein-Val di Mules fault, previously unknown) and a penetrative set of sub-vertical N-S to NE-SW directed faults and joints, parallel to the Brenner low angle detachment. The NE-SW trending ridge between the Vizze and Senges valleys (Giogo di Trens -C. Cavo) and the E-W trending ridge between the Isarco and Vizze valleys (Giogo di Trens- M. Casaclusa) are strongly deformed by hundred-meters long trenches and up-hill facing scarps. Their location and direction are strictly related to faults and fractures.

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THE SPRECHENSTEIN-MAULSER TAL LINE: A NEW TRANSFER-FAULT OF THE PERIADRIATIC SYSTEM, EASTERN ALPS SOUTH OF THE TAUERN WINDOW

Andrea Bistacchi, Matteo Massironi, Rainer Brandner,
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The tectonic relationship between the Brenner low-angle detachment and some major faults of the Periadriatic lineament (North Giudicarie, Passeier, Pustertal, DAV) in the Eastern Alps has been a matter of long debate (e.g., RATSCHBACHER et al., 1991; FÜGENSCHUH et al., 1997; MANCKTELOW et al., 2001; MÜLLER et al., 2001). Our field survey for the Brenner Basis Tunnel (BBT) project has given new data on this problem, providing a more complete tectonic framework of the southern edge of the Austroalpine-Penninic wedge, Maulser tonalitic lamella (Oligocene) and Brixen granite (Permian) along the Franzenfeste-Pfischtal corridor (DAL PIAZ et al., 2001). This area is characterised by: i) numerous NNE-SSW (Brenner-type) faults, dissecting the overturned southern Austroalpine-Glockner nappe stack, and ii) a major WNW-ESE dextral shear-zone, called Sprechenstein-Maulser Tal (Val di Mules) fault. This previously unknown fault runs from the Sprechenstein castle (south of Sterzing alluvial plane, where it probably cuts the ductile-brittle Brenner deformation zone), through the Mauls valley, where it displaces the Pustertal fault, to the Valles valley, where it is evidenced by a wide cataclastic interval inside the Brixen granite. Its NW extension beyond the Eisack (Isarco) valley can not be excluded, as well as a second major fault below the Eisack alluvial deposits which would accommodate the dextral displacement between the Penser Joch and Mauls Permian-Triassic slices.

The dextral movement of the Sprechenstein-Maulser Tal fault is constrained by consistent kinematic indicators (slickensides, T and R-type joints) and the displacement of the Pustertal fault, Maulser Tal tonalitic lamella and Austroalpine-Glockner nappe contact. The dextral offset of the Pustertal line and Maulser lamella is of 1.5 km, while that of the Austroalpine-Glockner contact is of 4.5 km. This kinematics is compatible with the continuing N-S plate convergence, late evolution of the Brenner low-angle detachment and vertical to eastward lateral extrusion of the Penninic units. After the Oligocene magmatic pulse, the Sprechenstein-Maulser Tal fault was the most important tectonic feature in the study area. The recognition of Brenner SC' structures NE of this tectonic line (close to the Sprechenstein castle) and their absence in the opposite side suggest that also the Brenner detachment was dextrally displaced by the NW extension of the Sprechenstein-Maulser Tal fault.

Numerous NNE-SSW faults pervasively dissected the southern Austoalpine-Penninic nappe stack and the Oligocene Rensen pluton. Their sinistral transtensional kinematics is consistent with the brittle dextral movement of the Sprechenstein-Maulser Tal fault.

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POST-NAPPE HYDROTHERMAL ACTIVITY IN THE NORTH-WESTERN ALPS: RELATIONSHIPS BETWEEN GOLD-QUARTZ LODES, LISTVENITES AND EXTENSIONAL FAULT SYSTEMS

Nicola Bistacchi, Andrea Bistacchi, Matteo Massironi, Giorgio V. Dal Piaz & Paolo Omenetto

During the Oligocene, the collisional Penninic-Austroalpine wedge of the north-western Alps was affected by short lived extension and differential uplift. The tectonic pulse was associated to thermal perturbance, partial melting of previously enriched (Alpine subduction) mantle sources and hydrothermal activity supplied by CO_2 and metamorphic crustal fluids. This is evidenced by intrusion of calc-alkaline to ultra-potassic bodies, gold-quartz lodes, and listvenitic breccias. Listvenites occur as large and hard fault breccias arranged in an orthorhombic system (E-W and NE-SW) and, in the Aosta Valley, developed only across mantle-derived serpentinites of the Piedmont ophiolitic nappe.

Listvenitic breccias consist of partly to completely carbonatized serpentinite fragments, cemented by a matrix of polyphase hydrothermal carbonate (mainly dolomite and magnesite) ± quartz. Cr-rich muscovite (fuchsite, after relict spinel), provides the typical green-colour of the fresh rock. Cu-Fe and Pb-Zn sulphides locally occur, together with traces of cryptic gold.

Gold-quartz lodes are mainly located in the axial sector of the belt, from the Gran Paradiso massif to the Simplon dome. The gold-quartz lodes may be subdivided in two main groups, based on their regional trend: i) the southern and central lodes (Gran Paradiso: GP, Traversella: T, Arcesa-Brusson: AB, Val Sesia) have the same orientation of the listvenitic fault breccias and calc-alkaline to ultra-potassic dykes (E-W and NE-SW); ii) the northern lodes (Val Quarazza, Valle Anzasca, Val Bianca, Valle Antrona, Gondo and Crodo) show different orientations (NW-SE to NE-SW). In our opinion, the genesis of the GP-T-AB lodes are roughly coeval with the Oligocene igneous intrusions, on the basis of their areal distribution and structural similarities. Instead the Monte Rosa-Antrona-Simplon gold-quartz lodes are probably linked to the Neogene extensional and sinistral tectonics of the Simplon and Ospizio Sottile fault system. A similar distinction may be envisaged from the available geochronological ages: the T-AB lodes, as the listvenites and calc-alkaline to ultra-potassic bodies, show 33-30 Ma, while the Monte Rosa-Antrona-Simplon lodes show decreasing ages, from southwest to northeast, between 29 Ma and 11 Ma (PETTKE et al., 2000). As a whole, these gold-quartz lodes may be correlated to late metamorphic fluids generated by the devolatilization of the Lower Penninic nappe stack and related Antrona and/or Valais ophiolitic unit.

The E-W and NE-SW trending older group (GP-T-AB), listvenitic fault breccias and calc-alkaline to ultra-potassic bodies are related to the Oligocene extensional activity. The NW-SE to NE-SW trending younger group (Valle Anzasca, Val Bianca, Valle Antrona, Gondo and Crodo) is related to the extrusion of the Lepontine dome and lateral escape of the overlying Pennine-Austroalpine block. The interposed Val Sesia and Val Quarazza lodes display intermediate structural features (E-W and NW-SE trends) developed at around 29 Ma: they mark the change of the tectonic regime from Oligocene ephemeral wedge extension to tectonic denudation of the Lepontine dome and lateral escape of the overlying Pennine-Austroalpine nappes.

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SEISMIC VELOCITY STRUCTURE IN THE EASTERN ALPS ALONG THE TRANSALP PROFILE

Florian Bleibinhaus & TRANSALP Working Group

The state of knowledge of the seismic velocity structure in the eastern alps is based essentially on refraction seismic measurements from the 60ies and 70ies. Huge charges and large observation distances resulted in 70 km deep models, but due to only few observations with low resolution. During the TRANSALP experiment explosion and vibroseis signals had been recorded in an area between Munich and Venice by a network of up to 128 three-component stations. At some stations the vibroseis signal can be observed in distances of almost 100 km. Tomographic inversion of the traveltime information of the first breaks results in a high resolution image of the upper crust, which is well correlated with several geological features along the profile. Strong anisotropy in the upper crust in and around the Tauern Window with the fast axis oriented EW indicates dominant strain in this direction. Constraints on model refinement at deeper crustal levels is provided by explosion seismic wide-angle reflections recorded in up to 180 km offset.

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METAMORPHISM AND FLUID REGIME DURING CORE COMPLEX EXHUMATION: AN EXAMPLE FROM GLEINALM COMPLEX (EASTERN ALPS)

Ana-Voica Bojar, Harald Fritz, Hans-Peter Bojar & Jürgen Loizenbauer

Within the Gleinalm area, high grade Middle Austroalpine crystalline basement units are juxtaposed along a steep shear zone against low grade metamorphosed Upper Austroalpine Graz Nappe Complex (NEUBAUER et al., 2000; NEUBAUER et al., 1995). Condensed isotherms suggest large amount of vertical displacement associated with sinistral shear. In order to quantify pressure-temperature conditions and possible contribution of fluid circulation to metamorphism, collaborative pressure-temperature data from stable mineral paragenesis together with stable isotope and fluid inclusion studies have been performed within the Middle Austroalpine Micaschist–Marble–Complex (MMC).

Within the MMC, temperature-pressure conditions during onset of the Gleinalm core complex exhumation are constraint by: a) garnet I – biotite (FERRY and SPEAR, 1978) and plagioclase – amphibole thermometers (HOLLAND and BLUNDY, 1994) and b)garnet I-plagioclase-biotite-muscovite-quartz barometer (GHENT and STOUT, 1981). The first garnet generation are up to 1 cm, shows prograde zoning with rim P-T conditions of 6-7 kbar and 550°C–600°C. A second stage of exhumation with conditions of 5–6 kbar and ca. 500°C is constraint by garnet II-biotite thermometer and sphalerite-pyrrhotite-pyrite barometer (LUSK and FORD, 1978). This mineral assemblage includes small unzoned garnet II and is found on foliation planes surrounding the first generation of garnet.

Three different types of fluid inclusions, from tension gashes related to late stage exhumation, were used for microthermobarometry. Type one and two inclusions are CO_2 and $CO_2 - H_2O$ rich, low density and low salinity inclusions. Constructed isochores together with temperatures estimated considering the rheological behaviour of quartz define a field of ca. 2 kbar and 350°-400°C. Very late fluids with high salinity and solid NaCl crystals (ca. 30 wt% NaCl equivalent) define a box of ca. 1 kbar and temperatures up to 150°C.

The constructed P-T-path includes isothermal decompression during early stages of exhumation, followed by isobaric cooling at levels about 1–2 kbar. We interpret these data by rapid exhumation of hot Middle Austroalpine units close to surface, exhumation that disturbed the local isotherms.

Detailed oxygen isotope data across marble layers alternating with pelitic schists show modification of initial step function shape during Late Createaceous metamorphism. The oxygen isotope profiles have a shape which fits the modelled curves for advective-diffusive transport in a fluid phase (BICKLE & MCKENZIE, 1987; BICKLE & BACKER, 1990; BOWMAN, WILLETT, & COOK, 1994). The advective displacement of the profiles are around 40 cm towards the lower metamorphic grade which implies an upwards component of fluid flow. For the pinned boundary solution the calculated time integrated fluid fluxes are of ca. 0.3 m^3/m^2. Flow along interconnected porosity took place over a total time of ca. 0.5 Ma.

We interpret the data as follows. (1) During early exhumation internal fluid circulated mainly within lithological units. The calculated vertical fluid flux integrated during the time of fluid flow could not have induced a significant thermal anomaly during the metamorphism. (2) During final exhumation, interconnected pathways opened by brittle deformation. High salinity fluids suggest infiltration of marine surface water. (3) The highly disturbed isotherm is interpreted to reflect rapid exhumation of the Gleinalm core and coeval sedimentation of the Gosau sediments.

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THE METAMORPHIC HETEROGENEITY OF THE SCHISTES LUSTRÉS (ENTRELOR AREA, WESTERN ALPS): WHICH IMPLICATIONS FOR THE ALPINE EVOLUTION?

Romain Bousquet & Stefan Schmid

Eclogites and eclogites-facies rocks in mountain belts provide significant information on the early stages of orogenic processes. Their relationship the eclogites-facies rocks with lower metamorphosed rocks (i.e. blueschist- and greenschist–facies rocks) can provide information on the late stages of orogenic processes. In the Piemontese zone of the Western Alps, the eclogites and the other rocks are classically associated to two different units (figure 1). The first unit, called the Zermatt zone in the north or the Lower Unit in the South, is well known for its high-pressure mineral assemblages (more than 20 kbar, 600°C, REINECKE, 1991). The second and tectonically high unit, the Combin zone in the north or the Upper unit in the South, was metamorphosed under lower conditions (8-10 kbar, 400°C, BALLÈVRE AND MERLE, 1993).

In the Entrelor area, the Piemontese Schistes Lustrés occur as a small piece, pinched between eclogitic rocks of the Gran Paradiso massif below and blueschist rocks of the internal Briançonnais (13 kbar, 500°C, CIGOLINI, 1995) above. On one hand, this zone either represents the contact between the HP and LP units (Figure 1a, Elter, 1972, DAL PIAZ, 1999), or is considered as a piece of the HP unit (Figure 1b, BALLÈVRE AND MERLE, 1993). On the other hand, the contact of the Schistes Lustrés and the internal Briançonnais is interpreted either as a top-E backthrust acting between 34 and 37 My (Figure 2a, FREEMAN AND AL., 1997), or as an top-W extensional shear zone (Figure 2b, CABY, 1996).

A study of the metamorphism in this area, carried out on the metapelites, reveals that these rocks do not contain mineral assemblages indicating very high-pressure conditions. The mineral assemblage for pressure peak is formed by the association of Ctd, Pg and phengites included in almandine-rich garnets (Alm 60%, Gros 30%). The pressure peak is estimated from this assemblage at around 13-14 kbar for temperatures between 400 and 450°C. Additionally a detailed study of the metabasites shows that these rocks can be divided in two groups. The first is composed of rocks, which contain mineralogical assemblages, well preserved or as relic, which indicate HP metamorphic conditions (18-20 kbar, 500–550°C). The second type of rocks is formed by metabasites, which were never submitted to eclogitic conditions. These rocks contain mineralogical assemblages with glaucophane and tremolite as inclusion in albite. A preliminary estimate of the metamorphic conditions gives a pressure around 10 kbar for temperatures between 400 and 450°C. Such assemblages and conditions have been described for the Combin zone (BALLÈVRE AND MERLE, 1993).

As a consequence of this result there is no metamorphic jump between the Zermatt zone and the internal Briançonnais (Zona Interna). Rather, the Piemontese zone represents a melange, we refer to as the Entrelor melange in this area, consisting of eclogites facies mafic knockers embedded in a blueschist facies matrix consisting of metapelites and prasinites.

Structural data indicate that the Entrelor shear zone is not a backthrust (movement top-to-the-west!), which confirms the idea that there is no metamorphic jump between the metapelites of the Zermatt zone and the Zona Interna.

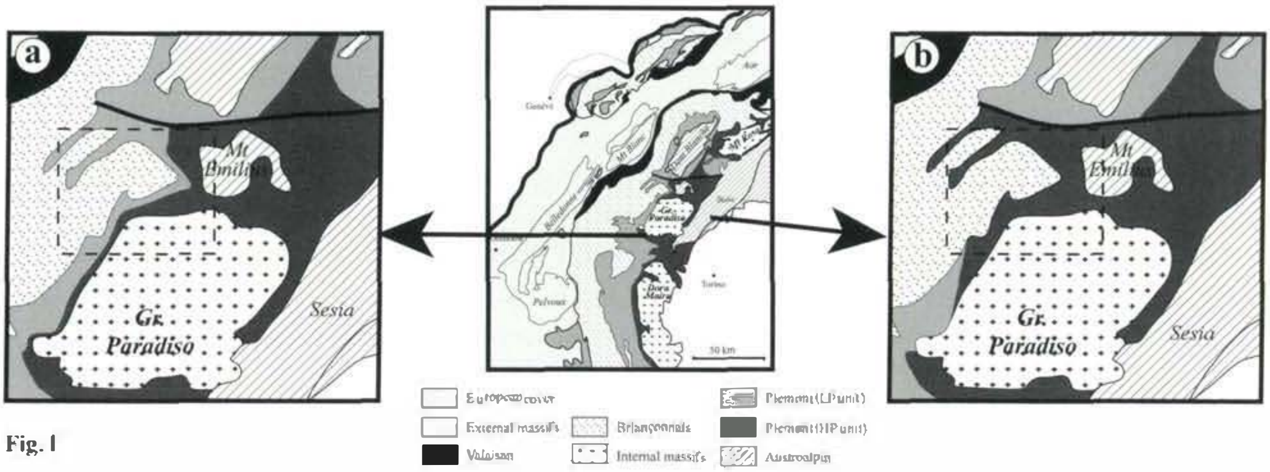

Fig. 1

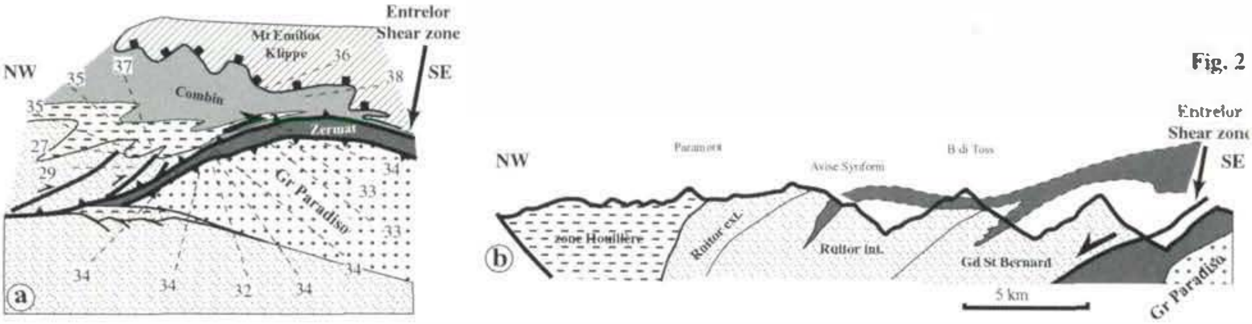

Fig. 2

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REGIONAL EXTENSION BETWEEN MESOALPINE AND NEOALPINE COMPRESSIONAL STRUCTURAL SYSTEMS NORTH AND SOUTH OF THE PERIADRIATIC LINEAMENT (LIENZ DOLOMITES AND EASTERN SOUTHERN ALPS)

Rainer Brandner, Alfred Gruber, Christoph Prager, Dieter Lutz & Hugo Ortner

Along the alpine retrowedge of the Eastern Alps the two structural domains of the Lienz Dolomites (LD, Fig. 1) and the North-eastern Dolomites (ND, Fig. 2) show different Eoalpine to Mesoalpine deformation histories, but similar tectonics in Oligocene and Miocene. In both domains extensive, grabenlike structures of Oligocene age are recognized.

NW of Cortina (Col Bechei area) NW-SE-trending grabens are filled with breccias, conglomerates and sandstones of a coastal marine environment with Oligocene index fossils (KEIM & STINGL 2000). This facies is correlatable with Southern Alpine molasse sequences of the Belluno basin toward the south. Normal faults of the grabens cut obliquely Eocene (CASTELLARIN & CANTELLI 2000) Dinaric top-to-SW thrusts and NW-SE-trending folds. Towards NE (Sexten Dolomites) the hanging-wall of the early Dinaric Sarlkofel-thrust is dissected by NW-SE-trending graben structures (Fig. 2). Both, the sediment-filled grabens of Col Bechei and the Sexten grabensystem are in the position of inward foreland basins in front of the Oligocene Dinaric belt, with SW verging thrusts and folds.

To the NW the belt was bounded by the Giudicarie-fault-system and to the N by a broad, NE-striking sinistral wrench corridor, concerning the whole area in between the DAV-line in the S and Inntal- and SEMP-line in the N. We consider the NW-trending folds and related NE-striking cross faults in this sinistral corridor to be kinematically connected to the Dinaric orogenic chains (see also POLINSKI & EISBACHER 1992).

The entire Drauzug, including the LD, is part of this sinistral transfer system. Along the "Defereggen-Drauzug-wedge", which is bordered in the N by the sinistral ductile DAV-line, E-W-trending transtensional structures affected the Permomesozoic cover rocks. Vertical displacements of normal faults inside the grabens attain up to a few kilometres. We emphasize, that these structures cut here the Eoalpine (N-S-trending) and Mesoalpine (E-W-trending) large scale folds and split them into several isolated slices.

From Oligocene the structural development of both domains was determined by the indentation of the Southern Alpine block. Sinistral movements along the ductile DAV-line ended in the Lower Oligocene (MÜLLER et al. 2000). During uprise of the Periadriatic magmatites a significant transition from sinistral to dextral shearing took place (MANCKTELOW et al. 2001): since then the dextral Periadriatic lineament (PL) starts its dominant tectonic role for LD and ND. A pattern of SE-directed thrust folds and NW-striking dextral cross faults developed in both areas, in the Southalpine ("Valsugana structural system", CASTELLARIN & CANTELLI 2000) as well as in the Austroalpine. The Bechei Basin and coeval grabens (e. g. Remeda Rossa) are closed by SSE-verging thrusts. NW-SE-trending normal faults of the Dinaric inward foreland basins in the Southern Alps have been reactivated as dextral strike-slip faults, e.g. the Rauhtal-masterfault (Fig. 2).

The Oligocene normal faults of the LD-grabens are reactivated as strike-slip faults, conjugated to the PL. In the vicinity of the "Südrandstörung" the polyphase and heteroaxial deformation caused the formation of E-W-trending zones of polymict cataclastic fault breccias ("Hochstein-Pittersberg-Breccie"). As in the Mauls area the Südrandstörung parallel to the PL is cut by NW-SE-striking normal faults (Auenbach-Griesbach shear zone) and dextral strike-slip-faults (Tuffbad shear zone, Fig. 1). All these NW-SE-trending dextral faults (including Gitschtal- and Mölltal line) displace the PL and are part of the indentation process triggered by the Adria plate motion to the NW during Miocene-Pliocene (CASTELLARIN & CANTELLI 2000).

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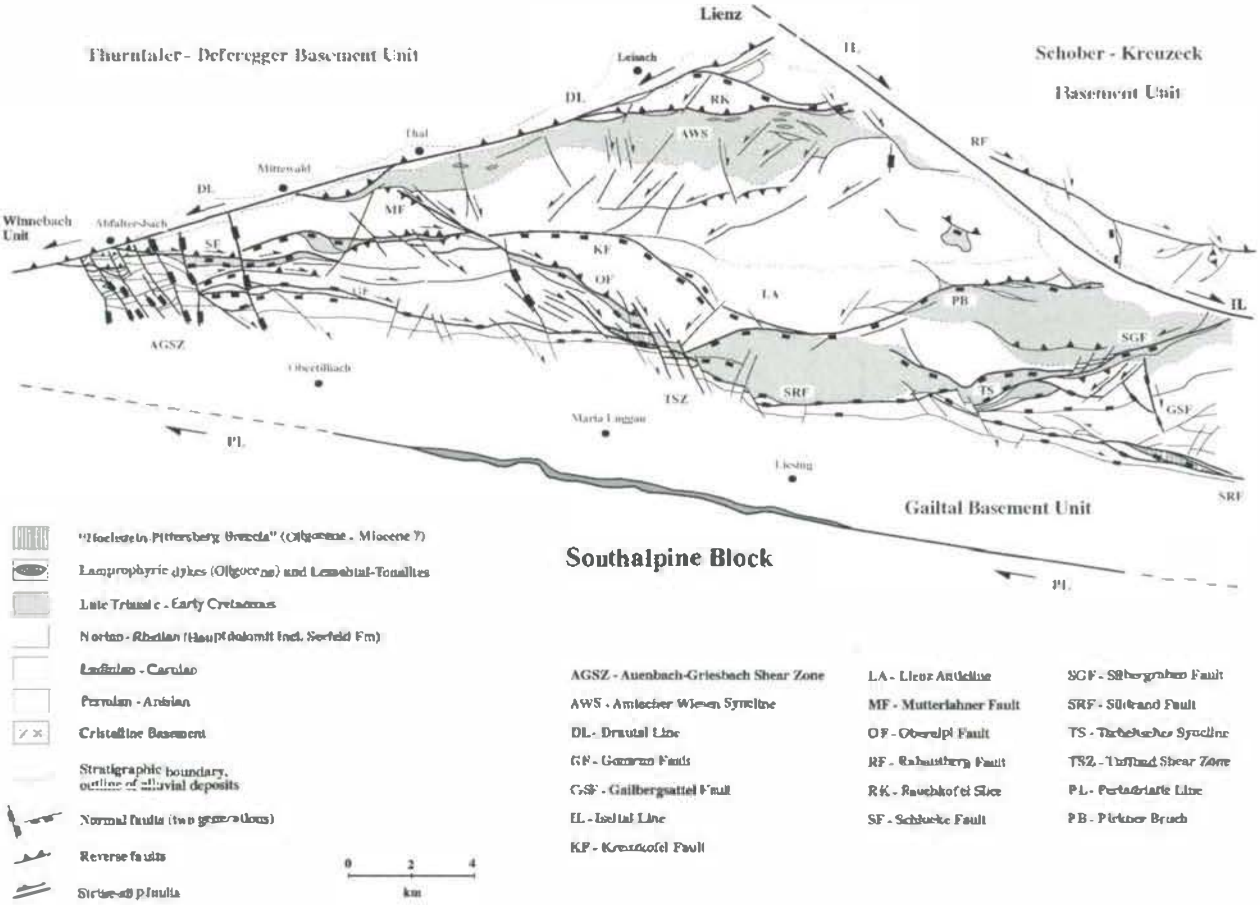

Fig. 1 - Tectonic scetch map of the Lienz Dolomites with main stratigraphic units


ZG
PG
RG
PTF
SKT
HGF
RRF
PATAL
CBG
VSL
RL
0 1 2

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POST-NAPPE FOLDING VERSUS BACKTHRUSTING IN THE WESTERN ALPS

Stefan Bucher, Stefan M. Schmid, Romain Bousquet & Bernhard Fügenschuh

The main schistosity along the ECORS-CROP profile changes from a SE-dip in the external part of the Briançonnais (Front Briançonnais) to a dominant NW-dip in the southeastern part (Gran Paradiso). This change in dip is directly linked to the overturning of the entire nappe pile. Metamorphic grade also changes from subgreenschist facies in the more external Zone Houillère to eclogite conditions in the more internal Schistes Lustrés and the Gran Paradiso "massif". In the west metamorphic grade increases towards tectonically higher units, while in the east a decrease in the metamorphic grade towards tectonically higher units is observed. Classically the change in dip, the so-called fan-structure of the Briançonnais, was explained by outward directed thrusting followed by inward directed backthrusting (e.g. BUTLER and FREEMAN, 1996).

New structural investigations carried out in the Zone Houillère form the Petit Saint Bernard Pass to the Gran Paradiso allow us to distinguish the following three deformation phases. The first deformation phase is only preserved as relicts such as microlithons of chloritoid or as an old schistosity formed by chloritoid and phengite in garnets. D1 is associated with peak pressure conditions in terms of metamorphism. The second phase of deformation is characterised by isoclinal folds and a strong W to NW oriented stretching lineation L2. D2 fold axes are sub-parallel to L2 and the strong axial planar cleavage of D2 folds forms the main foliation. In the internal parts the D2 schistosity is outlined by the orientation of white mica, epidote and chlorite, which replace high-pressure mineral assemblages. Therefore D2 corresponds to the decompression part of the P-T path. Over the entire area shear senses associated with L2 consistently indicate top-to-the W to NW movement. D3 is characterised by open folds on all scales with gently SE dipping (5°–20°) axial planes and, in general, by NE-SW oriented fold axes. Towards higher structural levels F3 folds become tighter.

D3 mega folds overprint a pre-existing nappe stack formed during D1 and D2. In particular the overturning of tectonic contacts such as (i) the contact between the Zone Houillère and the Ruitor massif in the external part and (ii) the contact between the Schistes Lustrés and the internal Brianconnais in the internal part can be directly observed in the field. Retrodeformation of the D3 post-nappe folds suggests that these contacts (including the so-called Entrelor shear zone which was erroneously attributed to backthrusting by BUTLER and FREEMAN, 1996) originally represented top-to-the northwest thrusts, which formed during the final stages of nappe stacking (D2).

Based on structural mapping the axial traces of two such large-scale D3 folds could be identified. In the external part the change of dip of the main foliation from a SE-dip in the Valaisan and the external parts of the Zone Houillère over a subvertical dip within the Zone Houillère, to a predominant NW dip within the Ruitor massif is due to the large-scale Ruitor antiform. In the internal part the Valsavaranche synform was evidenced in the upper parts of Val Grisenche and Val di Rhêmes. This second and structurally higher D3-megafold turns the nappe stack back into an upright position such as observed in the uppermost part of Valgrisenche (i.e. the Grande Sassière area).

These observations show that the third phase of deformation refolds the entire nappe stack on a large scale such as first described by Argand (1911). While similar large scale post-nappe refolding with subhorizontal axial planes has also been described by modern workers in the Swiss-Italian Alps (for example in the form of the Mischabel backfold or the backfolds of the Suretta nappe (MÜLLER, 1982; SCHMID et al., 1996) this old idea has not yet been revived in the French-Italian Alps.

These structural data show the so-called fan-structure of the Briançonnais as well as the overturning of the whole nappe stack are due to large scale post-nappe folding (Ruitor antiform and Valsavaranche synform). However, no evidence for backthrusting, frequently reported in the literature (e.g. BUTLER & FREEMAN, 1996), was found. Hence we purpose that post-nappe folding rather than backthrusting along the ECORS-CROP profile is responsible for the present day geometry of the nappe stack. The syn-D3 wedging of the Gran Paradiso massif into the nappe pile might be responsible for this refolding which is associated with vertical shortening, following Argand (1912) who wrote: "*Le rétroplissement par sous-charriage (Rückfaltung durch Unterschiebung) est une fonction normale des grandes chaînes en mouvement*" which we freely translate as following: "backfolding by underthrusting is a common feature of growing mountain chains".

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LITHOSTRUCTURALLY INDUCED FRACTURE FLOW SYSTEMS AND GROUNDWATER PROVINCES - ROUTE OPTIMISATION OF A DEEP LYING TUNNEL IN THE WESTERN CALCAREOUS ALPS, VORARLBERG, AUSTRIA

Ulrich Burger, Rainer Brandner & Gerhard Poscher

1. Introduction

A hydrogeological study is being carried out to select and optimise a route for a deep lying tunnel (Erzberg Tunnel, Stuben-Zürs/Lech) in the Northern Calcareous Alps west of the Flexen Pass, Vorarlberg, Austria. Besides a lithostructural elaboration of possible routes, a clarification of the fracture flow systems and groundwater provinces is seen as essential in order to understand the interplay between the proposed tunnel and groundwater, and the possible effects of a tunnel on the existing surface and groundwater supplies of the ski resorts of Stuben, Lech and Zürs.

Initial investigation results show, on the one hand, a close connection between the lithostructure of the investigated area and, on the other hand, the distribution of groundwater provinces, the course of the hydraulic systems and the physiochemical properties of the groundwater.

2. Methodology

A detailed lithostructural survey and evaluation of aerial photographs provide the basic data for the palaeo-stress analysis, the objective of which is to determine the orientation of the main stress direction ($\sigma 1$) and the corresponding conjugate main extension direction ($\sigma 3$).

The hydrogeological survey serves to identify and hydrogeologically characterise the lithological units and structural elements, as well as to locate the main groundwater discharges. Taking water samples and analysing the standard chemical parameters, determining the $\delta^{34}S$, $\delta^{18}O$ and tritium values, as well as measuring the physical parameters (°C, µS/cm, discharge) on site, as part a hydrologic status-quo documentation, allows for a typification of the encountered ground- and surface waters.

By overlapping the lithostructural and hydrogeological data, their connections are clarified, and enables the fracture flow systems and groundwater provinces to be located, defined and orientated and their hydraulic properties to be characterised.

3. Lithostructural Framework

As part of the western section of the Northern Calcareous Alps, the investigation area includes the characteristic geological stratigraphic sequence from Permian-Scythian Formations to Cretaceous Carbonate Formations. The distribution and structure of the geological formations within the region reflect the complex deformation history.

Jurassic to Cretaceous extension led to the development of a range (Zürser Schwelle) and deeper lying blocks, which were bounded by steeply dipping normal faults. Later the normal faults were reactivated as strike slip faults during ensuing compressive deformation phases. The Zürser Syncline is located in a distensive area of a sinistral transfer zone of two sinistral strike and slip faults striking NW-SE to N-S. Towards the south, the syncline is bounded by a steep dipping transfer fault striking E-W (Stubenbach Fault according to May (1998)). The development of the Zürser See Syncline, as a complex extension basin during the compression, can thus be described as an example of the development of Synorogenic Cretaceous Basins in the western Northern Calcareous Alps as postulated by MAY & EISBACHER (1999).

In the course of more recent compressive phases, the older structures were reactivated or sheared. Especially during the most recent compressive phase, faults striking NW-SE formed in the area of dextral transfer zones, along with deep and sometimes very wide open joints and fractures, striking NE-SW. During the construction of the Blisadonna Tunnel, Kloster Valley, Vorarlberg, these fractures were responsible for large water ingressions and therefore significant elements during the tunnelling process, as documented by RIEDMÜLLER (pers. comm. 2000) and STEINDORFER et al.(2000).

4. Hydrogeological Consequences

The complex structural geology is reflected in the distribution of the groundwater discharges, their physiochemical properties and their isotope values ($\delta^{18}O$ and $\delta^{34}S$).

4.1 Structural Influences

The groundwater flow systems are related to karstic geological formations and extension structures created during compressive tectonics. A paleo-stress assessment and division of the region in homogenous tectonic domains (using the methods of FERNANDES & RUDOLPH, 2001) shows that due to a roughly N-S oriented compression, dextral strike slip faults formed, striking NW-SE, in whose dextral transfer zones NE-SW striking extension structures developed which are of significance for the drainage of the southern section of the investigation area. While the southern part of the investigation area drains mainly toward the Kloster Valley, due to the geological structures, the middle and eastern sections drain toward the Flexen Valley.

4.2 Litological Influences

Especially the Ca/Mg-ratio, the SO_4 content and the $\delta^{34}S$ values provide information about hydrochemically important rock in the catchment area. These values also show traces of tunnelling relevant geological formations which do not crop out at the surface (e.g. Reichenhaller Formation). Based on the hydrochemical and $\delta^{18}O$ isotope data it can be ascertained that the lowest lying springs (Flexen Valley) have the highest lying catchment areas. Also, it can be probably ruled out that the eastern and western sections of the N-S striking Flexen Valley are hydraulically isolated, a fact which may significantly influence the amount of water ingress during tunnelling.

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AN ESTIMATE OF THE AVERAGE STRAIN RATE IN THE ITALIAN CRUST INFERRED FROM A PERMANENT GPS NETWORK

Alessandro Caporali, Silvana Martin & Matteo Massironi

Surface horizontal displacements in an area bounded by the Alpine chain to the North and Mediterranean/Ionian sea to the south have been determined by computing and analyzing time series of 33 permanent GPS stations with data coverage from one to five years of continuous operation. The horizontal velocities are defined consistently with the ITRF97 velocity datum. The covered area is characterized by a wide range of tectonic phenomena, such as indentation of the Adria block into the Eastern Alp, lateral extrusion of the Tauern Window, possible unbending of the Adriatic lithosphere, opening of the Thyrrenian sea and subduction of the Ionian lithospere beneath the Calabrian arc. This ongoing tectonics is accompanied by a relatively intense volcanism and seismicity, which could result in horizontal and vertical displacements. The velocities and their uncertainties are estimated on the basis of a detailed investigation of the noise model most suitable for the time series. We show that the estimated velocities, never larger than 5 mm yr^{-1} relative to those predicted by the NUVEL1A NNR rigid body model, in several cases do reflect qualitatively the expected kinematics. Areas characterized by fracturing and faults with orientations changing on a short scale (Tauern window, Apennines) exhibit instead a more irregular distribution of velocities, probably associated with more local phenomena. Eigenvalues and eigenvectors of a mean strain rate tensor are computed by optimally – in a least squares collocation sense – interpolating the station velocities to locations baricentric to clusters of stations. The estimated strain is every where smaller than 29 x 10^{-9} yr^{-1} with a mean uncertainty of 5 x 10^{-9} yr^{-1} (1 sigma). The areas with largest strain are the central Apennines and NE Italy. The azimuths of the strain rate ellipse are qualitatively compared with the directions of the stress estimated from fault plane mechanisms and borehole breakouts, and with the strike of major faults. In all cases we observe that the observed orientations are consistent within the estimated uncertainties, and conclude in favor of evidence of a yet qualitative but significant correlation between broad scale (~300 km) stress and strain rate patterns, and orientation of large scale active lineaments.

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THE UPPER CRUST STUCTURE OF THE SOUTHERN ALPS ALONG THE TRANSALP SEISMIC LINE

Alberto Castellarin, Luca Bertelli, Roberto Fantoni,
Alessandro Mosconi, Camillo Pessina & Mattia Sella

The eastern Southern Alps, located to the east of the N Giudicarie Line, has been originated by polyphase compressional evolution of Tertiary age.

The oldest structural system corresponds to the Mesoalpine (Eocene) and early Neoalpine (Oligo-Miocene) compressional events, which originated the Dinaric structural system (NW-SE trending), recognised in the NE side of the Southern Alps.

The subsequent tectonic belt is the Valsugana Structural system, ENE-WSW trending, Serravallian – Tortonian in age. The intense activity of this compressional event is documented both by stratigraphic- structural data and by fission track studies which indicate uplifting of some 4 km in the hanging wall of the Valsugana overthrust between 12 and 8 Ma B.P.

The most external structures NE-SW trending are located in the Montello-Friuli zone which were generated by the Messinian-Pleistocene compressions (whose principal stress axis is NW striking).

The Transalp seismic line (350 km from Munich to Treviso) in the Eastern Alps has been acquired during 1998–199. A combined survey with vibrator-explosive source provide a good resolution in the upper crust and a deep lithospheric penetration.

The results of the vibroseis profile in the Italian sector of the line are in substantial agreement with previous structural interpretation for the upper crust.

The profile shows along the foothill of the southern border of the orogenic chain, the Venetian foreland is thrusted by a large south-verging structure (S. Maria di Feletto-Montello Anticline, BVM thrust system in Fig. 1), involving both the syntectonic Paleogene-Pleistocene clastics and the underlying Mesozoic carbonatic units.

To the north, in the adjacent structural belt of the Southern Alps the Mesozoic carbonatic units are thrusted along three main south-verging overthrusts (S. Boldo, Belluno and Valsugana lines). These thrusts involve the underlying crystalline rocks of the metamorphic basement, largely outcropping in the Gosaldo-Agordo nucleus (Valsugana structural system, VV in fig. 1). These main trusts are decakilometrically spaced with about 10 km in shortening and 5 km in vertical displacement component, each one.

In the northern part of the Southern Alps (Dolomites) the seismic profile shows the outcropping Triassic units affected by south- and north-verging thrusts whose surfaces involve the Variscan basement.

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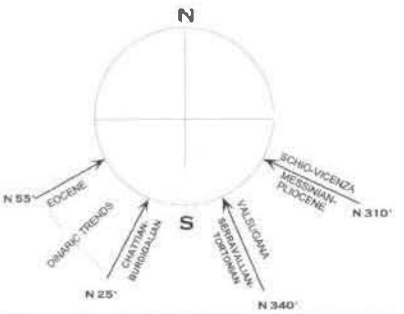

L.: tectonic line, lineament, overthrusting, transfer faults. S.: local structural system. B.: structural belt. Palmanova L. (PL); Udine L. (UD); Bernadia L. (BE); Sacile L. (SC); Bassano-Valdobbiadene-Montello L. (BVM); Caneva L. (CA); Pinedo-Avasinis L. (PAV); Barcis-Staro Selo L. (BT); Alto Tagliamento L.-Fella L. (ATF); Sauris L. (SA); Val Pesarina-Lozzo L. (VPL); Pontebba-Tarvisio L. (PT); Poludnig L. (PG); M. Zermula-M. Cavallo L. (ZC); Forni Avoltri-Ravascletto L. (FR); Croce di Comelico-Val Visdende L. (CCV); S. Candido-S. Stefano di Cadore L. (SCST); Val Bordaglia L. (VB); Dolomiti di Sesto S. (DS); Funes L. (FU); Falzarego L. (FZ); M. Parei-Col Becchei-Fanes S. (PB); Stava-Collaccio L. (ST); Marmolada-Antelao L. (MA); 'Giunzione Cadorina' (GA); Valsugana S. (VV); Val di Sella L. (VS); Colombarone klippe (C); Belluno L. (BL); Cisetta L. (CI); Duron-Fedaia L. (VDF); Foiana-Mezzocorona S. (FMZ); Trento-Cles L. (TC); Calisio L. (CAL); Val d'Astico L. (VAS); Schio-Vicenza L. (SCHV); Castel Madera klippe (MA); Rovereto-Riva-Arco transfer zone (R); Recoaro zone (RE); Cima Marana L. (CM); 'Flessura Pedemontana' (FP); M. Pastello-Ala L. (PAL); Volta Mantovana L. (VM); Doss del Vento L. (DV); Tremosine-Tignale-Costa L. (TT); Giudicarie S. L. (GS); Val Trompia L. (VTP); Brenta Group S. (BR); Ballino L. (B); M. Baldo-M. Stivo-M. Bondone L. (MB); Sarca-Paganella L. (S); Molveno L. (MO); Pre-Adamello B. (PA); Gallinera L. (GA).

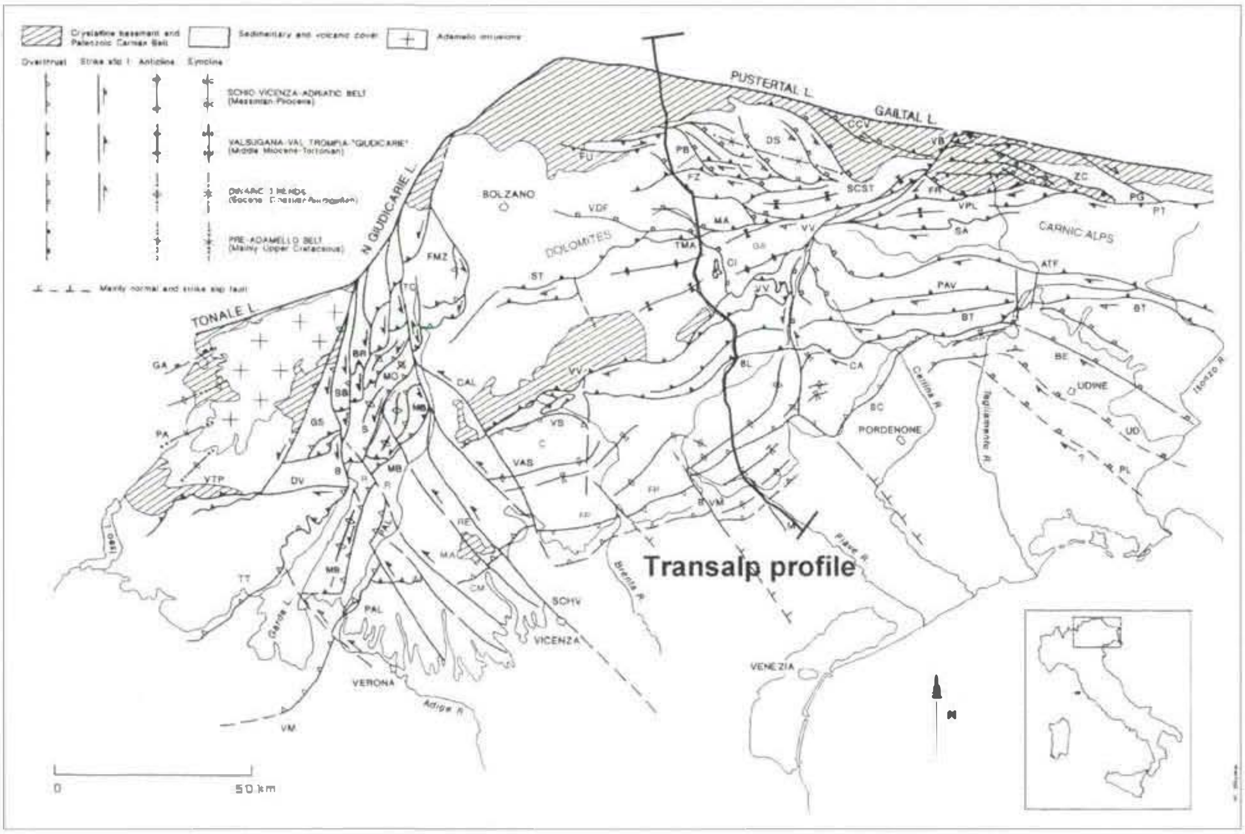

Fig. 1: Syntetic structural map of the eastern Southern Alps

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THE TRANSALP SEISMIC PROFILE: REMARKS AND INTERPRETATIONS FROM THE ITALIAN SIDE

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and the Transalp Working Group (***)

The Present structure of the Eastern Alps orogenic chain was mainly originated during their post collisional evolution which enhanced the intense difference between the Europe-N-vergent nappe thick stack of the Northern tectonic edifice and the contrasting Africa-S-vergent thrust belt of the Southern Alps. The Periadriatic Lineament corresponds to the strong structural divide of these two parts of the Eastern Alps (EA). The N vergent nappe stack of the EA originated during pre-collisional (Late Cretaceous-Paleocene) and collisional (early to middle Eocene) evolution. The N- and S-vergent thrust belts along both border sides of the EA, overrode the Oligocene-Neogene clastics of the Molasse (mostly Chattian- Tortonian) and are expression of the post-collisional, neo-Alpine evolution of the EA. The post Tortonian evolution occurred only to the S, and strongly affected the Montello kilometric Messinian deposits up to the overlying Pliocene marine cover

(Cornuda), along the external strongly deformed structural belts of the Venetian Plain N border. These Late Neogene to Pleistocene tectonic deformations are consistent with the Adria Micro-Plate motion to the NW for some 15-20 km in amplitude, as documented by field structural analysis (Castellarin et al.,1998). Thus, the EA neo-Alpine evolution occurred according to out of sequence opposite stuctural accretion along the N and S borders of the orogenic chain.

With regards to the buried crustal and lithospheric setting reconstruction, the deep seismic reflexion data along the Transalp Profile (TsAP) show a prominent major seismic break beneath the belt, roughly interposed between the Periadriatic (or Insubric) lineament (PL) and the southern surfacial limit of Alpine metamorphism (SAM). The break substantiates at depth the sharp surface limit between the Alps (Europe-vergent nappe stack) and the Southern Alps which is evident in the geological maps (Bigi et al., 1990) and at the surface, where the PL dips always to the N along the Pustertal with strong backthrusting of the Austroalpine units over the Southern Alps sequence (Dal Piaz, 1934). The most important intrusive bodies crossed by the Transalp Profile are the eastern tail of the Lower Permian Brixen granite and the Oligocene (30 Ma) Rieserferner tonalite (Bigi et al.,1990). The block to the N of the IL (Penninic wedge) is less reflective and locally transparent. These features are probably related to the still soft behavior at depth of the nappe stack and the subvertical to high angle attidute of major internal discontinuities. The Penninic wedge corresponds to the Penninic nappe stack exposed in the Tauern window (TW), consisting of gneissic granitoids

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(Zentral Gneis), pre-granitic basement and Permian-Mesozoic cover metasediments, capped by the ophiolitic Glockner nappe, exposed as two huge antiformal belts (e.g., LAMMERER & WEGER, 1998).These continental and oceanic units underwent intense N-S shortening and vertical extrusion, coupled with orogen-parallel extension and tectonic denudation of the Austroalpine orogenic lid (BEHRMANN, 1988; FÜGENSCHUH *et* al., 1998; CHRISTENSEN et al.,1994). Exhumation of 30-35 km in the last 40 Ma (mostly between 20 and 15 Ma, *i.e.,* in early-mid Miocene times) is documented by the 10 kb decompressional P-T path evolution recognized in the same interval (VON BLANKENBURG et al., 1989; etc.). Furthermore, the European Moho, along the Profile, dips regularly to the S attaining the zone below the N side of the TW. Consequently, ductile deformation and uplift of the TW structure are, very likely, representative of intra-crustal extrusion processes confined to the colliding orogenic wedge. To the S of the IL, unlike the TW, the Dolomite area underwent only moderate uplift (about 3-4 km) as documented by the outcropping low grade metamorphic basement and its Permo-Triassic non-metamorphic cover, located close to the IL (Plan de Corones) and by fission track studies. Furthermore, the block to the S of the PL is more reflective and is composed by a stack of strongly laminated, thick subunits mid angle dipping to the S and well marked from about 25 up to about 10 km. The laminated subunits are sharply interrupted by smooth, lobed up to rounded transparent zones beneath and close the PL from about 5 to 25 km depth. These seismic stuctures may be interpreted as intrusive bodies of Permian and/or Oligocene age as the bodies largely outcropping in the surrounding of the profile (BIGI et al., 1990) which can be referred to the E and W continuation in depth respectively of the Brixen Permian batholith and of the the Oligocene Rieserferner pluton. The contiguous reflective laminated subunits may be related to pre-granitic mafic interleavings and/or cumulus gabbro-ultramafic bodies and their possible pre-Alpine tectonic duplications along ductile shear zones, which may be interpreted as Hercynian (or older) lower crustal zones of the Southern Alps, dragged and upwarped by the Alpine extrusion of the TW structure.

In this frame, the N-dipping break zone beneath the PL can be interpreted as the N edge of the Adriatic indenter against the overturned rear of the Alpine orogenic wedge, a mantle-free float belt of continental and oceanic units above the subducted European lower plate. This northward protrusion of Adriatic lithosphere explains the exhumation of the TW Penninic wedge by **ductile extrusion** mechanisms. The structure and geometries of the Adriatic indenter are similar to those predicted by ARGAND (1924) and more recently recognised in the Western and Central Alps (ECORS-CROP and NFP20 Profiles, see from ROURE et al.,1990 onward). Wedge indentation by the Adriatic lithosphere is consistent with the upper crustal thrust belt of the Dolomites and, in general, of the eastern Southern Alps, which can be considered as the tectonic stack to the S of the decoupled upper crust, supplied by the underlying lower crust and lithospheric mantle during their indentation to the N. The shortening of some 40 km recorded across the Southalpine thrust system is consistent with the amount of the indentation to the N, shown by the seismic image, for a similar amplitude, under the TW structure. Finally, the relevance of the Adriatic indenter points to the late post collisional change in the tectonic growth of the EA orogenic chain. In fact, from the late Miocene (Messinian) onward, the tectonic accretion was transfered from the N frontal zones of the Alps to the S vergent thrust belt of the Southern Alps as a consequence of the deep underthrusting of the Adriatic lithosphere and of its further indentation to the N.

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KINEMATICS AND ROTATION OF THE WESTERN ALPS: PALEOMAGNETISM AND ANALOGICAL MODELISATION

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In the western Alps, most kinematic models have considered that, since the late Cretaceous, the convergence between the Adriatic and European plates has been dominantly accomodated by both thickening and horizontal translation of tectonic units. Some models have also inferred large rotations about vertical axis but no data are presently available to support this mechanism. In order to test this hypothesis, we have conducted a paleomagnetic study on the Briançonnais zone of the Western Alpine Arc. This zone features complexe folding structures associated with high pressure- low temperature metamorphism (about 300°), leading at least to a partial remagnetization of remanent magnetization (NRM) during late Eocene-Oligocene period. This remagnetization therefore allows to accede to the post-metamorphic history of the internal units of the Alpine Chain.

About 350 samples on 37 sites were sampled in upper Jurassic rocks (Ammonitico Rosso facies) of the southwestern Alpine Arc, in an area extending from the Grand Galibier massif to the North, to the Ligurian Alps to the South East. A stable component with unblocking temperatures between 200°C and 450°C, is well defined at all the sites and always shows a reverse polarity. Its declination is strongly deviated relative to stable Europe in a range from 47° to the North to 117° to the SouthEast.We interpret these deviations as counterclockwise rotations of the Penninic Alps relative to stable Europe.

This paleomagnetic study has been completed whith analogical modelisation experiments. The purpose of modelisation was to quantify influence of the Apulian plate rotation on the Alpine Arc formation. Crustal models using sand show that rotation could be a major boundary condition for the late Alpine Arc evolution.

Both paleomagnetic and analogical studies allow to propose a global kinematical model for the Western Alps. This model could explain actual deformation like active sismicity whereas GPS measurements do not indicate significant convergence movements between Lyon and Torino.

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TECTONIC INVESTIGATION STRATEGIES FOR THE PLANNING OF THE BRENNER BASE TUNNEL

Kurt Decker, Franz Reiter, Andrea Bistacchi, Rainer Brandner,
Matteo Massironi, Hugo Ortner & Gerhard Wiesmayr

The 55 km long Brenner Base Tunnel between Innsbruck and Franzensfeste is part of the European high capacity rail corridor from Munich to Verona. The tunnel crosses the main chain of the Eastern Alps and transects the entire Tauern Window below the Brenner detachment fault and adjacent Austroalpine and Southalpine Units. Proceeding from North to South, the corridor passes through or close to major Tertiary orogen-scale fault systems such as the Inntal Fault Zone, major faults at the northern border of the Tauern Window, the Brenner Detachment Fault, the Periadriatic fault system and several other, previously unknown faults within the Tauern Window and the South Alpine Units. Due to the possible unfavourable rock mechanic and hydrogeological properties of fault rocks zones such as the ones mentioned above form major risk zones for tunnelling.

Initial planning for the Brenner Base Tunnel includes detailed investigations on tectonics and structural geology accounting for the prime importance of tectonic structures. The ongoing investigations have been scheduled to (1) support geological mapping in the construction of well-constrained sections and extrapolated depth-maps at the level of the tunnel; (2) pinpoint, map and characterise major tectonic faults in the corridor of investigation; (3) provide semi-quantitative estimates of joint and fracture systems for subsequent rock quality assessment; (4) assess hazards imposed by active tectonic processes and earthquakes; and combine all information into a "tectonic hazard map", which supports further planning including the selection of the alignment of the tunnel within the present area of investigation.

The challenge of mapping a tectonically very complex corridor of some 550 km^2 in high Alpine regions within very short time enforced by the tight schedule of the Brenner Base Tunnel Company was met by the integration of geological, remote sensing, DEM, and "traditional" structural geology-data in a GIS. The investigation strategy uses a four step approach starting from the evaluation of existing data and a desk-top mapping of possible faults ("tectonic lineaments"), which was done by the integrated interpretation of geological maps, remote sensing (Landsat 7), and topographical data (DEM) using GIS-compatible digital image processing tools (step 1). The results were used for the efficient planning of field surveys carried out as step 2 in order to obtain structural and kinematic data from microtectonic outcrop analyses (ductile and brittle structural analyses) and to map major faults in the field. Field work also included the mapping of mass movements and the ground control of the interpretation of step 1. In a third part, the resulting structural and kinematic data were integrated into a regional structural model and deformational sequences for the individual major tectonic units (step 3). In order to account for their importance in tunnelling we strongly focused on the analysis of brittle structures. Step 4 includes the construction of a regional tectonic map considering mapping results and the re-interpretation of the data processed in step 1. By this procedure remote sensing and DEM-data are used to extrapolate spatially limited outcrop or mapping information to the whole area of interest. Field data are stored in a database which is linked to the GIS system. Finally all structural data of relevance to the project were attributed, weighted and superimposed in a grid-based approach to produce a map which shows in an entirely abstract way zones which are favourable or non-favourable for the project.

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NEW OCCURRENCE OF CLD- AND-BEARING METAPELITES IN THE SOUTHALPINE BASEMENT OF THE UPPER VAL CAMONICA

Valeria Diella, Guido Gosso, Nicola Pigazzini, Gian Bartolomeo Siletto, Mario Iole Spalla

The lithologically homogeneous metamorphic basement of the Southern Orobic Alps is constituted of four different tectono-metamorphic units (GANSSER and PANTIC 1988; SPALLA and GOSSO 1999). This pre-Alpine metamorphic basement consist of metapelites with interlayered quartzites, amphibolites, minor marbles and pegmatites and large metagranitoid bodies. Type I tectonometamorphic units are characterised by an earlier metamorphic imprint under intermediate-pressure amphibolite facies conditions (Ky-St-bearing metapelites) followed by a greenschist facies retrogradation; these metamorphic rocks are unconformably overlain by Permian terrigenous sequence. The dominant metamorphic fabric is a S2 foliation synchronous with the greenschist facies imprint (MILANO, et al. 1988; DIELLA, et al. 1992; BERTOTTI, et al. 1993). Type II tectonometamorphic units show similar relationship with the Permian cover and a similar metamorphic evolution with type I, from which they differ for the occurrence of an epidote-amphibolite facies metamorphic imprint (Bt-Cld-Grt-bearing metapelites) predating the amphibolite facies imprint (ALBINI, et al. 1994; SPALLA, et al. 1999). Type III tectonometamorphic units represent the shallowest pre-Alpine tectonic units displaying a polyphase structural evolution (pre-D2, D2, D3) fully recorded under greenschist facies conditions; the relationship with Permian sequences are comparable with those of the previous types (CERIANI 1994; GANSSER and PANTIC 1988). Finally type IV tectonometamorphic units are characterised by a high-temperature low-pressure metamorphic imprint (Bt-Sill- bearing metapelites), synchronous with S2, following the intermediate pressure amphibolite facies equilibration (Syn-D1) and predating the last greenschist re-equilibration (syn-D3); Permian sediments are exclusively in tectonic contact with these metamorphic rocks (DIELLA, et al. 1992; GOSSO, et al. 1997; MOTTANA, et al. 1985). In Upper Val Camonica a preliminary structural and microstructural analysis points out a new pre-Alpine metamorphic outline, in spite of still discontinuous new structural data. Here adjacent volumes of metapelites show the following contrasted structural vs metamorphic evolutions:

Cld-Bt-Grt- bearing fabric is overprinted by a pervasive greenschist facies foliation;

Cld-Bt-Grt- bearing fabric is followed by the development of Bt-St-Grt assemblage and subsequently overprinted by a greenschist facies foliation;

Bt-St-Grt fabric predates a greenschist facies foliation;

And-Chl-Ms assemblage randomly overgrows the Cld- and St- bearing fabrics.

The aim of this contribution is to correlate these apparently contrasted deformation -metamorphism relationship in a coherent regional scale outline on the basis of meso- and microstructural investigations.

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THE PALEOZOIC EVOLUTION OF THE BELLEDONNE, GRANDES ROUSSES AND OISANS MASSIFS (WESTERN ALPS): FROM SUBDUCTION TO COLLISION

Silvia di Paola, Stephane Guillot, Patrick Ledru, René Pierre Ménot & Maria Iole Spalla

The Belledonne, Grandes Rousses and Oisans massifs in the Western Alps, belong to the Alpine External Crystalline Massifs (ECM). Their Paleozoic basement is constituted by metapelitic, volcanic, plutonic and detritic rocks unconformably covered by Mesozoic sediments and weakly reworked by successive Alpine metamorphic and tectonic episodes.

The two main questions about these three massifs concern their mutual correlation in term of tectono-metamorphic evolution and lithological content, and their relationships with the other ECMs and with the European Paleozoic orogen.

For a better understanding of the signification of these massifs in the framework of the Hercynian belt, it is necessary to update the knowledge of the regional geology, as many new data come from recent 1/50,000 scale mapping program and related studies.

For the massifs of Belledonne, Grandes Rousses and Oisans, a summary of the geological data available in the literature and in the 1/50.000 geological maps has been realized. The cartographic synthesis, drawn with a GIS, allows to define some geological systems displaying a common origin and evolution, as suggested by their lithology, age, structural and metamorphic record. The new definition of geological systems and the synthesis of available data allow to propose an overall geodynamic evolution from Early Paleozoic to Permian time. Three major periods are distinguished:

1. during Lower Paleozoic magmatic rocks of oceanic origin testify a period of oceanisation (Chamrousses ophiolitic complex) and the development of an active margin (eclogitic relics in metabasalts);
2. From Middle Devonian to early Carboniferous, the magmatic activity recorded a contrasted evolution in different domains of the Belledonne and Grandes Rousses massifs. In SW Belledonne bimodal volcanics testifies an extensional regime on continental crust, interpreted as a back arc basin. In NE Belledonne and Grandes Rousses the emplacement of mantle-derive granites in a transpressive regime is accompanied with nappe stacking towards the NW. The temporal succession and the regional distribution of extension, plutonism and nappe stacking suggest the transition from a subduction to a collisional setting (from 370 to 330 Ma);
3. during Late Carboniferous (330-295 Ma) two crustal scale N-S trending normal faults split the collision zone in three blocks, corresponding to different crustal levels. The western and central blocks corresponds to shallow crustal levels, with brittle extensive and transtensive tectonics associated with the development of Westphalian and Stephanian basins. In contrast, in the easternmost block, a pervasive ductile extensional tectonics caused the exumation of deep crustal levels, with generation of HT-LP granulites and partial melting of the thinned crust.

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ALPINE SHORTENING AND 3D STRUCTURES IN THE CENTRAL DAUPHINÉ AREA (FRENCH WESTERN ALPS) : A REAPRAISAL OF JURASSIC AND HERCYNIAN HERITAGE

Thierry Dumont, Jean-Daniel Champagnac & Philippe Rochat

The relationship between surface data and crustal-scale structures is still a matter of debate in the Western Alps (SCHMID & KISSLING, 2000). In the Dauphiné zone, the following features have to be considered :

- The Hercynian basement massifs are uplifted recently due to activity of a northwestward crustal ramp, with possibly a transcurrent movement.
- The associated shortening consists in part of tectonic inversion of extensional Jurassic blocks created during the Tethyan rifting.
- Both Tethyan extension and Alpine shortening were likely influenced by the Hercynian structural grain in the basement.

The crustal structures can be interpreted in different ways considering each of these features as the most imporant one. In order to evaluate their relative input, we present here a geometrical and structural study about a key area in the northern Dauphiné region. Tertiary tectonic uplift and Quaternary glacial incision resulted in a rugged topography (about 3 km vertical range) which gives access to three-dimensional view.

Thanks to the collaboration with the Totalfina company, field data and maps have been correlated with a 25 m resolution digital elevation model and 1.7 m resolution satellite image, which provides a link between outcrop size and cartographic scale.

The post-Hercynian finite deformation, which can be measured in the Mesozoic sequence, can also be evaluated by analysing the present shape of the interface between the Paleozoic basement and Mesozoic strata, which was a horizontal plane in early Triassic times as shown by the shallow facies and constant thickness of the Triassic wedge. This shape has been modelled in 3D using correlation of data along 250 m-spaced EW profiles. It shows a strong relationship with late Hercynian structures, both following a curved path on the western side of the Grandes Rousses massif.

This horizontal curvature of the *third* Alpine event in the considered area, is correlated with the uplift of the centre of the massif and with conjugate strike-slip faulting (predominantly marked by dextral shear along N50 direction), all compatible with E-W shortening. To the same event must be assigned local backfolding in the vicinity of the Belledonne buttress.

Previously (*second* event) occurred steep west-verging basement thrusts produced ramp anticlines in the shallow basement and westward recumbent folds in the Liassic cover. These thrusts were nothing but a local reverse reactivation of the NS steeply eastward dipping late Hercynian structural grain, as an expression of basement shortening.

Previously again (*first* event) westward to southwestward recumbent folds in the Liassic cover probably existed associated with local detatchments towards the base of the Mesozoic section.

These three events all take place within the forward propagation of the Alpine front, and correspond to:

1) westward thrusting of the Penninic nappes above the Dauphiné sedimentary cover (reverse activity of th Pennine thrust, younger

than 31 Myr; TRICART et al., 2001), which suffered shearing and buttressing along the Jurassic normal faults.
2) forward propagation of shortening in the central Dauphiné basement, with reverse activation of the Hercynian grain and subsequent cover folding. This could take place around 20-25 Myr considering the paleomagnetic data (MÉNARD & ROCHETTE, 1992 ; CROUZET et al., 1996).
3) involvement of the western Dauphiné basement (Belledonne uplift) increasing buttress effect in front of the Grandes Rousses bulge. This should be younger than 13 Myr after paleomagnetic data.

This has important implications about the restoration of pre-Alpine structures:

- The NE-SW Belledonne trend, classically regarded as the major Hercynian heritage compared with the Cévennes fault trend, is here a recent Alpine feature. The observed Hercynian grain is close to NS, as within the Belledonne chain too, and has been sheared and locally rotated to NE-SW.
- This grain has been activated by Jurassic extension which was probably oblique to it. The NS Ornon fault was likely dying away to the north and extension was transferred northeasternwards « en échelon » to the Sabot fault, This classical rift figure could allow the Liassic depocenters to be arranged along a NE-SW trend, that is perpendicular to Tethyan extension (LEMOINE et al., 1989).

Since the Hercynian grain is playing a major role during both rift and compressional tectonics, the change in orientation of this grain which turns NW-SE in the Southern Pelvoux and Argentera massifs must be considered, together with the migmatitic-rich central Pelvoux area (dome?). Either this shape is due to Alpine rotation, but no data support this hypothesis, or the upper crustal structure of the Pelvoux, late Hercynian granitic core and surrounding enveloppes is a key feature for understanding both the Mesozoic margin pattern and the western Alpine sharply arcuate belt.

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THE DENSITY STRUCTURE OF THE EASTERN ALPINE CRUST

Jörg Ebbing, Carla Braitenberg, Hans-Jürgen Götze & Bruno Meurers

Recent results of the seismic profile TRANSALP initiated new investigations of the density structure in the Eastern Alps. This new experiment and results of previous western Alpine profiles lead to new ideas, which are tested by the use of inverse and forward modelling of potential fields.

The modelling indicates that the Bouguer gravity field in the Eastern Alps is mainly caused by two sources: the density contrast at the crust-mantle boundary (350 kg/m^3), and the density inhomogeneities in the upper 10 km of the crust, which contributes to the overall gravity field by amounts of approximately 30 $*10^{-5}$ m/s^2.

These uppermost 10 km of the model are well constrained by both observations from geology and seismic and clearly connected with the obvious near-surface tectonic regime.

This means that near surface geologic formations can be rather easily identified in the short wavelengths of the Bouguer anomaly, e.g. the uplift of the Tauern window. The small scaled structures cause gravity anomalies that superpose and interfere with the regional gravity field caused by the Moho interface. Therefore, it is impossible to separate the small and long wavelengths of the gravity field in such complex environment by a simple low-pass filtering. Forward modelling under constraining conditions seems to be the only possibility to eliminate gravity effects of near-surface structures with the consequence that a regional (deeper) field can be calculated on the base of constrained information. This kind of regional field eases the construction of deeper located density structures.

Aside of the "gravity stripping method" two other methods have been used to investigate lower crust and upper mantle density distributions, the first was an interactive 3D forward model matching. In this, a starting model was constructed on base of the seismic results and findings by the TRANSALP profile, which was stepwise interactively modified, and the second was gravity inversion.

The inversion procedure provides detailed insight into the crust mantle interface that is independent from the pre-existing seismic velocity model. It is of value that uncertainties, if present in the velocity model, are not propagated into the density model. Essentially, the two methods agree in the resulting Moho.

Important features of the Moho are the crustal roots along the central part of the Alpine arch, that achieves a depth of 55 km. In the southwest a shallowing of the Moho is found that coincides with the gravity high of the Vicenza area. Moho depth here is significantly less than in the seismic results. The deepening of the Moho towards the central part of the Alps is relatively steeper in the Adriatic domain than in the Alpine domain, indicating an asymmetry with respect to the Alpine Arch. To the North of the Alps the two models agree to a gradual shallowing of the Moho depth to 30 km.

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CONICAL FOLDS AND INTERFERENCE STRUCTURES: INSIGHTS FROM THE COL BECHEI - SASS DAI BAC AREA (NORTHERN DOLOMITES, EASTERN ALPS)

Claudio Ebblin & Andrea Zille

The Col Bechei – Sass dai Bac area, mainly covered by Jurassic thinly layered limestones, is essentially a kink country. Observed kink bands are often conjugate and are seen in places to split into higher-order ones, producing box fold patterns. In general the deeper lower-order kinks, appearing as reverse steeply dipping fractures, are rooted in the thicker Dolomia Principale (Hauptdolomit) layers. The layering, folded by the kinks, shows rounded concentric conical geometries, their hinges often marked by fractures.

Such field observations, together with those of interlayer slickensides and en-echelon gashes patterns, suggest that buckling occurred with flexural slip. Moreover, althought shear folding may have occurred, there is no direct evidence of disjunctive slip on single surfaces.

Two main sets of kink systems, striking E-W and NW-SE respectively, are observed in the area.

The NW-SE major kink considered here is that running along the SE slope of M. Pares, across the S. Antonio Pass, into Fanes Piccola, up and across the Limo Pass and likely further SE-wards. The absolute coincidence of the orientation and shape of the first-order structures obtained in the Limo and in the S.Antonio valley subareas, suggest that the two sites are intimately connected.

The purpose of the present work is to unravel the geometric relations between such structures and the nearly EW-running La Stiga-Sass dai Bac low-order folds west of it and the equally EW-striking Piz da Limo-Col Bechei folds east of it.

In the Bechei subarea the most recurrent orientation of the poles to the layering plunges steeply SE, the rest of them, spreading on a girdle with a shallowly NNW-plunging axis. A pole distribution similar to the one above is observed in the southern Sass dai Bac exposure, the most recurrent orientation being the same but weaker and the girdle axis slightly more NW-oriented. A second girdle is additionally present, as in the Bechei subarea, in a very weak form, with a SW-plunging axis. In the major transversal kink zone the girdle with a NNW axis, particularly strong in both the Bechei and Sass dai Bac subareas, is completely absent. Two alternative great-circle distributions are evident, with ENE-WSW and NE-plunging axes.

The lower-order folded surfaces, representing the enveloping surfaces, in the Bechei subarea are astonishingly similar to the higher-order ones described in the Sass dai Bac subarea. In the latter subarea the lower-order poles are dispersed within a 70-degrees open cone plunging steeply WSW, whereas in the Limo subarea a clear WNW-ESE dispersion girdle is apparent. In the whole area the lowest-order conical fold axes lie on a subvertical WNW-ESE plane, with the exception of some of them in the Limo subarea, which stay on a WNW-dipping plane.

Conical folds are the rule in the area. Observed mushroom-shaped structural patterns appear to be the result of complex 3D non-coaxial fold interference.

The ubiquitous strong subvertical undeformed cleavage striking NW-SE and crosscutting all structures together with the conical warping of cumulative fold axes about a shallowly SE-plunging pole suggest that the maximum shortening of the last deformational phase had a NE-SW direction.

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RELATIVE CHRONOLOGY AND ABSOLUTE AGE DATING OF STRUCTURES RELATED TO THE EXHUMATION OF HP-ROCKS IN THE SE ÖTZTAL BASEMENT

Ulrike Exner, Martin Thöni, Bernhard Grasemann

The polymetamorphic basement rocks of the SE Ötztal complex have been overprinted by a HP-metamorphic event in the Cretaceous. Outcrops of eclogite-facies metabasites have been found in a narrow zone to the W of the Passeier valley (HOINKES et al. 1991). Mineral isogrades in the whole Ötztal basement indicate increasing eo-Alpine metamorphic conditions from subgreenschist facies in the NW to amphibolite facies in the SE (PURTSCHELLER et al. 1987).

Together with eclogite-facies rocks in the Schober- and Kreuzeck Gruppe and the Sau- and Koralm units, these occurrences are regarded as part of the "eo-Alpine high pressure belt" (THÖNI & JAGOUTZ 1993).

The eclogites in the Saltaus valley form boudins of various scales within ortho- and paragneisses. Structural and geochronological investigations were performed in order to clarify the Alpine tectonic evolution of the metabasites and their acidic host rocks.

The main results of these new field and geochronological work are as follows:

The structures observed in the eo-Alpine eclogite facies metabasites and their acidic host rocks have been identified as related to exhumation and emplacement of the HP-rocks. This process can be described as polyphase but continuous, recording decreasing metamorphic conditions within a different kinematic frame.

The first penetrative deformation forms a mylonitic foliation with an E-W trending mineral lineation. Rb-Sr dating of white mica from mylonitic orthogneisses, which show dynamic recrystallisation during this deformation, gave ages around 90 Ma.

The mylonitic foliation is deformed by large-scale, S-vergent folds with plagioclase recrystallizing in fold hinges, indicating T-conditions above 500°C for this deformation.

Two subsequent ductile deformation phases acted under greenschist facies conditions, recording minor tectonic events in shallower levels.

Brittle faulting related to Tertiary movements along the Passeier and Jaufen Linie (MÜLLER 1998) is documented by N-S trending faults, often associated with pseudotachylites and ultracataclasites, but also low-T quartz-ultramylonites. This deformation is accompanied by the intrusion of an andesitic dyke. Biotite and garnet from this magmatic body have been dated by Rb-Sr and Sm-Nd methods, respectively. Mineral ages around 33 Ma are well in line with data for the Periadriatic magmatism along the Alpine chain.

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HYDROCARBON GASES IN SEDIMENTS FROM SHOT HOLES ALONG THE TRANSALP TRAVERSE

Eckhard Faber, Alfred Hollerbach, Manfred Teschner, Bernd Lammerer & Jürgen Poggenburg

The goal of the study is to derive information on the occurence of hydrocarbons along the TRANSALP section in the Alps by analysing near-surface samples. Therefore, sediments from nearly all seismic shot holes along the TRANSALP traverse have been sampled and degassed in the BGR laboratory using an acid/vacuum extraction procedure. The concentrations of the light hydrocarbons (hc) and the carbon and (hydrogen) isotope ratios of methane through propane for samples from the shot holes have been determined.

The hc-concentrations range from 6 to 5289, 1 to 2333 and 1 to 3586 ppbw (parts per billion by weight of wet sample material) for methane through propane. The carbon isotope ratios range from -65 to -27, -38 to -26 and -34 to -19 ‰ (relative to the PDB reference) for methane, ethane and propane. The geochemical data indicate that hydrocarbons from organic source rocks are present but also point to a contribution of 'artificial' hydrocarbons formed while drilling the shot holes (contamination).

The non-contaminated data of the hydrocarbon gases indicate the predominantly thermal origin related to organic source rocks, only in few samples bacterial methane is found. The organic source material consists mostly of a marine type, however, in few samples a contribution of a terrestrial source is indicated.

The thermal hydrocarbons migrated from the depth of the source rocks into the near-surface sediments. The thermal maturity of the source rocks, deduced from the carbon isotope ratios is between 0.5 to about 2% vitrinite reflectance (Rr). Source rocks of the gas samples from shot holes 3 and 4 are low in maturity – around 0.5% Rr, whereas those from other sections of the transvers section are higher in maturity.

Details will be given in the poster on the geochemical data of the hydrocarbons extracted from the sediments.

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THE RECORD OF SOUTH-ALPINE STUCTURAL EVENTS IN THE VENETIAN FORELAND AND FOREDEEP

Roberto Fantoni, Chiara Barbieri, Daniele Catellani,
Alberto Castellarin, Andrea Di Giulio & Camillo Pessina

During the Cenozoic, the Friuli and Venetian plain represented the foreland of the three chains: the Dinaric, the South-Alpine and the Apennine. The tectono-sedimentary evolution of that foreland is analysed along a seismic transect orthogonal to South-Alpine structures and located between the southern end of the Transalp profile and the Adriatic coastline (fig. 1).

During the Lower Cretaceous, according to seismic data, Friuli Platform underwent a strong aggradation which led to an estimated elevation about 1200–1500 m with respect to the surrounding basins.

Such a space was inherited by the first Alpine tectonic phases (Upper Cretaceous-Eocene) and added to the accommodation due to the load of the South Alpine-Dinaric orogenic system.

In the Conegliano region, the slope dips NNW, and the Transalp profile, calibrated with Nervesa 1 and Volpago 1 wells, provides a good image of the original geometry and modes of space fill by the Paleocene-Oligocene siliciclastic wedge which outcrops in the north (Belluno syncline).

Particularly, the Eocene succession onlaps the pre-existing slope and the starvation of terrigenous input is recorded around the Bartonian-Priabonian boundary (Volpago 1 well), whereas the definitive basin infill occurred only at the end of the Oligocene, when the clastic wedge began to accumulate even above the platform margin (Nervesa 1 well). In the meantime, the western and southern margins of the Friuli platform were poorly fed by turbidites flowing from south and/or east and mostly mudstone accumulated in a prograding shelf environment (Jesolo well area, fig.1); also in these areas accomodation space was definitively filled only at the end of Oligocene.

Despite of the Eoalpine-dinaric compressive tectonic phases which occurred during the same time span, the creation of new accomodation space is recorded only in the eastern margin of the Friuli platform due to an eastward flexure toward the Dinaric belt.

The latest Oligocene basin filling led to the development of a wide terrigenous-carbonate platform, extended from the Belluno area, to the Southern Alps margin, to the Friuli-Venetian foreland (Cavanella Group), to the present-day margin of the Dinaric belt (Cargnacco well).

At a regional scale, integrated outcrop and subsurface data point out the thinning of the Chattian-Aquitanian sediments toward the Friuli Platform, while Burdigalian-Langhian units record the extension of a terrigenous shelf environment to the whole Friuli high, and still seem to record a feeble thinning toward the south (fig. 1). As a whole, this cause the Chattian-Aquitanian succession to thin from some hundreds to few tens of meters from the Piedmont area to the coast region. In addition, sandstone composition pointed out that in that time span, only the axial region of the belt delivered significant volume of clastic sediments, whereas the outer part, even though deformed, was not eroded so much. Furthermore, the foreland dipped only slightly northward, reflecting a still far Alpine load, while toward the east no flexure due to the Dinaric belt is recorded.

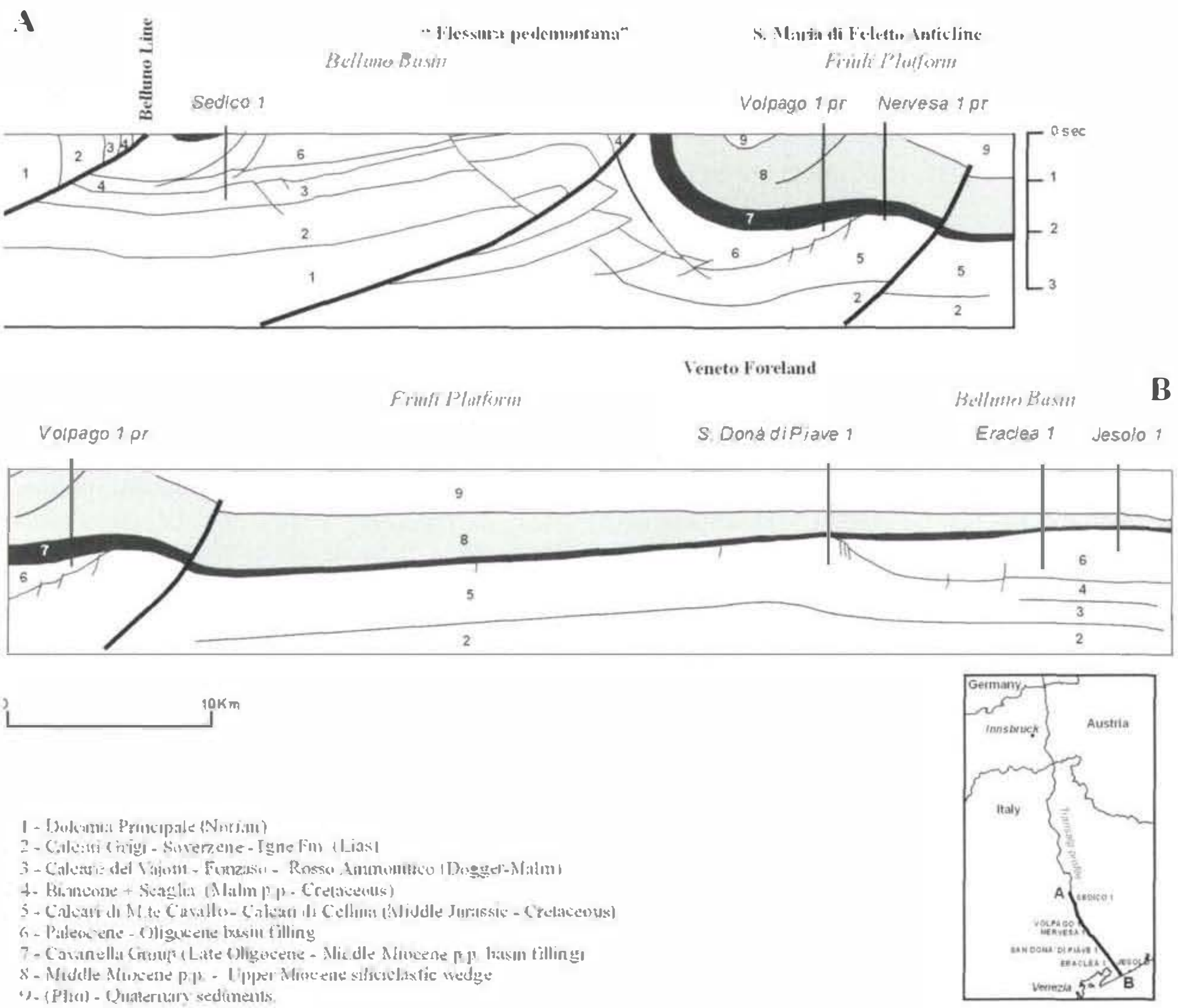

Fig. 1: Simplified seismic profile from South Alpine belt to Adriatic foreland south of TransAlp transect (thick line in the inset map)

From the Serravallian to the early Messinian, the southern margin of the South-Alpine chain experienced a strong subsidence, and a well recognisable foredeep developed, with outcrop successions exceeding 3000 m in thickness in the north, reaching 1500 m in the South Alpine margin subsurface (Arcade well) and rapidly thinning in the subsurface of the outer foreland region (S. Donà di Piave well; fig. 1). Contrasting with the older one, the petrography of sediments filling this foredeep indicates a South-Alpine mostly carbonate source, which records the fast uplift of the belt that began to deliver a huge amount of clastics whose accumulation exceeded even the fast accomodation rate in the area, causing a general shallowing trend of the succession. A Tortonian age of the deformation and uplift of the belt in the Valsugana-Giudicarie region would be consistent with fission track data, which record a 3–4 km uplift between 10 and 6 Ma. This tectonic phase and the related variation of tectonic load fit well the marked flexure contemporaneously recorded in the foreland.

From the late Messinian to the Pleistocene, the sedimentation rate became more regular at the regional scale, without significant thickness variations. The accomodation space was relatively small during Pliocene, but increased during Pleistocene.

During this period, it is not recognisable a significant northward or eastward tilting of the foreland, due to increased Alpine or Dinaric loading, notwithstanding the severe tectonic phases that affected Southern Alps. Only the southernmost part of the examined area shows the effects of the north-eastward shifting of the Apenninic foredeep, as the north-Adriatic turbidite system reached the present-day Venetian coastal area during middle Pleistocene, and the turbidite wedge onlaps the southern foreland slope and thickens south-westward.

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THE MATURITY OF ORGANIC MATTER IN SOUTHALPINE SEDIMENTS ALONG THE TRANSALP PROFILE

Roberto Fantoni, Camillo Pessina, Paolo Scotti & Mattia Sella

Data obtained from analysis of the maturity of organic matter during oil exploration activities are excellent indicators of the thermal evolution of sedimentary basins. The most commonly used maturity parameters are obtained from optical analysis of kerogen and Rock-eval pyrolysis on ground samples with a high organic matter content. The parameters used, are vitrinite reflectance (a component of carbon) expressed in Ro%, the Thermal Alteration Index (TAI – calculated on spores and pollens), and the Tmax parameter (expressed in °C and corresponding to the temperature at which there is maximum generation of hydrocarbons during pyrolysis of kerogen with standard heating rate).

These parameters are highly sensitive in the 60–200°C temperature range and record heating events that have affected the organic matter contained in the sediments for a suitable length of time. They also allow the sedimentary and/or tectonic burial history to be reconstructed by means of suitable simulations. Indeed, knowing this history is fundamental in reconstructing crustal processes.

The structural pattern of the sector of the Southern Alps crossed by the TransAlp profile is characterised by the presence of WSW-ENE trending compressional structures involving previous Mesozoic extensional structures. Predominantly Permo-Triassic sediments outcrop in the most internal sector of the chain above the Varisian crystalline basement and the Permian volcanic coverage; in the central sector there are units from the Upper Triassic and Cretaceous; more recent sediments are present in the synclines of the central sector and at the boundary of the chain.

In order to reconstruct the thermal history, samples, aged between the Permian and Miocene, were analysed; in areal terms, the samples are from sedimentary units outcropping in the chain and from units drilled by exploration wells located in the area of the chain (Sedico 1), at its buried boundary (Nervesa 1) and in its Veneto-Adriatic foreland (Legnaro 1 Dir and Assunta 1).

Almost all the maturity data is stratigraphically concentrated in the intervals with the highest organic matter content: Formazione a Bellerophon (Upper Permian); Formazione di Moena, Formazione di Livinallongo (Plattenkalke and Baenderkalke Members), Arenarie di Zoppè (Middle Triassic); Formazione di Igne (Liassic); Marne a Fucoidi (Aptian-Albian); Marne di S. Donà (Middle-Upper Miocene).

Profiles with maturity data arranged in series are provided by wells drilled in the Veneto plain, vertically ranging from the Middle Jurassic to the Eocene (Sedico 1) through the Miocene (Nervesa 1), from the Upper Permian to the Oligocene (Legnaro 1 Dir), and from the Carnian to the Lower Cretaceous (Assunta 1). In the Southalpine belt maturity series can be reconstructed for the Agordo area (Permian-Ladinian).

The burial histories and relative thermal evolutions of each area in this sector of the Southern Alps mainly depend on their position during the Mesozoic extensional stages (progressive burial stage). In the foredeep and foreland areas the signal produced by the different arrangement during

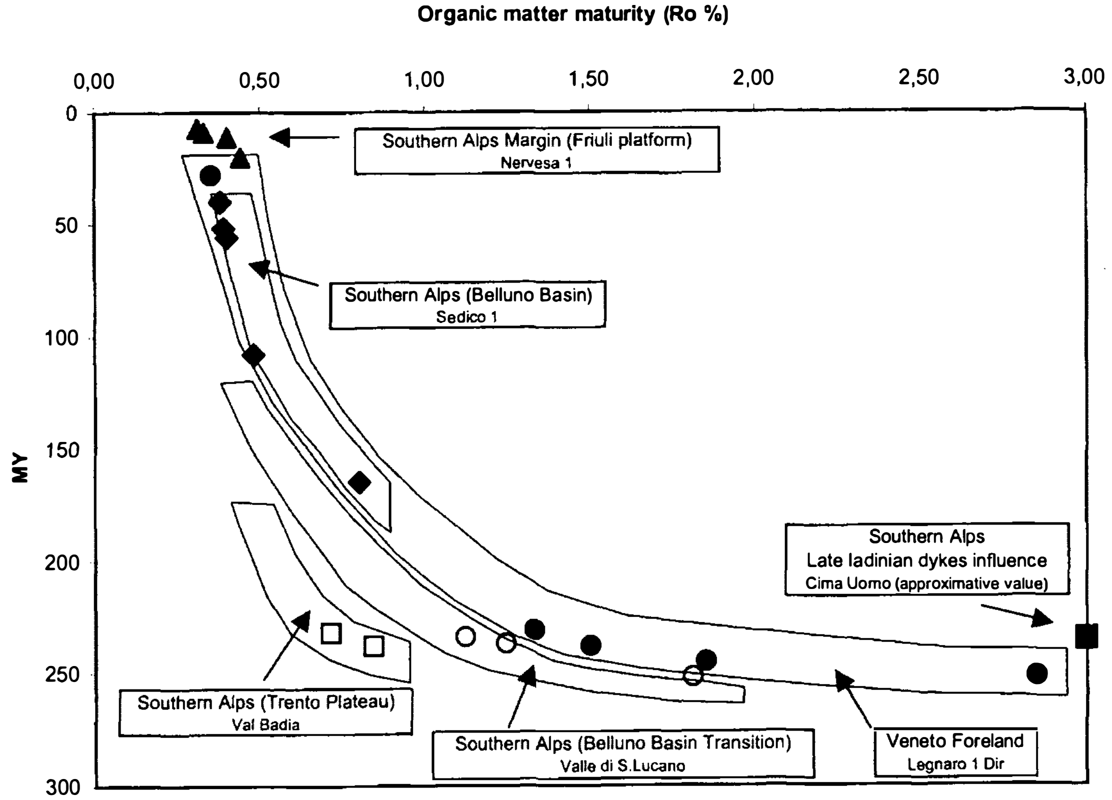

Fig. 1: Organic matter maturity for different thermal evolutions

the alpine compressional stages (further burial or partial exhumation stage) overlies that signal.

The distribution of the available maturity values in the Southalpine belt indicates an area in the south (Agordo area) that is tendentially maturer than the central-northern area (Marmolada and Val Badia). In the Agordo area the Upper Permian units contain kerogen with high maturity (Ro 1,8%), the Middle Triassic units contain a very mature kerogen (Ro 1.1–1.2%) while in Marmolada the Formazione di Moena (Upper Anisian) has Ro values of less than 0.6%, indicating a substantially immature kerogen.

The maturity trend, with decreasing values for SSE to NNW trending coeval units, can probably be attributed to different burial events between the Upper Triassic and Lower Cretaceous.

The values (as regards the Middle Triassic unit) gradually become smaller towards the north (Marmolada, Val Badia) and should correspond to transition zones to Mesozoic structural highs with reduced sedimentation (continuation of the Adige Plateau).

The maturity values (already within the "oil window") observed in the Jurassic unit at the south eastern boundary of the chain (well Sedico 1) correspond to the depocenters of the Belluno Basin.

The rise in isotherms, during the Norian-Liassic extensional stages and recorded throughout the whole Southalpine area, emphasises the different levels of maturity of the kerogen in those areas with different burial values during the Mesozoic.

Significant local maturity anomalies recorded in the Ladinian units (high maturity or even organic metamorphism) were noted. These anomalies can be attributed to localised heating phenomena during the late Ladinian. For example, at Cima Uomo (S.Pellegrino Pass) the influence can be clearly seen of the numerous dyke intrusion linked to Upper Ladinian magmatism on the organic matter contained in recently sedimented just deposited (Lower Ladinian). The kerogen in the Plattenkalke Member of the Formazione di Livinallongo is in full organic metamorphic phase (petroleum potential zero, despite the high organic carbon content).

A similar phenomenon is recorded in the Middle Triassic carbonate platform series drilled in well Corte Vittoria 1, located in the Veneto subsoil near the area studied, where there are no rocks with a minimum organic matter content, but where clear signs of contact metamorphic phase are noted on the mineral matrix.

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THE TECTONIC EVOLUTION OF THE CENTRAL NORTHERN CALCAREOUS ALPS

Wolfgang Frisch & Hans-Jürgen Gawlick

The classical concept of the nappe structure of the Northern Calcareous Alps (NCA), nearly a century old, is in contradiction with modern stratigraphic, metamorphic and geochronological data. We present a new concept with the following nappe stack (from deeper to higher structural levels) (see Fig. 1): (1) Bavaric unit divided into a Lower and Upper sub-unit (Tief- and Hoch-Bajuvarikum). The Bavaric unit is largely eliminated in the central NCA by lateral extrusion in

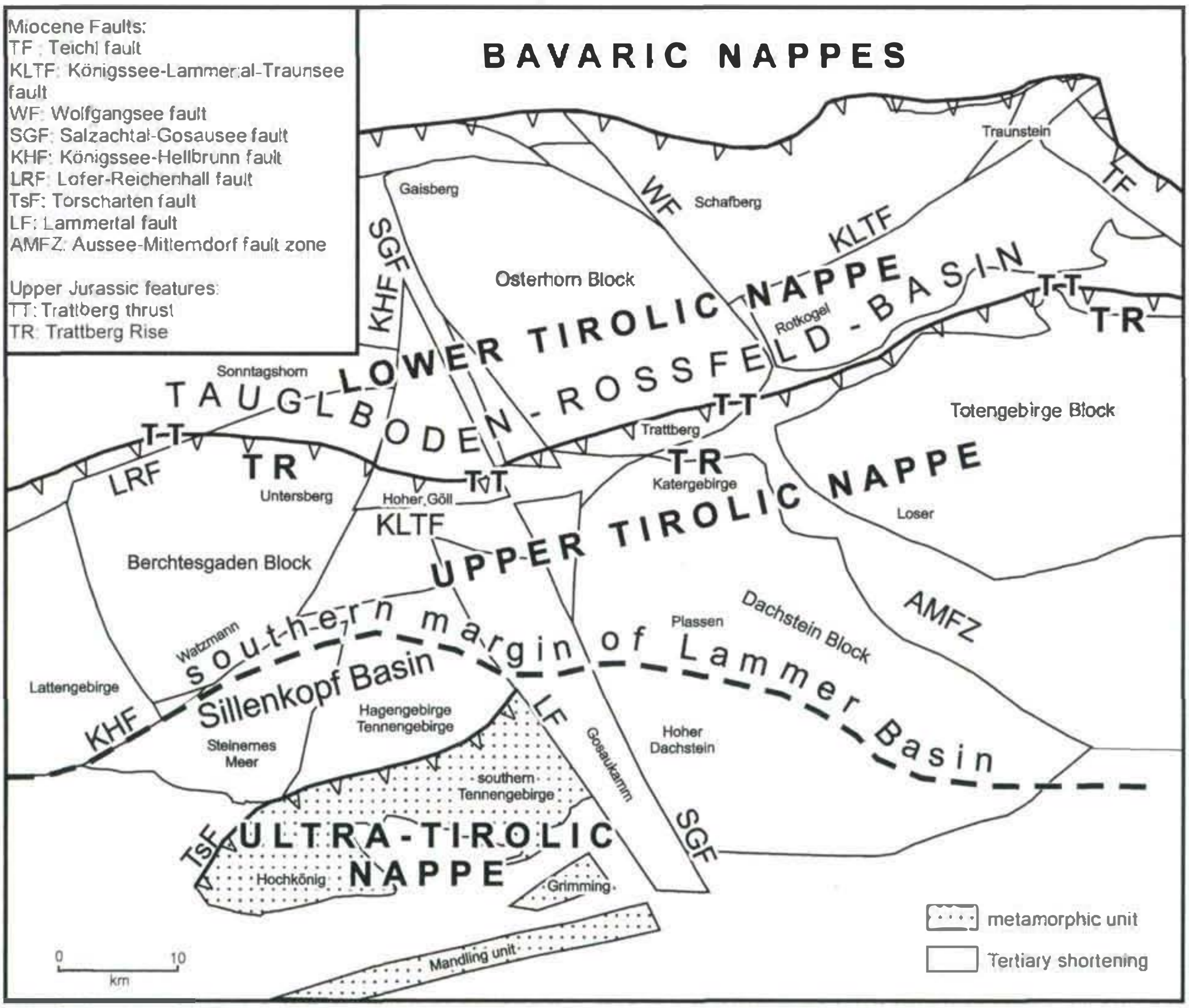

Fig. 1: Reconstruction of the Tirolic unit in the central NCA for Eocene (post-Gosauic) time. Further Eocene shortening occurred in shaded zones. Block movement and shortening in accomodation zones occurred during Miocene lateral tectonic extrusion.

Miocene time. (2) Tirolic unit, divided into two sub-units (Lower and Upper Tirolic sub-unit; Tief- and Hoch-Tirolikum) separated by an Upper Jurassic thrust fault (partly rejuvenated in Eocene time) and strongly block-faulted during Miocene lateral tectonic extrusion. (3) Metamorphic units of the (originally) southeastern margin of the Triassic carbonate platform, highly dismembered in the present state (Ultra-Tirolic unit; Ultra-Tirolikum). (4) Iuvavic unit (Juvavikum), which corresponds to the Hallstatt mélange nappe, also partly metamorphic and preserved in isolated bodies on top of the Tirolic unit. The classical subdivision into several Tirolic (e.g. Staufen-Höllengebirge and Totengebirge nappe in the central NCA) and „Upper Iuvavic" nappes (Berchtesgaden, Dachstein nappe), which are characterized by Upper Triassic carbonate platform sediments but thought to have been separated by the Hallstatt zone, is no more backed by the reconstruction of the geodynamic evolution since Triassic times. We propose a concept with an Upper Jurassic and a late Lower to early Upper Cretaceous orogenic event, which is in concordance with the diachronous history of the Austroalpine basement zone.

The Middle to Upper Jurassic („Late Kimmeric" or Eohellenic) orogeny caused formation of the Hallstatt nappe complex and thrusting over the external parts of the Triassic carbonate platform, which were also imbricated. In front of the advancing Hallstatt nappe, a deep-sea trench (Lammer Basin with carbonate-clastic radiolaritic flysch derived from the Hallstatt facies belt) was established in Callovian to Oxfordian time. The Kimmeridgian to Tithonian Trattberg thrust, a probably steep thrust with limited shortening, divided the Tirolic unit into the Upper and Lower Tirolic sub-units or nappes. The Upper sub-unit carried the Hallstatt nappe, the Lammer Basin, and the Trattberg Rise (as a thrust-related feature along its northern margin). It includes, from W to E, the former Berchtesgaden nappe, parts of the former Staufen-Höllengebirge nappe (Steinernes Meer, northern parts of Hagen- and Tennengebirge), the former Dachstein nappe, and the former Totengebirge nappe. The Trattberg Rise is represented in Untersberg, Hoher Göll, Trattberg, Katergebirge, and western Totes Gebirge. Immediately north of the Trattberg thrust, i.e., in the Lower Tirolic sub-unit, the Tauglboden Basin (Kimmeridgian to Tithonian) formed a trench and received carbonate-clastic radiolaritic flysch material from the Trattberg Rise.

The advent of an unknown source terrane (island arc?) from the southeast is manifested in Kimmeridgian time by the formation of the Sillenkopf Basin south of the former Lammer Basin, which was also filled by radiolaritic flysch and received detrital material from this terrane. This event may reflect the soft collision stage of the Upper Jurassic orogeny.

Deep-water conditions persisted in the Tauglboden Basin until Aptian time. In the Lower Cretaceous, the sedimentation shows a general coarsening-upward trend coupled with increasing input of siliciclastic material with crystalline and magmatic components. The youngest formation in this sequence is the Rossfeld Formation, which ended up in wildflysch sedimentation in Aptian time and reflects another orogenic paroxysm connected to prograding crustal shortening of the Austroalpine realm and remobilization of parts of the Hallstatt mélange. During this event, the internal parts of the Triassic shelf area were imbricated into nappes (Bavaric units), thus forming the external nappes of the NCA.

These two phases of nappe formation in the NCA correspond perfectly with the polyphase diachronous metamorphic history in the Austroalpine basement. A first metamorphic cycle, which included high-pressure metamorphism in the Hallstatt zone, yielded radiometric ages roughly between 160 and 130 Ma. This event affected the Greywacke Zone and its Paleozoic equivalents and parts of the NCA (see above). The second cycle, which includes high-pressure metamorphism in the crystalline basement, embraces ages from roughly 110 to 80 Ma. It is found in the Austroalpine crystalline basement and overprinted Paleozoic terrains and the southern parts of the NCA.

The Gosau Group (Turonian to Eocene) sealed the nappe stack and reflects a prominent extensional event. Post-Gosauic (Eocene) orogeny caused final detachment of the NCA from their basement and thrusting over the Rhenodanubian Flysch as well as backthrusting along their southern margin. Internal deformation of the NCA included folding and rejuvenation of thrusts and caused out-of-sequence thrusting of individual blocks formerly considered as „Upper Iuvavic" nappes. Early to Middle Miocene lateral tectonic extrusion dissected the nappe stack and created a block puzzle, which veils the true nature of many of the older structures.

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EXHUMATION AND LATERAL EXTRUSION BETWEEN TAUERN WINDOW AND PERIADRIATIC LINEAMENT: VARIATION OF FLOW BETWEEN NONPARALLEL PLATES

Harald Fritz, Christian Biermeier, Kurt Krenn & Veronika Tenczer

The Adriatic-African-plate motion during Oligocene released combined transpression and extrusion between the southwestern margin of the Tauern Window and the Periadriatic Lineament. Major structural elements include subvertical foliations and subhorizontal east-west oriented stretching lineation. These structures are related to coeval activity of shear deformation within an eastward widening wrench corridor and backthrusting of Penninic Tauern Window units to the south onto the Austro-Alpine block. Oligocene shear deformation was accompanied by intrusion of magmatic bodies, namely the Rensen and Rieserferner magmatic bodies (MÜLLER et al., 2000; BORSI et al., 1978).

Lateral, east-west variations of vertical and horizontal displacement components are inferred from flow parameters and intrusion depth of syntectonic granitoids as well as from data on strain and flow geometries in host rocks. Data suggest major vertical displacement in western parts of the wrench corridor that is decreasing to the east. Vorticity analyses accounts for pure shear dominated transpression simultaneously with east west extrusion. The orientation of compressional flow apophyses with 20°–40° in respect to stable Europe is interpreted to reflect the relative plate motion vector during Oligocene convergence. Rotation of shortening axes from NE to NNW is inferred from progressively evolving structures and interpreted as post-intrusional anticlockwise rotation of the African plate.

A variable amount of vertical displacement along strike of the wrench corridor is evident from syntectonic textures and microstructures as well as from intrusion depth of granitoids. Intrusion depth decrease from the western Rensen Pluton (ca. 8 kbar) towards the eastern Rieserferner Pluton (ca. 2–3 kbar). This goes along with different amount of horizontal north-south shortening. In order to explain the situation a 3 dimensional kinematic model of flow between nonparallel plates was established that has to fit data on the flow regime, published data on Tertiary plate motion and variable amount of exhumation. The corridor can be described as a obliquely convergent pure shear dominated wrench zone. Divergent flow and variable amount of horizontal shortening between non-parallel plates accounts for exhumation of rocks from variable depth (Fig. 1). Boundary effects include west-east coaxial stretch along the rheologically soft Tauern Window boundary and discrete shear along the stiff Periadriatic Lineament.

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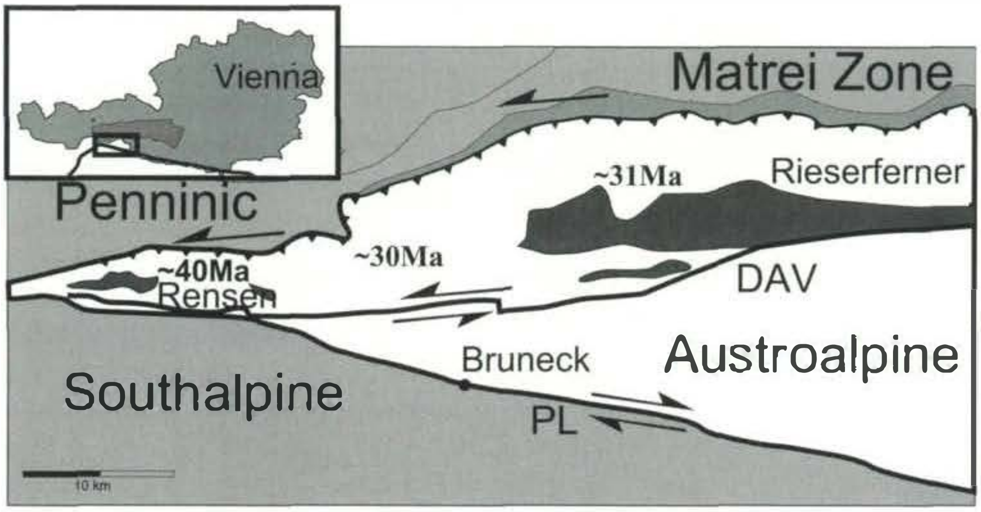
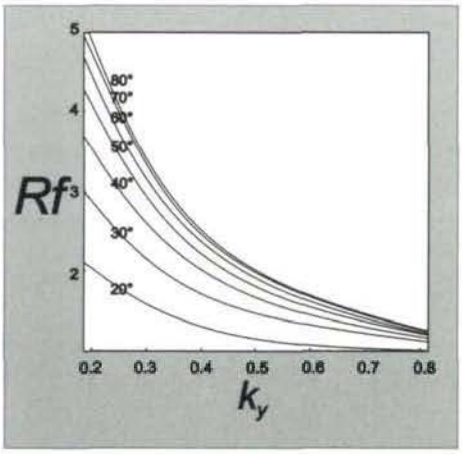
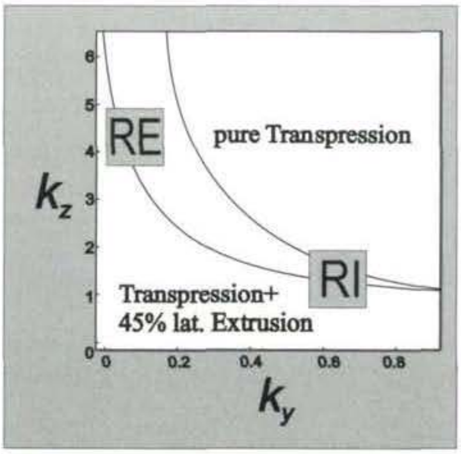


Sketch of eastward widening wrench corridor between Tauern Window and Periadriatic Lineamen



Transpression Model shows Variation of vertical strain (RF) against horizontal (~N-S) shortening for different angles of plate convergence



Kombined Transpression and 45% Extrusion translated to variable exhumation (stretch). The model suggest major exhumation at Rensen (RE) and minor exhumation at Rieserferner (RI)

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CONSTRAINTS ON THE EXHUMATION OF THE ADULA NAPPE (PART 1): A TOP-NORTH MEGA-SHEAR ZONE IN THE ROOF OF THE NAPPE

Niko Froitzheim, Jan H. Pleuger, René Hundenborn
Kerstin Kremer, Slavica Babinka & Ekkehard Jansen

The Adula nappe in the Central Alps is one of the world's best exposed and studied eclogite-bearing terranes. Metamorphic conditions determined from Alpine, Tertiary-age eclogites and garnet peridotites display a southward increase of maximum P and T, in accordance with the generally assumed southward subduction direction. The Adula nappe is overlain by the Tambo nappe across the metasedimentary, ophiolite-bearing Misox zone. Since the Tambo nappe is devoid of Alpine eclogite and suffered much lower P than the Adula nappe, and in view of the assumed southward subduction, top-S directed shearing along the Misox zone would be expected if the exhumation of the Adula nappe had occurred in the way of popular exhumation models (e.g., CHEMENDA 1995, ERNST 1999). We conducted a combined field mapping and textural study in the area San Bernardino pass – San Bernardino village in order to test this prediction. This study largely confirmed earlier results (e.g., BAUMGARTNER & LÖW 1983, MEYRE & PUSCHNIG 1993, PARTZSCH 1998) but added some important modifications.

The upper Adula nappe and the overlying Misox zone together form a mylonitic mega-shear zone active during the „Zapport phase" under amphibolite to greenschist facies conditions. Older fabrics of the „Trescolmen phase" are preserved within eclogite boudins found in several layers near the top of the Adula nappe. Two samples of eclogite-facies mylonite measured on the neutron diffractometer SV7-b at Forschungszentrum Jülich yielded strong omphacite fabrics, symmetric with respect to the Y-Z plane, suggestive of non-rotational, constrictional rather than plane-strain, deformation under eclogite facies conditions. The stretching lineation in the least overprinted boudins is east-west (associated with a foliation dipping east at steeper angles than in the surrounding Zapport-phase mylonites) and rotates towards N-S with increasing degree of Zapport-phase structural and metamorphic overprint. Inferences on the kinematic directions of the high-pressure deformation and the early stages of exhumation remain speculative because we do not know if and by what amount the presently east-west-trending eclogite-facies lineation has been rotated during the Zapport phase. The pressure gap between the high-P Adula nappe and the lower-P overlying units approximately coincides with the top of boudin-rich layers in the uppermost Adula nappe which contain not only the above-mentioned eclogite boudins but also olivine-rich boudins representing mantle rock. This suggests that the material missing between the Adula nappe and the overlying units, whose removal was responsible for the pressure gap, was constituted in part by mantle rock.

The eclogites were exhumed *from below into* the top-N-directed Zapport-phase shear zone. The orientation of the Zapport foliation (shallowly E-dipping) and lineation (N-S to NNW-SSE) is uniform in the Adula nappe and the Misox zone. Abundant and consistent shear sense criteria indicate top-N sense of shear. Overprinting of the Zapport foliation by southeast-vergent minor folds of the Niemet-Beverin backshearing phase indicates that the Zapport phase predates the Niemet-Beverin phase, in contrast to earlier WORK (PARTZSCH 1998, SCHMID et al. 1996) suggesting contemporaneity between Zapport phase and Niemet-Beverin phase. This overprint is also demonstrated by combined neutron texture and grain shape analysis of quartz mylonites, showing that an asymmetric, top-North quartz fabric (Zapport) was overprinted and rotated during top-east shearing (Niemet-Beverin), and by spectacular fold overprinting in the southern Adula nappe (NAGEL, this volume).

The following inferences are made regarding the early exhumation of the Adula eclogites:

After the closure of the Valais basin represented by the Misox zone, the Adula nappe, representing the distal European continental margin, was subducted under a mantle wedge belonging to the Briançonnais (Tambo-Suretta) terrane.

Removal of the Briançonnais mantle wedge led to the pressure gap between the Adula and overlying nappes. The Zapport top-north shear zone formed during this event, when the Tambo and Suretta nappes were detached from their lower crust and mantle and were underthrust by the Misox zone and the Adula nappe.

The Adula nappe was exhumed from below into this shear zone, the kinematic direction of this exhumation still being unknown. A top-S shear zone as predicted by models may have existed but if it did, has been completely erased by Zapport deformation.

Although top-SE to top-E extensional shearing occurred in the area, this was not responsible for the early exhumation of the eclogites because these had already been exhumed to amphibolite-facies conditions before or during the preceding Zapport-phase shearing.

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RADIOLARIAN BIOSTRATIGRAPHY, COMPONENT ANALYSIS AND GENESIS OF THE MIDDLE TO UPPER JURASSIC CARBONATE CLASTIC RADIOLARITIC FLYSCH BASINS IN THE CENTRAL NORTHERN CALCAREOUS ALPS

Hans-Jürgen Gawlick, Wolfgang Frisch, Eva Wegerer, Sigrid Missoni & Hisashi Suzuki

The sedimentation pattern in the Alpine-Carpathian region changed around the Middle/Upper Jurassic boundary. A significant increase in the sedimentation rate occurred with the deposition of radiolarian chert (Ruhpolding Fm.) in the Early Callovian and the formation of new, elongate, W-E striking basins (Lammer Basin, Tauglboden Basin) separated by a structural high (Trattberg Rise). Another radiolarite basin (Sillenkopf Basin) is formed in the southern part of the Lammer Basin and south of it. All basins contain carbonate clastic radiolaritic flysch.

The basins be can clearly distinguished by radiolarian biostratigraphy and component analysis.

Lammer Basin: Early Callovian to middle Oxfordian. The Lammer Basin contains a more than 1.5 km thick series of Callovian/Oxfordian deep-water cherts and shales intercalated with breccias, mega-olistoliths and slides (Strubberg Fm.). This trough was formed in the former area of the Upper Triassic lagoonal carbonate platform and shows a migration of the basin axis to the north during Callovian to early Oxfordian times. The redeposited rocks were derived from the continental margin along the southern rim of the Northern Calcareous Alps (Dachstein reef tract and Hallstatt Zone).

The basin fill is composed of Callovian/early Oxfordian deep-water sediments, which contain different types of mass-flow deposits and large slide masses. Examination of the stratigraphy and facies of the resedimented clasts and blocks suggests that the Hallstatt Zone and adjacent facies strips (Dachstein reef tract, Pötschen Fm, Hallstatt limestones, Meliaticum) were destroyed and that their Triassic to Liassic sediments were eroded or mobilized as slides and redeposited in the Lammer Basin. Contemporaneous with the emplacement of the reef tract slidesmetamorphic slides derived from the Hallstatt Salzberg facies zone also occur , indicating late-stage out-of-sequence thrusting. Sediment redepostion ended in the Lammer Basin in the late Oxfordian, contemporaneous with the formation of the Trattberg Rise and the Tauglboden Basin to the north. The Lammer Basin stretches from the Berchtesgaden area in the west (former Berchtesgaden-Kühroint Basin) to the area of Bad Mitterndorf in the east.

Tauglboden Basin: Oxfordian/Kimmeridgian boundary to Tithonian. In the Tauglboden Basin, the lower part of the radiolarien chert (black and red radiolarite) is unaffected by gravitative resedimentation. The gravitative resedimentation from the Trattberg Rise in the south started in the Kimmeridgian. The Kimmeridgian to early Tithonian Tauglboden Fm. attains a thickness of about 500 m near the depocenter in the southern part of the asymmetric Tauglboden Basin. Including the Oberalm, Schrambach and Roßfeld Fms., the thickness of the sedimentary succession is nearly 2000 m. The Tauglboden Fm. consists of resedimented and pelagic limestones, turbidites, grain flow deposits, and slides. They contain clasts of Upper Triassic to Oxfordian age derived from the adjacent Trattberg Rise to the south = local material (e.g. Dachstein limestone, Kössen beds, Adnet limestone, Klaus limestone, limestones of the Allgäu Fm., radiolarite). The mass flows show a south-to-north change from

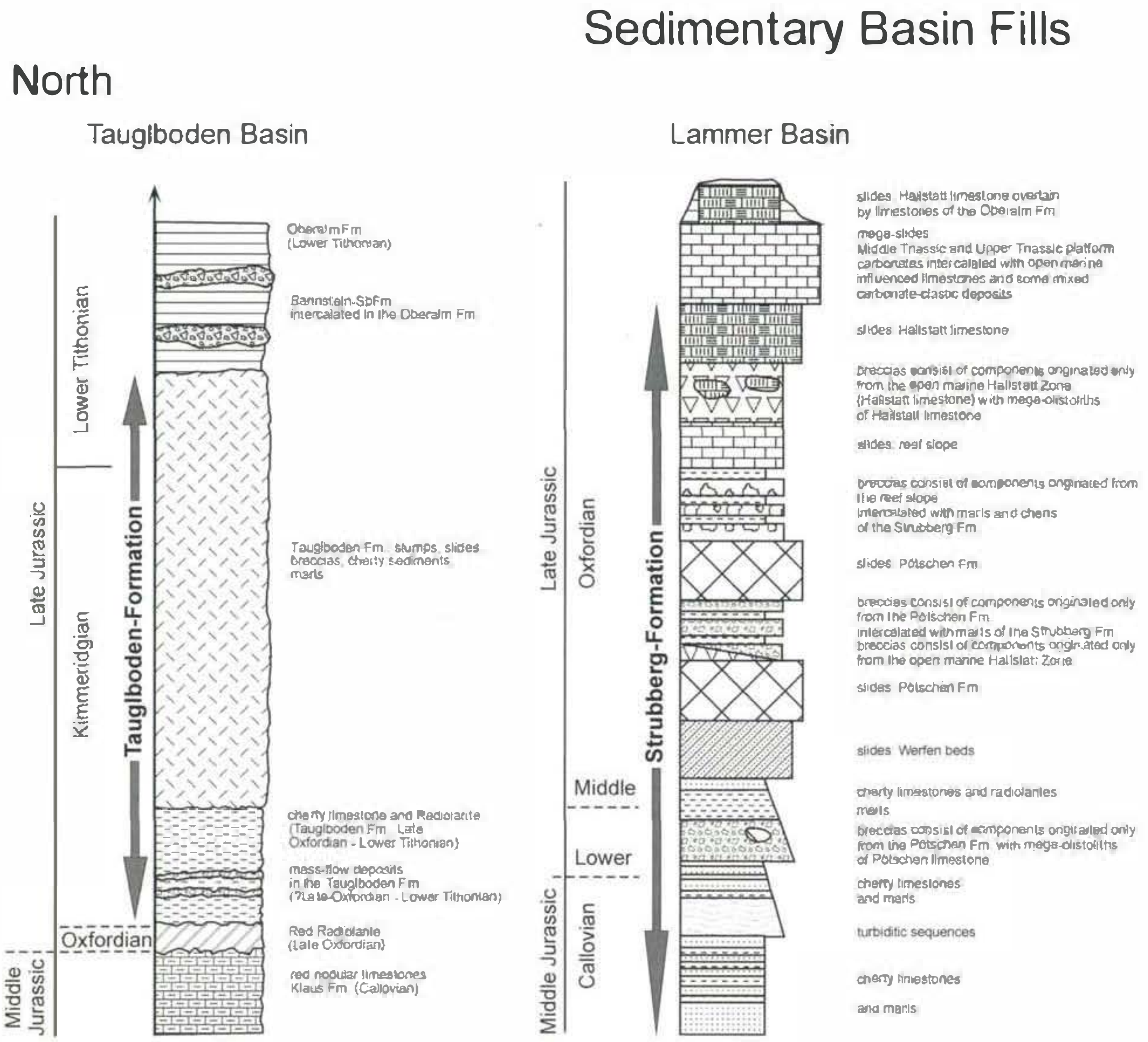

Fig. 1: Sedimentary sequences of the Lammer, Tauglboden and Sillenkopf Basin

proximal to distal facies. Flute casts, imbrications, and slumping also indicate transport from southerly directions. The Tauglboden Basin stretches from the Unken area in the west to the area of Bad Ischl in the east.

Sillenkopf Basin: Early Kimmeridgian to Tithonian. The Sillenkopf Basin contains mass-flow deposits in the late Kimmeridgian (dated by resedimented shallow-water components) with: 1. Dolomites and limestones of the Upper Triassic Pötschen Formation. 2. Cherty sediments of the Ruhpolding Fm. 3. Late Kimmeridgian shallow-water carbonates. 4. Protoglobigerina-wackestones, Klaus Formation. 5. Carbonate-cemented sandstones. 6. Phyllites. 7. Haselgebirge (salt-clay mudstone, gypsum), Permian. 8. Metamorphic and volcanic quartz. The stratigraphic range of the cherty sediments of the Sillenkopf Fm. is therefore equivalent to the Tauglboden Fm. The pebbles of these mass-flow deposits are completely different to those of the Tauglboden Fm., where the components derived from the Trattberg Rise. The Sillenkopf Basin is exposed in the southern Berchtesgaden Alps and southern Salzburg Calcareous Alps.

In the central Northern Calcareous Alps the Lammer and Tauglboden basins formed in sequence, indicating migration of tectonic activity. The Sillenkopf Basin is related to out-of-sequence shortening. All basins are interpreted as deep-sea trenches in front of advancing nappes as a result of soft collision related to the closure of parts of the Tethys Ocean. The tectonic structures (basin and rise formation), which are related to the closure of the Tethys Ocean, are sealed by latest Jurassic pelagic and shallow-water carbonates representing a period of tectonic quiescence (Plassen and Oberalm Fms.: late Kimmeridgian-Berriasian).

The Upper Jurassic configuration was generally stable during the Cretaceous, although tectonic rejuvenation occurred partly in late Lower Cretaceous time. Tertiary shortening and lateral extrusion destroyed this configuration and produced the block puzzle of the Northern Calcareous Alps.

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CONODONT COLOUR ALTERATION INDEX (CAI) INVESTIGATIONS IN THE SOUTHEASTERN BERCHTESGADEN ALPS AND EVIDENCE FOR THE EMPLACEMENT OF THE HALLSTATT MÉLANGE AND THE „BERCHTESGADEN NAPPE“

Hans-Jürgen Gawlick, Richard Lein & Sigrid Missoni

The emplacement of the Hallstatt Mélange and of the „Berchtesgaden nappe“ in the southeastern Berchtesgaden Alps is in the moment discussed controversially (Oxfordian, Tithonian or Barremian). The most important argument for an emplacement of the Hallstatt Mélange and of the „Berchtesgaden nappe“ in Barremian are the Hallstatt slides (Ahornbüchsenkopf and Klingereck slide) on top of the Roßfeld Fm. This interpretation is in contradiction of the general tectonic evolution in the late Middle and early Upper Jurassic.

In the late Middle Jurassic a significant increase in sedimentation rate occurred with the deposition of radiolarian chert (Ruhpolding Fm.) by the formation of new, elongate basins (Lammer Basin, Tauglboden Basin) with carbonate clastic radiolaritic flysch, separated by a structural high (Trattberg Rise). These radiolarite basins formed in sequence indicating migration of tectonic activity due to the closure of parts of the Tethys Ocean: only the older Lammer Basin (Early Callovian to Middle/Late Oxfordian = Strubberg Fm.) contains mass-flows and slides originated in the former Hallstatt Zone (= Hallstatt Mélange).

On base of these CAI investigations it is possible to demonstrate, that the Hallstatt slides on top of the Roßfeld Fm. are remobilized from southerly zones (area of the Torrener-Joch-Zone) with a moderate diagenetic overprint (late Upper Jurassic/early Lower Cretaceous).

These CAI zonations in the southern Berchtesgaden Alps are equivalent to the CAI zonations to the east (southern Salzburg Alps) with a slight decrease of the diagenetic overprint from CAI 2.0 in the south, CAI 1.5–2.0 and CAI 1.5 northerly, CAI 1.0–1.5 and CAI 1.0 in the north. The CAI zonation strikes generally east-west crossing nappe boundaries between the Tirolicum and the Hallstatt nappe: the northern boundary of the CAI zone CAI 1.5 strikes from Kuchlbach in the east to Bluntautal and Jenner, than to the northwest to Krautkaser valley and Schönau north of Königssee and than to the west to Zauberwald north of Ramsau. To the north follows the CAI zone CAI 1.0–1.5 and CAI >1.0. This zone strikes from Unterscheffau in the east to Hohes Brett, from there to the northwest to Scharitzkehl and southern Berchtesgaden. North of this area only CAI values of CAI 1.0 occur. The southern boundary of this zone strikes from the Golling Hallstatt zone in the east to Hoher Göll, from there to the northwest to the centre of Berchtesgaden and than to the west of Hirscheck. An exception are the CAI values (CAI 1.0–1.5) on base of the "Berchtesgaden nappe" in the area of the Gschirrkopf window and the slides of Pötschen Fm. in the Gschirrkopf window. The Ahornbüchsenkopf slide on top of the Roßfeld Fm. shows also CAI values of CAI 1.0–1.5. A slide with strong alteration (CAI 6.0) occurin the area of Bad Dürrnberg south of the Jakobberg gallery. Another described slide with strong alteration (CAI 6.0 – BRAUN 1998) on the base of the salt mine of Berchtesgaden can not be confirmed by own reinvestigations and show CAI values of CAI 1.0. Conodonts of this slide are partly strongly corroded (?evaporitic fluids) with no thermal overprint.

The emplacement of the Hallstatt slides in this area are dated by component analysis and radiolarian stratigraphy as Late Callovian to Lower Oxfordian (Strubberg Fm.; Lammer Basin) with a remobilization in Late Kimmeridgian (Sillenkopf Fm.; Sillenkopf Basin). The diagenetic overprint of the Hallstatt Mélange can be dated as younger than Kimmeridgian. But the Ahornbüchsenkopf slide on top of the Roßfeld Fm. was remobilized in Barrêmian. The upper limit of the diagenetic overprint can be dated as older than Barrêmian.

The "Berchtesgaden nappe" itself has a paleogeographic position (in Late Jurassic to Early Cretaceous) southwest of its recent position and can be demonstrate in the area northeast of Königssee by the transsection of CAI zones. In this area a sinistral lateral tectonic movement of CAI zones occurs along a fault zone striking from Königssee to Hellbrunn related to Miocene lateral tectonic extrusion.

The Hallstatt slide with strong alteration in the area of Bad Dürrnberg is transported and predates Upper Jurassic gravitational tectonic emplacement of Hallstatt Mélange onto the Upper Tirolicum. High CAI values are related to tectonic burial in an accretionary wedge formed during the closure of the Tethys Ocean.

The CAI data from area of the southern Berchtesgaden Alps confirm the polyphase diagenetic history of the Northern Calcareous Alps (GAWLICK et al., this volume).

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UPPER CARBONIFEROUS EXTENSIONAL TECTONICS IN THE ARGENTERA MASSIF (EXTERNAL CRYSTALLINE MASSIFS, WESTERN ALPS)

Guido Gosso, Silvia di Paola, Jean Marc Lardeaux, Patrick Ledru, Maria Iole Spalla

In the Paleozoic orogen of Europe, an extensional tectonic regime active during Permian and Carboniferous has been inferred by the tectonic and metamorphic evolution of the basement and of the Upper Carboniferous and Permian covers (ECHTLER & MALAVIEILLE, 1990; FAURE, 1995; GARDIEN et al., 1997; LOBKOWICZ et al., 1998).

In the Argentera-Mercantour massif (External Crystalline Domain of the Western Alps) scattered Upper Carboniferous continental sedimentary sequences have long been described (Faure MURET, 1955; MALARODA, 1970) but less is known about the tectonics which controlled their development..

The Upper Carboniferous deposits located at Punta Marges-Punta Barnon in the south-western sector of the Argentera massif, (Mollièresite of ROCCATI A., 1911, and SACCO, 1911), consist of conglomerates with minor sandstones and silts, transgressively lying upon the polymetamorphic para- and orthogneisses of the crystalline Malinvern-Argentera complex (FAURE MURET, 1955). In the crystalline basement a a newly recognized pattern of the Upper Carboniferous extensional tectonics provides an evidence of the Paleozoic orogenic evolution within the Alpine orogen. An earlier high temperature foliation underlined by brown biotite and white mica is reactivated in greenschist facies conditions by an extensional crenulation cleavage. Kinematic indicators (s-c structures and asymmetric pressure shadows) are compatible with a north-eastern direction of extension. This tectonic imprint is interpreted as contemporaneous with the basin opening since it does not affect the sedimentary sequence. On the contrary conglomerates and sandstones display a spaced foliation in the fine-grained fraction (e.g. CALLEGARI et al, 1974), and the clasts show asymmetric tails, in places recrystallized; similarly, in the basement a spaced and discontinuous foliation, marked by fine-grained withe mica and opaque minerals, occurs.

The geometry of the foliation which reactivated both the cover and the basement indicates a shortening effect that may be attributed to Alpine upthrusting on the base of its regional orientation compatibilities.

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DEFORMATION – METAMORPHISM RELATIONSHIP DURING THE EMPLACEMENT OF PERMIAN INTRUSIVES IN LANGUARD - CAMPO NAPPE (SOUTHERN STEEP BELT – CENTRAL ALPS)

Guido Gosso, Michele Morosini, M. Iole Spalla & Michele Zucali

Along the Southern Steep Belt of the Central Alps, in the Languard Campo Nappe (Austroalpine domain), Permian intrusives are emplaced in metapelites recording a HT-LP pre-Alpine metamorphic imprint. In this contribution we show a detailed map of field relationships between these Permian intrusives and their country rocks around the southern side of M. Varadega, near Passo del Mortirolo (in Upper Val Camonica, just south of the *Sondalo gabbro*); through this map, which graphically represents the superposed trajectories of successive foliations, we investigate the pre-Alpine deformation-metamorphism interaction between these two rock groups. We selected this area because of the weak Alpine metamorphic and structural reactivation under HP-LT metamorphic conditions, followed by greenschist facies re-equilibration (GAZZOLA et al., 2000).

The Languard-Campo Nappe consists of low to medium grade muscovite-biotite and minor staurolite-bearing gneisses and micaschists with interlayered amphibolites, marbles, quartzites and pegmatites (BONSIGNORE & RAGNI 1966, 1968, VENZO et al. 1971). In biotite-sillimanite-cordierite-bearing metapelites, the S2 regional foliation is marked by Bt + Sill, in films, while Pl + Qtz + Grt ± Tur occur in lithons; these metapelites are the country rocks of the Permian intrusives (GAZZOLA et al. 2000). Relics of St are preserved in And porphyroblasts. Radiometric estimates on the intrusives yielded a range between 298 and 224 Ma (BORIANI et al. 1985, DEL MORO et al. 1981, TRIBUZIO et al. 1999) and are interpreted as igneous cooling ages. Meso- and microstructural analysis suggest that the emplacement of granitoids occurred during S2 development; in addition the *Gneiss Listati del M. Varadega* (BONSIGNORE & RAGNI 1966) which are recognised to be locally affected by a pre-Alpine high-T lineation are re-interpreted as the deformed equivalent of the *Tremoncelli Granodiorite* (BOCKEMUEHL & PFISTER 1985).

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FABRIC EVOLUTION AND DOMINANT METAMORPHIC IMPRINT INTERACTION WHEN EXPLOITING THE ROCK MEMORY: EXAMPLES FROM THE ALPINE CHAIN

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Silvia di Paola, Michele Zucali, Fabio Zulbati Petrillo

When reconstructing mountain building processes crustal thickness variations are perceived as mechanically discontinuous translation processes of discrete crustal elements envisaged as kilometre-scale tectono-metamorphic units.

In this contribution we compare the P-T-d-t paths from various nappe belts of the Alpine chain, considering the influence of regional fabric distribution upon development of the metamorphic imprint which dominates locally within a metamorphic unit; subsequently we speculate on the physical significance of the metamorphic field gradient. This may be done on the ground of the evaluation of the spatial distribution of diagnostic equilibrium mineral assemblages and of their relationships with successive foliations by means of integrated mapping of structural and metamorphic signatures. The general scope is an approach to a physical definition of tectonic units on the ground of their tectono-metamorphic memory. An analysis of the metamorphic history together with the planar fabric evolution for several tectono-metamorphic units, from the Western Austroalpine and Central Southalpine domains, demonstrates that the dominant metamorphic imprint does not coincide with T_{max}-P_{Tmax} of each P-T-d-t loop; actually the dominant metamorphic imprint is that of the most pervasive fabric at the regional scale, provided the degree of granular scale reorganisation overstepped a critical stage. In addition our results point out that the regional distribution of dominant metamorphic imprints does not necessarily correspond to the "metamorphic field gradient" (e.g. ENGLAND and RICHARDSON, 1977; SPEAR, et al. 1984; SPEAR 1993; PEACOCK 1989) and therefore it cannot be used to distinguish tectono-metamorphic units in terrains that underwent polyphase deformation and metamorphism without considering the areal distribution of superposed syn-metamorphic fabrics. Indeed within a single tectono-metamorphic unit different metamorphic imprints can areally dominate or the same dominant metamorphic imprint can occur in different tectono-metamorphic units.

Where nappe belts are lacking tectonic intercalations of paleogeographically significant sedimentary units, the size of tectonic units that contributed to thickening of the metamorphic crust may therefore be derived from the full tectonometamorphic history.

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ALPINE EVOLUTION OF THE LANGUARD-CAMPO AND SERIE DEL TONALE: STRAIN PARTITIONING VS. REACTION RATE (AUSTROALPINE DOMAIN - ITALIAN CENTRAL ALPS)

Guido Gosso, Maria Iole Spalla, Michele Zucali, Davide Gazzola and Francesca Salvi

The Central Austroalpine domain, right north of the Insubric tectonic line (Monte Padrio-Passo del Mortirolo-Monte Serottini, Upper Val Camonica), has been classically divided, on the base of lithological affinities and dominant metamorphic imprints, into three units: the „Serie del Tonale“, the „Cima Rovaia Schists“ and the „Punta di Pietra Rossa“. The association of these three units should correspond to a complete section of a pre-Alpine continental crust (BONSIGNORE & RAGNI, 1966; 1968; SCHMID et al., 1996; VENZO et al., 1971) and an Alpine metamorphic imprint under greenschist facies conditions is interpreted to affect only kilometre scale shear zones (e.g. Mortirolo Line; FROITZHEIM et al., 1994; MANCKTELOW et al., 1999).

The study of the relationships between the evolution of meso- and microfabrics and metamorphic transformation during pre-Alpine and Alpine times suggests a relative timing of the superposed structural events, which results as follows:

i) D1 and D2 deformation phases developing a S1+2 composite foliation marked by biotite + sillimanite + feldspar + garnet in micaschists and gneisses; ii) emplacement of Permian age granitoids, diorites and minor gabbros (BORIANI et al., 1985; DEL MORO et al., 1981; TRIBUZIO et al., 1999) during development of the S2 foliation; iii) syn-D3 metamorphic transformations and S3 fabrics occurring within Permian age metaintrusives and their country rocks. HP/low to intermediate -T metamorphic parageneses (GAZZOLA et al., 2000; SPALLA et al., 1995; TOMASCHEK & BLÜMEL, 1998) mark the S3 foliation in all lithologies. Large-scale D3 fold structures mainly occur in the central part of the area (Cima Cadì – Passo del Mortirolo); they deform the S1+2 surface and are associated to the development of an S3 axial plane foliation. Within smaller volumes, D3 deformation occurs as meter scale shear zones deforming coronitic metaintrusives (metaintrusive preserving igneous textures) and country rocks (Alpe Troena – Cima Verda – Monte Serottini – Pian di Locher) as shown by GAZZOLA et al. (2000) at Monte Pagano. Moreover syn-D4 metamorphic transformation occurred under greenschist facies conditions affect all lithologies in the whole area but the corresponding fabrics (S4 tectonitic and/or mylonitic foliations) better developed in the central part, across the Passo del Mortirolo (kilometre-scale shear zone) and in the northern part along the Cima Tre Comuni – Monte Tremoncelli divide (metre-scale shear zones). Detailed mapping of all these structures was accomplished within the “Progetto Carte Prototipali” of the ItalianCNR , a project devoted to improvement of mapping techniques. Mapping of foliations was conducted together with definition of their mineralogical support and therefore associated with corresponding metamorphic conditions, in an area of ~40 km^2; it allowed to contour the volumes which record equivalent Alpine tectono-metamorphic evolutions. Overlapping of such contours with those of the previously proposed three-unit subdivision (“Serie del Tonale”, “Cima Rovaia Schists” and “Punta di Pietra Rossa”) shows that they correspond to a single tectono-metamorphic unit during Alpine evolution and that kilometre scale interaction between strain gradients and reaction rate generated the prominent lithological differences and, ultimately, the distribution of the dominant metamorphic imprint. In conclusion, under the light of this new analytical perspective, the geological distinctions "Serie del Tonale", "Cima Rovaia Schists" and "Punta di Pietra Rossa" are kilometer-size volumes showing different dominant metamorphic imprints and relative timing of structures.

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TECTONOMETAMORPHIC EVOLUTION OF THE AUSTROALPINE NAPPES IN THE NORTHERN ZILLERTAL AREA, EASTERN ALPS

Beatrix Grasbon, Andreas Piber & Peter Tropper

This project is closely related to the international geophysical TRANSALP project which provides a continuous seismic reflection profile through the Eastern Alps along the transect Bad Tölz (D) – Venice (I). In the frame of the TRANSALP project, this investigation addresses the problem of the tectonometamorphic evolution of the Austroalpine nappes in the northern Zillertal Area. The three units to be studied in the course of this project are the Innsbrucker quarzphyllite, the Kellerjochgneiss, an acidic orthogneiss body, and the Wildschönauer Schiefer. These units are separated by shear zones, from less than a meter in diameter up to several meters diameter. The Innsbrucker quartzphyllite is part of the lower Austroalpine units and the Wildschönauer Schiefer is part of the upper Austroalpine Grauwacken Zone. The Kellerjochgneiss is still of debated origin, since it has been attributed over the years to either the lower- or the middle Austroalpine units.

Most importantly, these units lack modern petrological investigations, to determine the P-T conditions of the pervasive metamorphic overprint and relate them to the structural history. The detailed tectonometamorphic investigation of these units and their tectonic contacts provides an important key to the understanding of the paleogeographic reconstructions of this part of the Eastern Alps.

During this project, detailed field mapping of an area of ca. 60 km^2 between the Finsinggrund in the south and the Inntal in the north was performed. Combining the structural observations of the three units with previous structural data by SCHMIDEGG (1943), WEZEL (1981), ROTH (1984), STEYRER et al. (1996), KOLENPRAT et al. (1999) and REITER (2000) yields the following tectonic successions:

Four stages of deformation could be distinguished in all three units. The first three stages are ductile, whereas the last stage is brittle. The earliest stage, D_1, is associated with a NW-SE oriented transpression and structures indicating a transport top NW could be discerned. D_2 is the result of a NE-SW oriented transpression and indicates transport top NE. D_3 is manifested by the formation of semi-ductile kink bands. The subsequent brittle deformation D_4 can also be divided into two stages. The earlier stage is due to NE-SW directed extension and the later stage is due to movements along the Inntal and Zillertal faults.

Correlation of these data with other structural- and geochronological investigations from this area (ANGELMAIER et al. 2000; GENSER et al. 2000), suggest that the observed stages of deformation are thought to be associated with the Alpine orogenic cycle.

Thermobarometric investigations in the Kellerjochgneiss, by using multi-equilibrium methods yield temperatures of 350–430°C and pressures of 8.5–10.5 kbar whereas in the Innsbrucker quartzphyllites pressures are significantly lower and yield 3.5–6 kbar for the same temperature range. These data suggest that both units were probably separated during the early stages of Eo-Alpine metamorphism (e.g. situated in different crustal levels), and the Kellerjochgneiss and Wildschönauer Schiefer were subsequently juxtaposed onto the Innsbrucker quartzphyllite during Eo-Alpine nappe transport to the NW.

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THE P-T-t-D EVOLUTION OF CRETACEOUS METAMORPHISM IN THE CENTRAL SCHNEEBERG COMPLEX (EASTERN ALPS, ITALY/AUSTRIA): ANDALUSITE-FORMATION DURING DECOMPRESSION

Gerlinde Habler, Manfred Linner, Rasmus Thiede & Martin Thöni

The metamorphic evolution of the Upper Austroalpine Schneeberg Complex (SC) in the southern Ötztal basement comprises pressure-dominated metamorphism with subsequent static (re)crystallization (KONZETT & HOINKES, 1996). This metamorphic event is correlated with eclogite facies metamorphism in the SE Ötztal crystalline basement S of the SC.

New findings of andalusite in the „Monotone Serie“ (garnet-micaschists from the core of the SC synforms) allow to constrain the metamorphic evolution after the pressure peak. An interdisciplinary (petrological, geochronological and structural) investigation of metapelites was performed to decipher the tectonometamorphic evolution of the central SC.

Metapelites from the “Monotone Serie” have a common whole rock (WR) composition with mainly insignificant Ca and Mn content. They can be described in the KNFMASH (+ms +qtz +H_2O) system, with Ab and Pg representing the only Na-bearing phases. The Al_{WR}-content varies locally and allows a distinction of Al-rich (Als-bearing) and Al-poor (Als-free) metapelites.

A continuous succession of four mineral (re)crystallization phases (K1 to K4) is recorded by compositional zoning of mineral phases and microstructures. K1 minerals grew syn-, inter-, and/or postkinematically relative to D1 (mylonitisation and penetrative microfolding with NW to WSW dipping stretching lineations and fold axes). K2 minerals formed synkinematically relative to D2 (large-scale tight S-vergent folds with E-W-striking fold axes), while K3 and K4 are characterized by static mineral growth, which took place postkinematically relative to D2.

Al-rich metapelites:

K1: Idioblastic Grt1 is the only Ca-bearing phase (Xgrs = 0.12), with slightly increasing X_{Mg} =$Mg/(Mg+Fe^{2+})$ from core to rim. Inclusions are fine-grained Qtz, Ilm, Mt and rare Ab and St. The matrix contains phengitic WM1 (Si^{IV} 3.20–3.23 per 11 oxygens), Pg, Qtz, Bt, Chl, Ky, Ab and Ilm.
K2: Grt2 formed idioblastic rims around Grt1, with decreasing Ca-content and X_{Mg}-ratio. A second Mn maximum in Grt reflects Chl-breakdown by overstepping the KFMASH univariant reaction grt+chl+ms = bt+st+qtz+H_2O. Coarse-grained Ky2 and St2 grew due to Pg-breakdown. The matrix consists of phengitic WM2 (Si^{IV} 3.15–3.18 per 11 oxygens), Qtz, Bt, Pg, Ab and Ilm.
K3: Mineral growth continued postkinematically to the ductile deformation. Idioblastic Grt3 rims display again increasing X_{Mg}, at further decreasing Ca-content. Coarse-grained Bt, Ab and Ky as well as medium-grained St (re)crystallized in the matrix.
K4: Dm-sized andalusite grew along with oligoalbite by Pg-breakdown, as indicated by reaction rims of Pl between andalusite and the matrix.

Al-poor metapelites:

In contrast to the Als-bearing rocks, Al-poor metapelites only show the first garnet generation (Grt1). During K2 and K3 garnet was resorbed. St is rarely present, and aluminosilicate does not occur.

PT-conditions:

Phase equilibrium calculations with the program THERMOCALC (Powell & Holland, 1988, Holland & Powell, 1998) show, that the garnet stability in andalusite-bearing rocks is confined to conditions near the pressure peak (at P > 0.7GPa). New data concerning the pressure peak correlate with the results of Konzett & Hoinkes (1996; 580–600°C/0.8–1GPa). The K1 assemblage formed in the KFMASH-divariant field Grt–St–Chl. Due to local variations of the equilibrated WR composition, the assemblages Ky–Chl–St locally have been stable in the matrix surrounding Grt, and a first Bt generation was formed in Al-poor domains. First Ky-formation obviously was a product of continuous reactions in the KFMASH-system rather than Pg-breakdown, which is probably the main Ky-forming reaction in the SC, as described in the literature (Hoinkes, 1981).

At the onset of decompression (=K2-D2), the KFMASH-univariant reaction Grt+Chl+Ms = St+Bt+Qtz+H_2O was overstepped, leading to the stability of the divariant assemblage Grt–St–Bt. This reaction induced the disappearance of Chl, indicated by a second Mn maximum in Grt2, and an increase in St modal abundances. For an H_2O-activity of 1 this reaction occurs at about 600°C/0.75GPa. This mineral reaction may have also been induced by a reduction of the H_2O-activity during the first decompressional stage, which would shift the dehydration reactions towards lower T-conditions. Assuming a reduced H_2O-activity of 0.7, the univariant Chl-breakdown reaction would have taken place at about 565°C/0.75GPa.

Postkinematic mineral formation already started in the divariant field Grt–St–Bt (=K3). Grt3 shows a continuous but significant increase of X_{Mg} towards the rim. During decompression this zonation may be explained by continuous reduction of the H_2O-activity, as the $X_{Mg}{}^{Grt}$ isopleths have a very shallow positive slope in the Grt–St–Bt field and are therefore rather T-insensitive. Coarse-grained Ky and Ab overgrew the D2 structures statically due to the Pg-breakdown-reaction Pg+Qtz = Ab+Ky+H_2O. During nearly isothermal decompression the KNFMASH-divariant mineral reaction Bt+Pg+Qtz = Ab+St+Ms+H_2O probably took place, which led to the reequilibration of Bt and St with higher X_{Mg} than the previous assemblage with Grt3. It is important to note, that the Grt3 rim does not show any diffusional reequilibration, retrograde zoning or corrosion.

A second phase of static mineral growth took place in the andalusite stability field, where the Pg-breakdown reaction to Als and Pl continued, now producing coarse-grained andalusite. As Bt is part of the stable assemblage with andalusite instead of Chl, T-conditions higher than about 500°C (aH_2O=0.5) to 540°C (aH_2O=1) are required at low-pressure (0.2–0.4GPa). As the only observed univariant mineral reaction in the andalusite stability-field is the Pg-breakdown reaction, the absolute metamorphic conditions at the low-pressure stage are strongly dependent on the H_2O-activity.

Geochronology

In order to constrain the age of metamorphism, 0.5–1cm sized garnet grains were used for Sm-Nd geochronology. The Fe-poorer fraction (= Grt1) yielded 94.1±2.2 Ma, the Fe-richer fraction (= Grt2/3) 92.7±1.2 Ma. The period of garnet growth therefore ranges between 96.3 and 91.5 Ma, constraining an eo-Alpine age for the metamorphic peak and the major deformation phases. Eo-Alpine cooling below 300°C is indicated by a Bt-whole rock Rb-Sr age at 79.5±0.8 Ma, derived from the same sample.

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^{40}AR/^{39}AR DATING OF ECLOGITE-FACIES DEFORMATION IN THE TAUERN WINDOW (EASTERN ALPS, AUSTRIA)

Robert Handler, Walter Kurz & Christian Bertoldi

^{40}Ar/^{39}Ar laser-probe dating and electron microprobe study on bulk-grain white mica from the Eclogite Zone and the Rote Wand – Modereck nappe of the Tauern Window, Eastern Alps (Austria), has been carried out in order to constrain the age of eclogite-facies metamorphism and deformation.

Four concentrates from three samples of eclogite-mylonite show similar chemical composition with an average of c. $Ms_{40}Cel_{51}Pg_9$. ^{40}Ar/^{39}Ar dating of these four concentrates yielded similar flat Ar-release patterns, with ages ranging between 31.9 ± 0.4 Ma and 33.3 ± 0.4 Ma. ^{36}Ar/^{40}Ar vs. ^{39}Ar/^{40}Ar plots yielded isotope correlation ages ranging between 32.0 ± 0.5 Ma and 33.4 ± 0.3 Ma with ^{36}Ar/^{40}Ar intercepts close to atmospheric composition.

One paragonite sample ($Ms_5Pg_{93}Mrg_2$) from a fine-grained eclogite of the same tectonic level yielded a total-gas age of 37.9 ± 2.1 Ma and an isotope correlation age of 40.1 ± 4.2 Ma. The relatively large error of the age results from the low K- and therefore Ar-content of the sample. For comparison, a concentrate of phengitic muscovite ($Ms_{64}Cel_{32}Pg_4$) has been separated from Triassic calcite-marble (sample 5) of the Rote Wand – Modereck nappe, which experienced blueschist-facies metamorphism, followed by a greenschist-facies metamorphic overprint. ^{40}Ar/^{39}Ar dating yielded a total-gas age of 38.9 ± 0.4 Ma, and an isotope correlation age of 38.8 ± 0.3 Ma. Ar-release paterns and ^{36}Ar/^{40}Ar vs. ^{39}Ar/^{40}Ar isotope correlation analyses indicate only negligible influence by incorporation of extraneous ^{40}Ar-components. Both samples are significantly older than the ages obtained from the eclogite-mylonites.

Our results indicate that the Ar-isotopic system in all these white micas have only slightly been influenced by incorporation of extraneous ^{40}Ar-components or ^{40}Ar-loss after initial closure. Therefore, the integrated ages are interpreted to be geologically meaningful, and the age difference of c. 6 Ma between white micas separated from eclogite-mylonites and those from fine-grained eclogite and calcite-marble is interpreted to be significant.

We conclude that in the area of investigation local shear deformation led to the development of high-temperature ductile fabrics, as indicated by the plastic deformation of garnets within the eclogite-mylonites, and subsequent regional cooling below respective closure temperatures for the Ar-isotopic system in white micas at c. 38 Ma. Strain softening localized shear deformation within the eclogite-mylonites and there caused (re-)crystallization of phengites under low-temperatures eclogite-facies metamorphic conditions until c. 32 Ma. This localized deformation caused no disturbance of the previously closed isotopic systems of the phengite and paragonite samples in less deformed rocks. These samples still record older ages, but indicate no presence of extraneous Ar-components.

Furthermore, our study shows that isotope correlation plots significantly help to understand and interpret results obtained by ^{40}Ar/^{39}Ar age dating, and that phengites do not always contain erxtraneous ^{40}Ar-components.

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FORMATION OF VEINS IN THE TAUERN WINDOW RELATED TO CONTINENTAL ESCAPE IN THE EASTERN ALPS: CONSTRAINTS FROM ^{40}AR/^{39}AR DATING OF ADULARIA AND WHITE MICA

Robert Handler & Franz Neubauer

Formation of open, crystal-filled extension veins within the Tauern Window of the Eastern Alps (Austria) has been dated by ^{40}Ar/^{39}Ar incremental laser ablation of adularia and white mica bulk-grain samples separated from up to cm-large free crystals. Dating of chlorite has not been successful because of the low Ar-content. As adularia and white mica from the same locality report similar ages, we conclude that temperatures for vein formation were lower than the respective closure temperature for the Ar-isotopic system in K-feldspar (c. 250°C), and interpret these ages to directly date crystallisation within, and therefore formation of, these open veins. Although Ar-release spectra and ^{36}Ar/^{40}Ar vs. ^{39}Ar/^{40}Ar isotopic correlation plots indicate variable contributions of extraneous ^{40}Ar-components to the isotopic systems, results indicate three different pulses of vein formation. We do not observe any correlation between the dated minerals (e.g. muscovite or adularia), the metamorphic isogrades, the obtained ages, or with the amount of incorporated extraneous ^{40}Ar-components. The ages obtained are significantly different, and indicate: (a) a first pulse at c. 19 Ma (one muscovite, three adularia analyses) is interpreted to closely date formation during ca. ESE-WNW extension in accomodation zones along a strike-slip zone (Möll valley fault), which separates distinct culminations of the Tauern metamorphic dome. A second event (b) at c. 15 Ma (two muscovite, three adularia analyses) is interpreted to represent a distinct thermal pulse which coincides in age with a weak thermal pulse found in mylonites of adjacent, overlying nappes. One well defined analysis (c) of an adularia found in the western part of the Tauern Window reports an age of c. 13 Ma and coincides with regional cooling found by zircon fission track dating. We conclude, that the new ^{40}Ar/^{39}Ar ages presented in this study closely date three pulses of fluid flow during exhumation of the Tauern metamorphic core complex, which was associated with c. orogene-parallel extension and continental escape of hangingwall Austroalpine units in the Eastern Alps.

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SUMMARY OF NEW ^{40}AR/^{39}AR DATA ALONG THE TRANSALP-SECTION

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^{40}Ar/^{39}Ar dating of various units along the TRANSALP section N and S of the Tauern window has been carried out in order to constrain the tectonic evolution of the Austroalpine basement, and of Penninic units exposed in the Tauern Window. In the following the tectonic units are discussed from hanging- to foot-wall:

White mica from the Paleozoic clastic sequences of the **Graywacke Zone** south of Schwaz record disturbed Ar-release spectra, with ages of c.180 Ma in low-temperature gas release steps, which increase to c. 267.2 ± 6.0 Ma in medium- and high-temperature gas release steps. These ages are interpreted to record late-Variscan cooling and an Early Jurassic tectonothermal overprint.

The underlying **Kellerjoch gneiss** is a deformed pre-Variscan meta-granitoid, which is, due to its tectonic position, considered to be part of the basement unit of the Middle Austroalpine nappe complex (STEYRER et al. 1996). The protolith is regarded as a coarse-grained felsic biotite-granodiorite (SiO_2 68–75%) with K-feldspar phenocrysts up to 20 mm and magmatic quartz up to 5 mm. The weak peraluminous composition (A/CNK c. 1–1.1) points to an I-type granitoid, as well as high Ba- (500–700 ppm) and moderate Rb- (130–160 ppm) contents (STEYRER & FINGER, 1996). Preliminary dating of monazite and thorite (method see FINGER et al., 1996) yielded a monazite Th-U-Pb-model age of 468 ± 38 Ma (STEYRER & FINGER, 1996), which is interpreted to closely date the time of protolith formation. Variscan regional metamorphism is indicated by thorite Th-U-Pb model ages of 323 ± 49 Ma and 353 ± 26 Ma; STEYRER & FINGER 1996). These data are in concordance with phengite Rb-Sr reported by SATIR & MORTEANI (1978). ^{40}Ar/^{39}Ar incremental heating of white mica bulk-grain samples generally show strongly disturbed age patterns which record late-Variscan ages in high-temperature argon release steps and Cretaceous ages in low-temperature increments, indicating two low-grade metamorphic overprints.

Nearly all ^{40}Ar/^{39}Ar age spectra of the **Innsbruck Quartzphyllite** show staircase patterns due to polyphase tectonothermal events.Three events can be clearly deduced: (1) Late Variscan metamorphic imprint (e.g. 282.8 ± 2.9 Ma); (2) a possible Early Jurassic rejuvenation is indicated by ages between 180 and 200 Ma. We preliminarily interpret the Early Jurassic ^{40}Ar/^{39}Ar ages to record a thermal imprint most probably associated with ductile shearing along low-angle normal faults during extension, which subsequent led to formation of Penninic oceanic crust. This poses the question whether some of the present-day observed nappe contacts within Austroalpine units were initially formed during extension. Finally (3) a Cretaceous overprint is indicated by a weakly defined “plateau age” of c. 93.1 ± 5.3 Ma. These data show that the Cretaceous metamorphic overprint, which was associated with ductile thrusting, did not significantly exceed the Ar retention temperature in white mica.

Within the Penninic units of the **Tauern Window** (however, west of the TRANSALP-line) three major events are recorded: ^{40}Ar/^{39}Ar incremental heating of phengites from the Eclogite zone and the overlying Rote Wand -

Modereck nappe record cooling subsequent to eclogite facies metamorphic conditions at c. 38 Ma. Local shear deformation within the eclogite zone caused mylonitization at c. 32 Ma. Late stages of brittle deformation are constrained by analyses of vein-filling adularia and white mica, which record ages of c. 20–15 Ma, interpreted to closely date formation of the veins during exhumation of the Tauern Window and lateral continental escape of the hangingwall Austroalpine nappe complex. These results are in accordance with a staircase-type Ar-release pattern obtained by dating of crenulated white mica from the Penninic-Austroalpine boundary (Liu et al., 2001).

Samples from Austroalpine mylonitic rocks **close to the DAV fault** (S of the Tauern window) record a Paleogene metamorphic overprint of the Austroalpine units there (integrated plateau ages of 44.6 ± 0.7 and 59.3 ± 1.3 Ma) with subsequent rejuvenation (< 40 Ma).

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ASPECTS OF THE GEOMETRY OF DEEP SEATED GRAVITATIONAL SLOPE DEFORMATIONS. EXAMPLES FROM THE EASTERN ALPS. WE KNOW MANY DETAILS BUT WE KNOW A VIEW OF THEM ONLY

Siegfried W. Hermann, Peter Ramspacher, Gunter Riedmüller and Arnold Steidl

In the Eastern Alps large scale gravitational slope deformations (DGSDs) have been recognised usually only by coincidence during building and mining activities. Thereby knowledge of principle morphological characteristics has become well known since the outcome of older descriptions (e.g. AMPFERER, 1939; ZISCHINSKY, 1966). Until recently, the descriptions by these early authors have been used as the basis for the identification of both dormant and active DGSDs. In contrast, subsurface information is singular, therefore the interpretations of the mechanics of DGSD have been gathered by surface data only. However, less than about 40 sites have been studied to some extend with respect to their rheological behaviour.

In recent projects we have mapped 35 new DGSD sites within a 800 km^2 region in the Wölz mountains (HERMANN et al., 2000), indicating that several hundreds of DGSDs remain undiscovered in the Eastern Alps.

Here, we present some ideas on the mechanics of DGSD formation using structural geological methods we have shown to be successful at several sites in the crystalline basement of the Wölz region. Our interpretations on the deformation geometry of DGSD collected from the hanging wall mass of several sites fit with detailed documentation of the localisation of the basal displacement surfaces, accepted from the site "Rosone" (BARLA and CHIRIOTTI, 1995) and the site "Kaponig" (KNOLL et al., 1994; RAMSPACHER et al., 2000).

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ALPINE (CRETACEOUS) METAMORPHISM IN THE WESTERN CARPATHIANS: P-T-t PATHS AND EXHUMATION OF THE VEPORIC CORE COMPLEX

Marian Janák, Mike Cosca, Fritz Finger, Dusan Plasienka,
Balazs Koroknai, Branislav Luptak & Peter Horvath

The Central Western Carpathians (CWC) represent a tectonic system that correlates with Austroalpine units extending eastward from the Alps. The pre-Tertiary complexes of the CWC originated during Cretaceous collisional shortening and stacking of the lower plate following Late Jurassic closure of the Meliata ocean, the most intense metamorphism affected the Veporic unit. The tectonometamorphic history of this area was previously interpreted as essentially pre-Alpine, with only minor, greenschist facies Alpine overprint. In contrast, recent results (JANÁK et al., 2001; KOROKNAI et al., in print) emphasized that the Alpine overprint reached amphibolite facies. In this study, new geochronological data on monazite are presented, constraining the Middle Cretaceous time for the peak metamorphism in the Veporic unit, and the *P-T-t* paths are reconstructed.

The Veporic unit comprises pre-Alpine basement (Variscan granites and high-grade metamorphic rocks) overlain by the Upper Palaeozoic–Triassic sedimentary cover. All these rocks show a heterogeneous Alpine overprint related to the development of the metamorphic core complex structure during Cretaceous orogeny. The complex is intruded by Late Cretaceous Rochovce granite.

Three Alpine metamorphic zones are recognized in the central and eastern part of the Veporic unit: (1) chloritoid + chlorite + garnet; (2) garnet + staurolite + chlorite; and (3) staurolite + biotite + kyanite (JANÁK et al., 2001). The isograds separating the metamorphic zones are roughly parallel to the north-east dipping foliation related to extensional updoming along low-angle normal faults. The sequence of metamorphic reactions and their topology in *P-T* space suggests a single metamorphic cycle. Thermobarometric data yield *P-T* conditions from c. 500°C and 7–8 kbar to c. 620 °C and 9–10 kbar (JANÁK et al., 2001). The metamorphic zonation reflects a coherent and continuous metamorphic field gradient from greenschist to middle amphibolite facies, the metamorphic grade increasing with depth.

Chemical Th-U-Pb dating of monazite by means of the electron microprobe has been applied to broadly constrain the peak-PT age of regional metamorphism in the Veporic unit. The results can be taken from the total-Pb vs Th* diagram in Fig. 1. Monazites from three samples were analysed together with a monazite age standard (F-5 Std.; recommended value 341±2 Ma). Monazites from two metapelite samples (V8b from the chloritoid + chlorite + garnet zone and VV4/99 from the staurolite + biotite + kyanite zone) indicate a unique Mid-Cretaceous formation age (weighted averages: 91±25; 92±16 Ma). A mylonitic granite (CL3) contains two generations of monazite, one with an older (c. 370-350 Ma) Variscan age and the second with an Alpine (c. 100-90 Ma) age. Some monazites in sample CL3 have old cores and young rims, the latter being also compositionally distinct (e.g. lower Y, U).

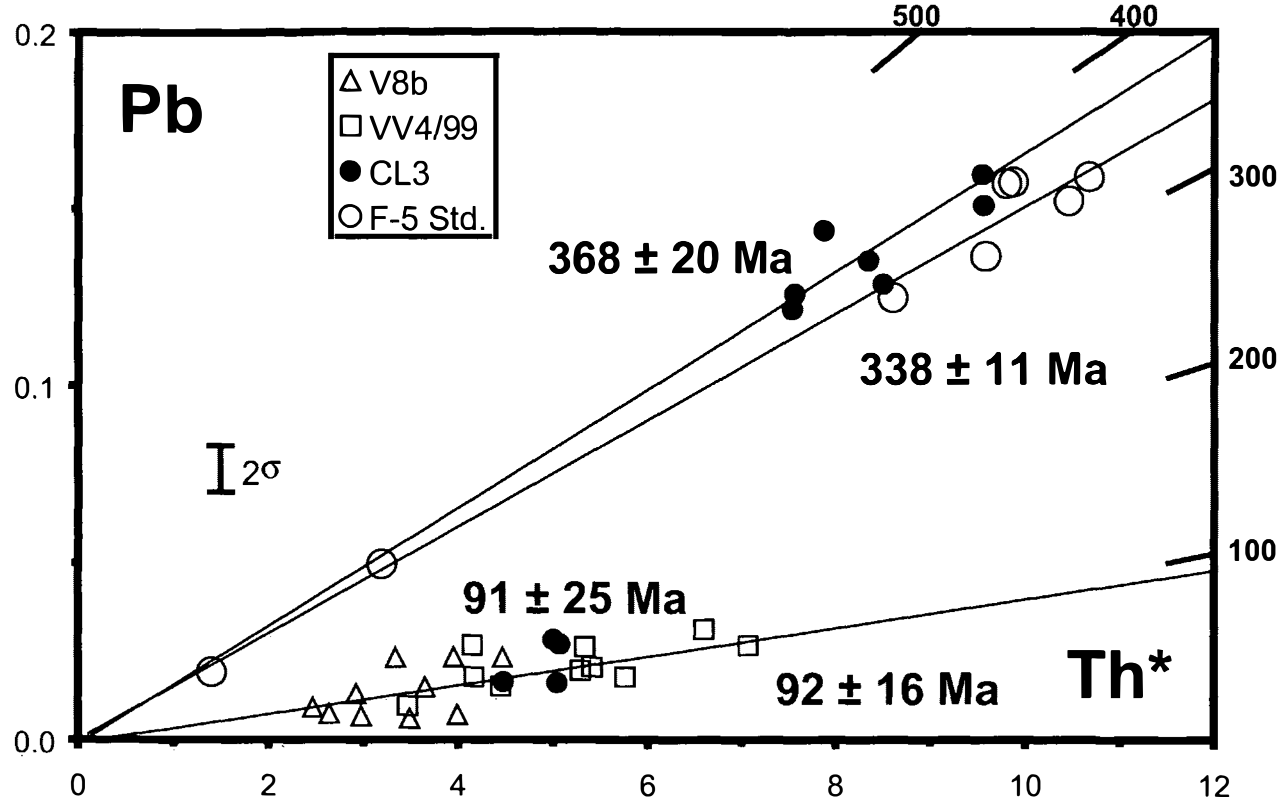

Fig. 1

^{40}Ar/^{39}Ar data obtained by *in situ* UV laser ablation of white micas (JANÁK et al., 2001) constrain the timing of cooling and exhumation in the Late Cretacous. Mean dates are between 77 and 72 Ma, however, individual white mica grains record a range of apparent ^{40}Ar/^{39}Ar ages indicating that cooling below the blocking temperature for argon diffusion was not instantaneous. No pre-Alpine dates have been determined, implying that all white micas equilibrated during the Alpine cycle.

The *P-T-t* path followed by individual rocks in the highest-grade (staurolite + biotite + kyanite zone) metapelites is depicted by the trajectory in Fig. 2, crossing dehydration reaction curves and metamorphic field gradient near the metamorphic peak (T_{max}) conditions. This part of the *P-T-t* path was presumably related to post-burial heating as a consequence of thermal relaxation of the geotherm after crustal shortening and thickening. Based on monazite dating we suppose that the peak metamorphic conditions were reached in the Middle Cretaceous time (c. 92 Ma). The retrograde portion of the *P-T-t* path is inferred from the development of (C')-shear planes and partial transposition of porphyroblats oblique to the primary foliation (S) planes. Partial transformation of kyanite to sillimanite in high-strain domains indicates a post-peak decompression and cooling close to the boundary between the kyanite and sillimanite stability fields. Cooling through a temperature of c. 400°C at c. 72 Ma is recorded by the ^{40}Ar/^{39}Ar system in the white micas. Early stages of unroofing involving nearly isothermal decompression were probably triggered by erosional denudation, whereas the final stages of exhumation were facilitated by extension along a low-angle normal faults.

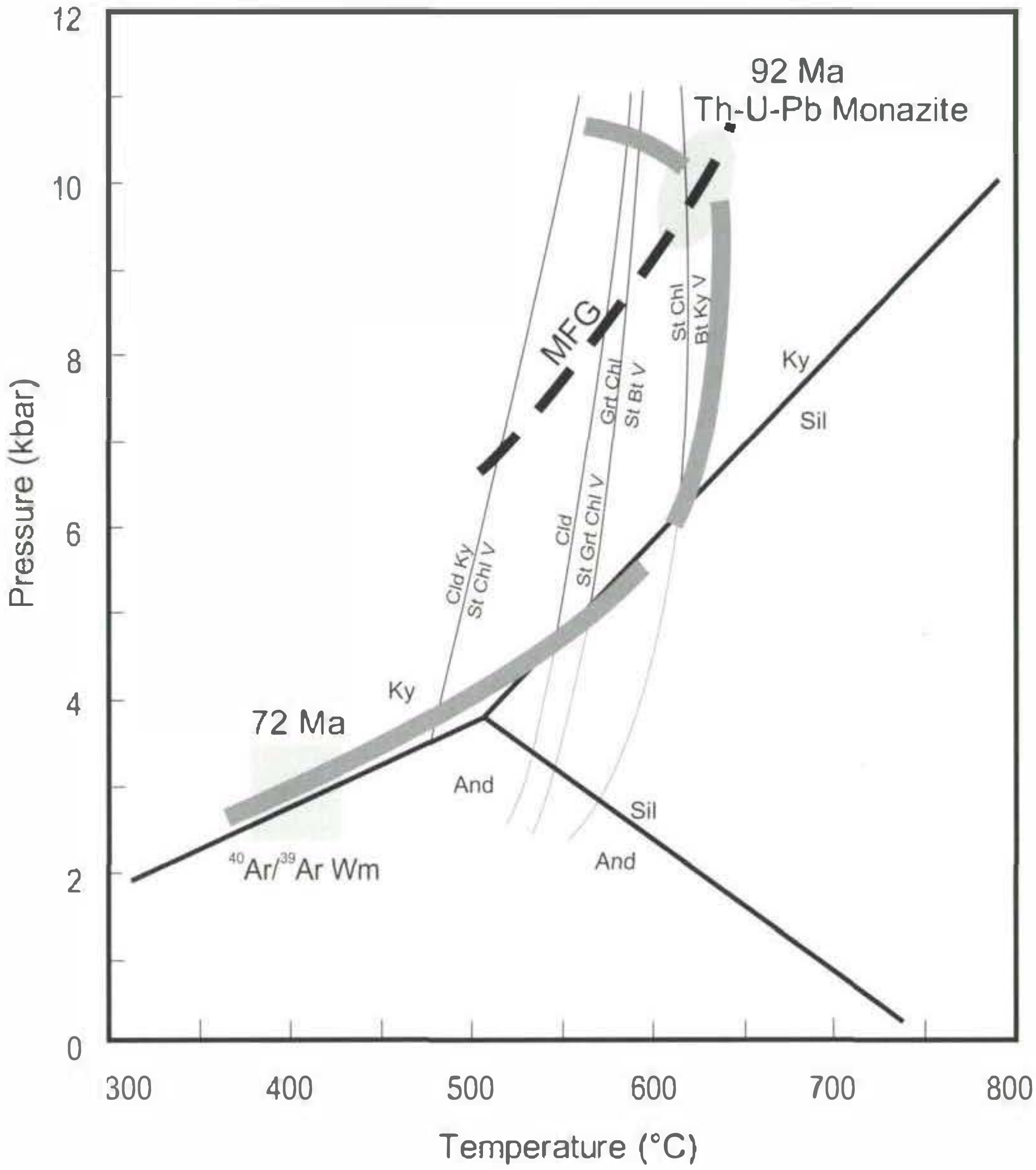

Fig. 2

The southernmost part of the Veporic unit investigated from drillholes in northern Hungary (KOROKNAI et al., 2001) yield lower amphibolite facies metamorphic conditions (c. 550±30°C and 9±1 kbar). K/Ar and ^{40}Ar/^{39}Ar dating of micas and amphibole yield exclusively Cretaceous ages (87–95 Ma). Zircon fission tracks of 75–78 Ma and Early Paleogene apatite FT data indicate rapid cooling after the medium-grade Eoalpine event.

These results clearly document the effects of intense- amphibolite facies Alpine metamorphism during Cretaceous time in the central Western Carpathians, analogous to the so called "Eoalpine" events in the Alps. Metamorphism was related to collisional crustal shortening and stacking, following subduction of the Meliata ocean and exhumation occurred by synorogenic (orogen-parallel) extension and unroofing in an overall compressive regime.

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ACTIVE TECTONICS, DOMAINAL DEVELOPMENT OF TOPOGRAPHY AND DRAINAGE PATTERNS IN THE CENTRAL EASTERN ALPS: A GEOMORPHOLOGIC INDICES STUDY

Rafael Jimenez & Franz Neubauer

The geomorphologic evolution of drainage basins and river systems of the Eastern Alps as well as the Cenozoic formation of peneplain surfaces reflect the Neogene extrusion and uplift processes (e.g. FRISCH et al. 2000). We have defined two principal research areas for this study because these areas reflect two different tectonic domains affected by these tectonic processes: the Tauern window area with strong Neogene exhumation and Pliocene and Quaternary surface denudation and the Gurktal/Murau Mountain area with Neogene to Quaternary block uplift following an early Neogene peneplanation. We used quantitative geomorphic indices which have been developed in areas of active tectonics (e.g. KELLER & PINTER, 1996) to describe the present landscape in the two test areas and to test methods in an area with glacial overprint on morphology.

The Tauern window is characterized by almost orogen-parallel strike-slip faults with eastwards trend due to the continental plate collision. N-trending joints are common in the interior, low-angle normal faults are located along the western and eastern margins of the window and display a SSW-NNE trend (NEUBAUER et al., 1999 and references). In the Gurktal/Murau Mountains, the valleys follow WSW- and dominantly NW-trending faults not considered in present tectonic models.

The Gurktal/Murau Mountains show a lower overall elevation, extended remnants of former peneplains and short and steep valley systems with various directions. Low rates of uplift and small differences in relief caused less intense erosion and denudation and therefore, the preservation of elevated Neogene peneplains. The entire region was uplifted and tilted eastwards after Middle/Late Miocene. Incision of recent valleys is a result of the block uplift (EDER & NEUBAUER, 2000). We can observe flat peneplain surfaces at high altitude (at 2.000 meters a.s.l.). Two different sorts of valleys with different features can be observed. (1) Valleys placed at the upper part of the mean stream are very short (2 to 7 km) with higher river gradients. Some of these rivers present longitudinal sections with peneplain surfaces that are separated by steep slopes that sometimes include gorges/incised valleys range between 50 and 300 meters in elevation. These features may indicate apparent discontinuous uplift, glacier activity and that these valleys were affected by the uplift and tilting process during standstill periods of the uplift process. (2) Other valleys are located at lower altitudes further east and show very flat final portions and no peneplain surfaces. These features may indicate that the valleys are affected by lower rate of uplift than further to the east. The peneplains studied along these valleys were observed at the upper part of the Gurk between 1.000 and 1.800 meters.

In the Tauern window area the valleys are controlled by the fault patterns therefore the general drainage basin structure in Tauern window follows parallel and perpendicular valleys. All valley systems present deep and long valleys (10-20 km long) with north trending direction. The highest points range between 2.100 and 2.800 meters high and the confluence to the Salzach base level river is placed between 750 and 900 meters elevation. The deep, flat ground and wide valley floor portions with U-shape reflect the Quaternary glacier activity. Incision of the recent valleys can be observed as steep portions with gorges, which also reflect the Pliocene to Recent uplift. A common feature can be found in several valleys: Sometimes the peneplain surfaces can be correlated at the same height level, for example, between 1.500 and 1.700 meters high, a peneplain surface can be observed along the Krimml Ache, Obersulzbach, Kapruner Acher and Stubache.

Within the Tauern window, the peneplains can be observed in all the valleys studied from 800 metres to nearly 2.500 meters altitude. The peneplains are separated by steeper portions including gorges and deeply incised valleys whose thickness range from 50 to 800 meters. Even four levels of peneplains were found in some of these rivers and sometimes the peneplain surfaces placed in different valleys can be correlated at the same elevation level.

Holocene river terraces present in this region were deposited after the last glaciation both in the Tauern and Gurktal areas. Two or even three sedimentary levels can be observed along the different valleys studied. The river terraces deposited before the last glacier span were eroded by the glacier-cap. Therefore these sedimentary levels would reflect the same processes as the terraces in Gurktal and they can be correlated. The river terraces in the Tauern window area are thicker than the terraces in Gurktal. The reason may be a higher rate of subsidence and posterior uplift due to the glacier-isostasy which produced thicker terraces in the Tauern window than in Gurktal. Due to the glacier sheet, which in the Tauern window may have reached even 2000 meters thickness, the subsidence and uplift rates were higher than further east in the Gurktal area where the sheet reached only about 500 meters.

Morphometry in geomorphology is defined as a quantitative measurement of landscape shape. Drainage basin asymmetry (*AF*) is 100(Ar/At) where *At* is the total area of the drainage basin, *Ar* is the area of the basin to the right (facing downstream) of the trunk stream. The drainage basin asymmetry *AF* was studied for two areas along the eastern and western margins of the Tauern window. *AF* in the *Lieser* drainage basin is 62.3 %, that of the *Ziller* drainage basin 64.9 %. In this region the uplift and the tilting process occurred westwards therefore the same effects are supposed to be found on drainage basins but in the opposite direction.

Vf is the Valley-floor width-to-height ratio. When calculating *Vf* these parameters are measured at a set distance from the mountain front for every valley studied. This index differentiates: (1) Broad-floored canyons, with relatively high values of *Vf and (2)* V-shaped valleys, with relatively low values of *Vf*. High *Vf* values are associated with low uplift rates, so these streams cut broad valleys floors, low values of *Vf* reflect deep valleys with streams that are actively incising, commonly associated with uplift. Different measurements of *Vf* have been performed for the Krimml stream, Tauern window area. We have obtained both high values as well as low values where high values corresponding with low uplift rates and broad-floored canyons were found not only next to the confluence but also at the distance of 10 kilometers from the confluence where a peneplain is situated. The low values of Vf, which indicate V-shaped valleys and uplift were measured not only at the upper part of the stream but also at the distance of 4.75 Km. These values corresponding with the steep sections of Krimml.

The principal reason is that some peneplain surfaces are placed along the Krimml stream at different height levels. These peneplain surfaces were formed before the uplift process. They are very flat ground and wide areas with very high width of the valley floor. This sort of valley formed by the Quaternary glacier activity that modeled the valleys in this region as *U-shaped* valleys resulted. Contemporaneously they have been affected by uplift during Pleistocene and Holocene. At the present these peneplains can be observed in different areas like Gurktal or Tauern at different elevations, although we have not observed any at the lowest part of Gurk. All *Vf* values have been measured 3 km from the confluence of the streams. In general *Vf* values are low which indicate an uplift process. Within the Gurktal area the highest values are in secondary streams at the lowest part of the Gurk river. The lowest values correspond to a higher uplift rate measured in secondary streams at the upper Gurk valley. We can see that the streams at the upper part of the Gurk are very narrow in contrast to the streams in the lower Gurk, which are very wide.

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EXPORT OF SEDIMENTS FROM THE ALPS TO THE FORELAND BY RIVERS

Achim Kamelger & Matthias Hinderer

From various literature sources the present-day sediment yield of ca. 200 Alpine catchments have been compiled. Analysis of the data comprised (1) correlation analysis for all catchments with basic controlling parameters such as relief, water discharge, and glaciated area, (2) grouping into morpho-tectonic zones and quantification of further controlling parameters e.g. slope, forest cover, unvegetated land, snow and ice, crystalline rocks, sedimentary rocks using a GIS, (3) estimation of the present-day export rate of sediments from the Alps (Hinderer & Kamelger, in prep.) and form Swiss Alpine drainage basins (Kamelger, 2001).

Plots of sediment yield of all 200 measuring stations versus maximum elevation in the catchments, river discharge, and glaciated area show the expected positive correlations. In contrast, sediment yield declines with the size of the drainage area. These patterns together with a relatively strong scatter of the data was found in many earlier studies on sediment yield (e.g. Milliman & Syvitski, 1992; Hovius, 1998). In a second step, the sediment yield data have been grouped into six morpho-tectonic zones. These are: (1) Northern Helvetian Alps, (2) Western Crystalline Alps, (3) Southern Crystalline Alps, (4) Northern Calcareous Alps, (5) Eastern Crystalline Alps, (6) Southern Calcareous Alps (Hinderer & Kamelger, 1999). The characteristic statistic values of sediment yield are higher for the Western Alps (zones 1 to 3) than for the Eastern Alps (zones 4 to 6). Within the western Alps the crystalline part (zone 2) exhibit the highest mean, median, and quartiles of sediment yield whereas the Northern Helvetian Alps and the Southern Crystalline Alps show lower values. The transsect from zone 4 to zone 6 shows a similar pattern, however, the sediment yield of the Southern Calcareous Alps are almost equal to the Eastern Crystalline Alps. The relief, land cover, and lithology of the morpho-tectonic zones have been quantified using a GIS. Relief parameters such as slope, maximum, minimum, and mean elevations have been derived from a DEM with a resolution of 100 m horizontal and 18 m vertical. Forest cover, unvegetated areas, and snow- as well as ice-covered areas have been quantified by global land cover data from satellite surveying which are provided by the USGS. Portions of crystalline and sedimentary rocks have been determined from a generalised geological map (Hinderer & Kamelger, 2001). In addition to quantify how different lithologies affect the sediment discharge in a drainage area, a modified version of the Swiss geotechnical has been used.

Correlation analysis show significant correlations ($p < 0.05$) of the mean or median of sediment yield with mean elevation, difference between maximum and minimum elevation, forest cover, unvegetated area, and snow and ice cover. All are positive correlations except forest cover which is negative.

In a third step, mean sediment yield of rivers leaving the Alps from the various morpho-tectonic zones are used to estimate the total sediment export. We end up with a total of $50*10^6$ [t/y]. This converts to a mean denudation rate of the Alps of 0.125 [mm/y] at present.

The denudation rates of the Swiss Alpine drainage basins range from 10 [mm/ky] to 700 [mm/ky]. For the entire Swiss Alpine study area including parts of the foreland a total sediment discharge of about 6.3×10^6 tons per year yields a mean denudation rate of 0.11 [mm/y] (KAMELGER, 2001). This rate corresponds to mean denudation rate measurements found by (KEMPE, MYCKE & SEEGER, 1981) for central Europe. Obviously, the mean denudation rate for the entire Swiss territory is strongly reduced by the extended low-elevated areas of the Molasse basin. If the drainage basins of the Penninic units, the Helvetic units, the Eastern Alpine units and the Southern Alps are treated separately from the drainage areas located in the Molasse basin, a mean denudation rate of 0.21 [mm/y] and 0.03 [mm/y] respectively can be calculated. Taking into account the mean surface uplift rates in each area, the recent mean surface uplift is roughly 5 to 8 times faster than the mean denudation rate from river loads.

Comparison with the mean sediment yield of small rivers (<500 km^2) inside the Alps show that ca. 52% of the sediments transported by headwaters are stored, e.g. in alluvial plains or lakes and do not leave the Alps.

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HP METAMORPHISM AND TECTONICS IN THE SOUTHWESTERN PART OF THE SESIA-LANZO-ZONE (WESTERN ALPS)

Matthias Konrad, Jochen Babist & Mark R. Handy

The Sesia-Lanzo zone (SLZ) is a piece of continental crust that underwent Alpine high pressure (HP) metamorphism and presently occupies a position atop the Penninic nappe pile in the Western Alps. It is bounded to the W and NW by the ophiolites and sediments of the Piemont unit, and to the E and SE by the steeply dipping Canavese mylonites that mark the boundary to the Southern Alpine Ivrea-Verbano Zone (IVZ). The SLZ comprises mainly three lithotectonic units: (1) The seconda zona dioritica kinzigita (II ZDK) unit, a sliver of IVZ containing pre-Alpine HT metamorphic rocks with a local Alpine overprint; (2) the eclogitic micaschist (EMS) unit, mainly containing continentally derived rocks with Alpine HP mineral assemblages; (3) and the gneiss minuti (GM) unit, consisting of fine-grained greenschist facies gneisses.

Crucial to understanding the exhumation of the HP assemblages is the correlation of Alpine structures and metamorphism within the SLZ, as well as knowledge of the continuation of the Tertiary Insubric mylonites towards the W and SW. The first Alpine deformations (D1, D2) in the central part of the SLZ are associated with HP metamorphism (e.g., GOSSO et al. 1979). Relicts of garnet+omphacite+/-Na-amphibole within a S1/S2 composite foliation are found in the EMS. This foliation is steeply dipping in areas with only weak D3 overprint. In the GM, D1 and D2 structures are not found. In both units, garnets have a grossular-rich core, presumably related to HP metamorphism, and an almandine-rich rim. This suggests a similar Alpine evolution of the EMS and the GM.

D3 occurred under retrograde conditions. In the EMS, D3 comprises km scale isoclinal folds with horizontal to moderately NE-dipping axial planes and a weak axial plane foliation. The retrogression during D3 initiated under blueschist facies conditions and is manifest by growth of foliation-parallel glaucophanitic amphibole at the expense of almandine-rich garnet. Deformation continued under greenschist facies conditions, with the Na-amphibole partly replaced by barroisitic amphibole and chlorite, also oriented parallel to the S1/S2 foliation. In F3 fold hinges, garnet was replaced by brown biotite and chlorite which together define an axial plane foliation. In the absence of unequivocal D3 kinematic indicators, we tentatively relate this retrograde evolution to top-SE extensional shearing observed in the NE part of the SLZ (see BABIST et al., this volume).

In the GM, adjacent to the contact of the SLZ with the Piemont ophiolites, the rocks have a tight, moderately SE-dipping mylonitic foliation. Stretching lineations and associated shear bands indicate a top-down-to-SE movement of the SLZ in the hanging wall. This deformation is related to Eocene movements along the Gressoney Shear Zone. Biotite, chlorite and epidote grew parallel to the foliation. Garnet clasts show only weak retrogression indicating upper greenschist to amphibolite facies conditions during D3. The relationship of this deformation with D3 in the EMS remains unclear. Both structures are younger than S2, but are truncated by D4 shear zones that are related to Oligo-Miocene Insubric mylonitization in the NE part of the SLZ (Babist et al., this volume). We suspect that D3 pre-dates the Eocene Gressoney Shear Zone, as D3 involved retrogression under (Late Cretaceous?) blueschist to greenschist facies conditions.

D4 occurred under greenschist facies conditions and comprises NE-SW trending tight to isoclinal F4 folds with steep axial planes and subhorizontal fold axes up to 100 m in amplitude. In some areas, isoclinal F4 folds merge with subvertical mylonitic zones some 10 to 100 m thick. These accommodated strike-slip shear parallel to **ENE-WSW trending** subhorizontal stretching lineations. D4 structures are found in the external part of the EMS and mostly in the internal part of the GM. There, D4 shear zones cut the mylonites of the Gressoney Shear Zone. The progressive structural overprint coincides with a strong metamorphic retrogression marked by the replacement of biotite, garnet, epidote and amphibole by chlorite, plagioclase and calcite.

D5 deformation is only locally developed and comprises open to tight F5 folds (mm to 100 m scale) with moderately to steeply dipping axial planes. An axial plane foliation is not developed. The regional significance of this deformation is unclear, but certainly indicates final shortening of a variably oriented main foliation.

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PETROLOGY OF AN UNUSUAL CA-AMPHIBOLE + STAUROLITE BEARING AMPHIBOLITE AND ITS IMPLICATIONS FOR THE HIGH PRESSURE METAMORPHISM IN THE SCHNEEBERG COMPLEX, EASTERN ALPS

Jürgen Konzett & Peter Tropper

Within the paleozoic Austroalpine Schneeberg Complex, unusual Al-rich staurolite-bearing assemblages have been found. In two localities, the assemblage staurolite + kyanite + zoisite + clinozoisite/epidote + margarite assemblages were found in metamarls. These assemblages form within the contact between calcite marble, interlayered calc-micaschists and amphibole-bearing metamarls.

In one of these localities, the assemblage staurolite + Ca-amphibole was found within an garnet amphibolite sample, but careful textural examination revealed that Ca-amphibole and staurolite are part of entirely different kinds of domains: staurolite occurs within Al-rich domains in the assemblage staurolite + margarite + kyanite + clinozoisite/epidote + plagioclase + biotite + muscovite without quartz, while Ca-amphibole is confined to Al-poor domains containing the assemblage Ca-amphibole + calcite + clinozoisite/epidote + biotite + plagioclase + quartz with strong similarities to assemblages from adjacent amphibolites. Although both assemblages occur within a thin section, they show different reaction histories. The Al-poor domains are characterized by the breakdown of the assemblage Ca-amphibole + muscovite and the Al-rich domains show an equilibrium assemblage containing margarite + kyanite + plagioclase + clinozoisite/epidote, which probably developed by a complete consumption of quartz.

Application of thermobarometry to the adjacent rocks and the Al-rich domains within the sample of these staurolite + Ca-amphibole bearing garnet amphibolites yields pressures of 8–10 kbar at temperatures of 540 – 590°C, by using selected equilibria in the system NCMASH. These high pressures may be interpreted in favour of an overall pressure increase of the Eo-Alpine metamorphism from NW towards SE within the Ötztal-Stubai Crystalline Complex, culminating in the formation of Eo-Alpine eclogites in the southwest of the Schneeberg Complex.

Therefore a continuous transition from a regional metamorphic amphibolite facies to an eclogite facies due to crustal thickening in the course of a beginning Penninic subduction during early Cretaceous may be assumed.

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MIOCENE SHIFTS OF THE DRAINAGE DIVIDE IN THE ALPS: EVIDENCE FROM SEDIMENT BUDGET, PROVENANCE AND GEOCHRONOLOGICAL DATA

Joachim Kuhlemann, Wolfgang Frisch,
István Dunkl,Balazs Szekély Achim Brügel, Cornelia Spiegel

The sediment budget of circum-Alpine basins has been quantified in order to compare sediment masses derived from the northern (western) versus the southern (eastern) flank of the Alps. The evolution of the major catchment areas since Oligocene time is shown in a series of sketch maps.

A fast shift of the drainage divide towards the N at ~17 Ma and back to the S at ~11 Ma is deduced in the Swiss and Western Alps. The shifts affected a catchment area of ~ 6,000 and ~13,000 km^2 in size, respectively. Although the tectonic setting and exhumation history of the Swiss Alps in Miocene time suggests that the area of the Lepontine dome was affected by this shift, thermochronologic data prove that at least the northwestern part of this core complex constantly discharged freshly cooled crustal material to the N. Since no indications of a relevant asymmetry in climate, especially contrasting precipitation, exist in Miocene time for the two opposite flanks of the orogen, a tectonic explanation for the shifts of the drainage divide is favoured. Important catchment reorganizations in the Alpine foreland, occurring also at 17 Ma and 11 Ma, were forced by Alpine thrusting and uplift in Lower Austria (Amstetten swell, as part of the Bohemian massif) and of the Swiss Jura, respectively.

In the Eastern Alps, no such dramatic shift of the drainage divide is observed. Marker pebbles in Molasse foreland fans indicate that until about 11 Ma a part of the Adamello pluton and thus the South Alpine realm was part of the paleo-Inn catchment. Probably, the Periadriatic lineament provided a west-east dewatering line, whereas the Brenner line provided a dewatering line to the N. Marker pebbles from south of the Tauern window were probably transported westward to the Brenner line and then to the N. Since 11 Ma, the drainage divide probably stepwise retreated towards the NE. According to longitudinal river profiles, the Rienz river N of the Dolomites was the last to be captured by the the Etsch/Adige river system.

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TRANSALP: RESULTS FROM THE PASSIVE SEISMIC EXPERIMENT

Joern Kummerow, Rainer Kind & TRANSALP WORKING GROUP

In 1998 and 1999, a passive seismic array was operated along the TRANSALP deep reflection profile with an average station spacing of 5km. The 30 short-period instruments recorded for approximately 9 months.

We present results obtained from receiver function (RF) and shear wave splitting analysis. In the receiver function method, 3 component recordings of teleseismic events are processed to isolate *S* wave energy converted from incoming *P* waves at crustal and upper mantle discontinuities below the seismic network. A stacked N-S orientated RF section reveals the southward dipping European Moho. This converter can be traced continuously to about 20km south of the Pustertal Line, where it reaches a maximum depth of 55-60km. Moho signals are less clear below the Dolomites. We interpret a weak, but coherent signal in about 40 km depth as the Adriatic Moho. Average crustal *Vp/Vs* ratios obtained by stacking Moho energy and its multiples range between 1.70 and 1.78.

Splitting parameters of *SKS* waves observed at the TRANSALP stations are calculated to investigate anisotropy of the mantle at the transition between European and Adriatic plate.

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EXHUMATION OF ALPINE ECLOGITES – DATA AND MODELS

Walter Kurz, Nikolaus Froitzheim, Franz Neubauer

In general, eclogites as well as blueschist facies metamorphic rocks are important as records of ancient subduction. These rocks are either exposed within accretionary wedges, within obducted ophiolite units, or within single eclogite facies nappes. Furthermore, high pressure rocks may occur within continental basement sequences that indicate a former rift environment, and an extended continental margin. This suggests that many Ultrahigh Pressure/High Pressure (UHP/HP) units may represent the distal portions of former passive continental margins. The conditions of eclogite facies metamorphism are reached at relatively deep levels within the subduction zone, beginning at 40 to 50 km depth. Therefore, special mechanisms are necessary to bring these eclogite facies rocks back to shallow crustal levels ("exhumation"). Basically, the long-term preservation of high-pressure/low-temperature assemblages requires a mechanism of either continued refrigeration by a cold subducted lithospheric slab and uplift to avoid reequilibration during prolonged periods of static heating, or very fast exhumation. Several mechanisms may contribute to remove material in the hanging wall of HP units within an ancient subduction zone, and to the emplacement of these rocks in shallower lithospheric levels. The processes by which HP rocks reach the Earth's surface are important to an understanding of the thermal and barometric evolution of metamorphism and the preservation potential of peak metamorphic assemblages. The scope of this study on the evolution of Alpine high-pressure units is to combine the textural and microfabric evolution of eclogites with P-T data. This gives access to a more detailed view of the eclogitic and post-eclogitic deformation history from burial by subduction to subsequent exhumation.

Eclogites that are related to the early Alpine history (Cretaceous) are restricted to the Austroalpine nappe complex (ANC), especially to the Middle Austroalpine basement complexes of the Kor- and Saualpe, the Kreuzeckgruppe, the Schobergruppe, the southern part of the Ötztal-Silvretta nappe (Texel Group), and the Sesia Zone. Eclogites that are related to the Paleogene evolution are exposed in the Penninic units of the Western and Central Alps, and within the Tauern Window (TW) of the Eastern Alps.

Within the Koralm/Saualm unit of the ANC most eclogites are eclogitic mylonites documenting plastic deformation of omphacite and garnet. The meso- and macroscale structures indicate an overall extensional regime, possibly related to a large-scale SE-directed ductile low-angle normal shear zone. The eclogites are associated with migmatite-like structures and are intruded by pegmatites. This indicates decreasing pressure, but isothermal or even increasing temperature conditions during exhumation.

In the Eclogite Zone (EZ) of the central southern TW, eclogites and associated high pressure metasediments are intercalated between Penninic basement units (Venediger Nappe (VN)) in the footwall and the Rote Wand-Modereck Nappe (RWN) in the hanging wall). The EZ experienced a polyphase metamorphic evolution, described by a b–shaped P-T path. The EZ and southern (oceanward) parts of the RWN were affected by eclogite facies metamorphism (20–22 kbar, 600–620°C) (M1). However, pressures of only 12 kbar are documented within the VN. The VN, EZ, and RWN were subsequently affected by blueschist facies metamorphism (7–12 kbar, ca. 450° C)(M2), and by upper greenschist to lower amphibolite facies metamorphism (M3). Nappe stacking postdated subduction-related M1, and was contemporaneous to M2. M2 overprint of the eclogites indicates refrigeration by a cold subducted lithospheric slab during exhumation. Long-term preservation of high-pressure/low-temperature assemblages requires such a mechanism. This evolution is compatible with an emplacement model similar to channel flow. However, the EZ behaved as a coherent unit during its emplacement, which suggests thrusting as emplacement mechanism. Anyhow, the M2 overprint requires the emplacement of the eclogite facies assemblages while heating was delayed within an active subduction channel. Remnants of eclogite facies assemblages have been observed within the ophiolitic Glockner Nappe (GN), too, which forms the hangingwall of the RWN. However, M2 has not been observed there. The P-T evolution of the GN is described by a clockwise P-T path, showing moderate cooling during decompression. This argues for a different exhumation mechanism for the eclogites that are associated with former oceanic assemblages than for passive-margin-related ones.

In the Western Alps, recent investigations in the Monte Rosa area have shown that subsequent to the closure of the Piemonte-Ligurian and Valais oceans the European margin descended into the subduction zone, leading to eclogite facies metamorphism in the Monte Rosa Nappe (MR) at about 37 Ma, and melange formation in the Furgg Zone (FZ). The FZ and the EZ of the TW are in a comparable tectonic position. The MR is interpreted to have ascended towards the surface in the back of the Briançonnais nappes in a corner flow mode. In the hanging wall, the Piemont Ophiolites of the Zermatt-Saas Zone (ZS) consist of eclogites structurally beneath greenschist facies rocks. The latter form the kilometre-wide Gressoney Shear Zone, which is dominated by top-to-the SE movement related to crustal extension (Reddy et al., 1999). It operated over the entire period during which the footwall units evolved from eclogite to greenschist facies. Therefore, this shear zone was interpreted to be responsible for eclogite exhumation (Reddy et al., 1999). Post-metamorphic cooling and exhumation of the ZS eclogites must have been taking place while subduction was still operating. Basically, the eclogites of the Sesia Zone in the hanging wall had undergone a significant part of their exhumation before the ZS eclogites had reached their metamorphic peak (Reddy et al., 1999), and these were already exhumed when the MR descended. This is similar to the evolution of the Eastern Alps. In this area the eclogites of the ANC Koralm-Saualm Complex have already been exhumed to at least amphibolite facies metamorphic conditions, while the eclogites of the Penninic lower plate reached their pressure peak.

In particular, two mechanisms of eclogite exhumation have been proposed for the Alps:

Foot-wall accretion causing stretching and extension in the upper plate; this has especially been proposed for the exhumation of eclogites in the ANC units, and for the exhumation of the HP rocks of Piemonte-Penninic ophiolites (e.g., the ZS and Monte Viso units). Normal-sense shear zones, that are related to these extensional processes may also develop due to crustal velocity gradients in the hanging-wall of rock packages while thrusting is taking place at the base of this unit. Such a model may be applicable to the Alps.

Exhumation in terms of a channel flow model; this has especially been proposed for the exhumation of eclogites in the Penninic units which have been derived from the European margin (EZ in the Eastern Alps; MR, FZ in the Western Alps).

Actually, several exhumation models seem to be related to a continuous process of subduction, footwall accretion, and stretching of the upper plate. Therefore, these processes affected both the Austroalpine upper plate, and the Penninic lower plate.

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THE TIMING OF PRE-ALPINE HIGH-PRESSURE METAMORPHISM IN THE EASTERN ALPS: CONSTRAINTS FROM U-PB SHRIMP DATING OF ECLOGITE ZIRCONS FROM THE AUSTRO-ALPINE SILVRETTA NAPPE

Christoph R. Ladenhauf , Richard A. Armstrong, Jürgen Konzett & Christine Miller

Partly retrogressed eclogites of MORB-origin are present in the Austroalpine Silvretta Nappe as lenses and pods within amphibolite-facies orthogneisses. The eclogite assemblage comprises omphacite + garnet + phengite + kyanite + barroisite + rutile + quarz. PT conditions derived from garnet, omphacite and phengite geothermobarometry yielded at 2.8 GPa (500°) according to SCHWEINEHAGE & MASSONNE (1999).

Zircons were separated from a quartz-rich domain containing the typical eclogite assemblage. The zircons are euhedral in shape and may contain inclusions of quartz, rutile, omphacite and barroisite, indicating at least partial growth during the HP-event. All analyzed zircons show complex cathodoluminescence (CL) patterns including irregularly shaped cores with low CL-intensity, oscillatory sector zoning and overgrowths with high CL-intensity. Zircon ages were determined using ^{206}Pb/^{238}U-ratios with a common-Pb correction according to TERA-WASSERBURG. Three different age groups could be distinguished that also correlate with distinct ranges in zircon Th/U-ratios: A low-CL irregular core with a Th/U ratio of 0.72 and an age of 507 ± 11 (1s) Ma is interpreted as a relic core. The age is consistent with intrusion ages of gabbros, tonalites and granites from the Silvretta Nappe (SCHALTEGGER et al. 1997, POLLER 1997) and the adjacent Ötztal Crystalline Basement (ÖCB) (MILLER & THÖNI 1995). Broad sector-zoned zircon areas with Th/U-ratios in the range 0.35-0.58 yielded a weighted mean age of 437 ± 7 Ma (n=11). This age is thought to reflect magmatic growth of the zircons in the eclogite precursor, reflecting a Silurian/Ordovician magmatic event within the Eastern Alpine basement. The youngest event recorded led to the formation of narrow, irregular rims around zircons with very low Th/U-ratios in the range 0.01–0.29. The weighted mean age of these rims is 351 ± 22 Ma which is interpreted as the age of the HP-metamorphic overprint. This would be consistent with Sm/Nd-mineral isochron ages of eclogites from the adjacent ÖCB that are in the range 370–340 Ma (MILLER & THÖNI 1995). The U-Pb zircon SHRIMP ages presented here clearly support the assumption of a widespread Variscan HP-event W of the Tauern Window.

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THE METAMORPHIC EVOLUTION OF THE MONTE ROSA NAPPE AND ITS RELATION TO EXHUMATION BY FORE- AND BACK-THRUSTING IN THE WESTERN ALPS

Ronan Le Bayon, Stefan M. Schmid, Christian de Capitani

Over the past thirty years, tremendous progress has been made towards a better understanding of the metamorphic and tectonic history of the Alps. However, clarifications regarding the tectonic and metamorphic evolution of the Monte Rosa nappe and other high-pressure units, and in particular their exhumation mechanism, are still necessary. The Monte Rosa nappe is one of the best-known tectonic units and a classical structural feature of the Western Alps. The Monte Rosa nappe is enveloped by two ophiolitic units: the Zermatt-Saas unit above and to the south; the Antrona unit below. The Portjengrat unit separates the Monte Rosa nappe from the Bernhard nappe.

The comprehension of the metamorphic evolution is crucial for understanding subduction and exhumation mechanisms. With the thermodynamic software DOMINO in the KFMASH and CaNaTiKFMASH systems a qualitative and quantitative approach to pressure-temperature-composition equilibrium phase diagrams for whiteschists and basic rocks has been carried out. The application of the new P-T grid to the Monte Rosa whiteschists leads to the conclusion that the characteristic assemblage talc-magnesiochloritoid, given a water activity of 0.6, was stable at approximately 23 kbar and 500°C. This is considered to be the peak of Alpine eclogite facies metamorphism in this area. Eclogitic boudins in Mesozoic sedimentary cover located in the nose of the Monte Rosa nappe confirm the above derived metamorphic conditions. Within the whiteschists from the Monte Rosa nappe, the association talc + magnesiochloritoid breaks down to a kyanite + chlorite + phengite assemblage with quartz and water in excess. This latter assemblage is replaced by chlorite + low-Si phengite in the presence of excess quartz and water. This series of mineral assemblages helps to constrain the high-pressure peak of metamorphism and the exhumation path in the Monte Rosa. The exhumation path is divided in two parts: a first near-isothermal decompression from 23 kbar and 500°C to 7 kbar and 450°C, followed by a second slow decompression with concommitant cooling.

Four major deformation-phases can be distinguished. The main foliation (S1) is axial-planar to isoclinal syn-mylonitic D1-folds. In the northwestern part of the Monte Rosa nappe the L1 stretching-lineation and D1-fold axes are parallel and dip northwestward. A second generation of isoclinal syn-mylonitic folds (D2) overprints the D1 foliation. In general, the stretching lineations and the foliations are parallel to the northwestward dipping D2 fold axes and to the D2 axial-planes, respectively. Kinematic indicators associated with the D1-2 general foliation show a top-to-the NW transport direction. D1 and D2 deformations are associated with ongoing nappe stacking. D3 represents an early phase of backfolding and backthrusting, linked to the Mischabel backfold which deforms the entire nappe stack. D3 reorientates earlier D1-D2 fold axes, particularly in the nose of the Monte Rosa nappe. The reoriented strike of the D1-D2 fold axes is W-E. In the Portjengrat unit, D3 also induces a top-to the E shearing with a stretching lineation dipping gently to the west. Postdating all the above deformations, the late SE vergent D4 Vanzone backfold deforms the entire Monte Rosa nappe a second time.

The correlation of metamorphic and structural data leads to the conclusion that D1/D2 forethrusting deformation phases are associated with the exhumation of the Monte Rosa nappe from its high-pressure peak of metamorphism (nearly 80 km depth) to approximately 7 kbar (nearly 25 km depth) and 450°C. The D3 backfolding and backthrusting stage began after this substantial amount of exhumation. This implies that most of the exhumation of the high-pressure Monte Rosa nappe occurred by near-isothermal forethrusting during D1 and D2 and is unrelated to D3 and D4 backthrusting and backfolding. The latter phase reflects a late exhumation event of relatively minor importance and occurs with concommitant cooling. The exhumation P-T path reveals two different exhumation regimes reflecting two different exhumation mechanisms.

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TRANSALP – NEW SEISMIC REFLECTION IMAGES OF THE EASTERN ALPS

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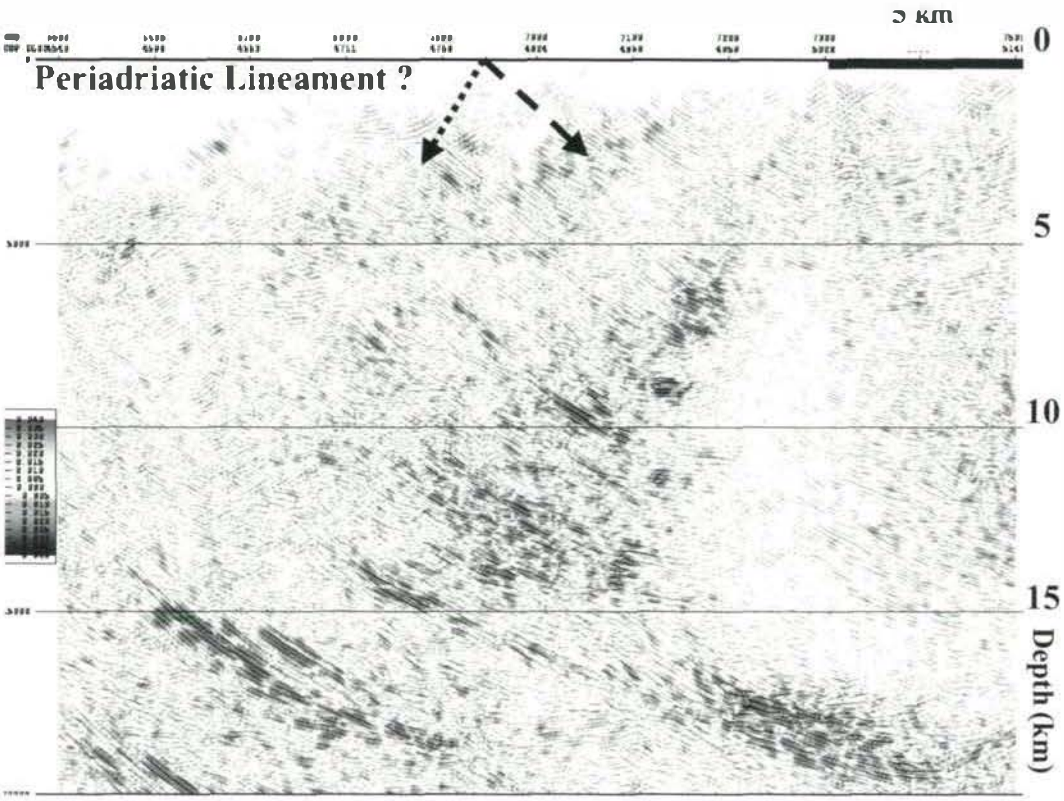
The TRANSALP Group comprising partner institutions from Italy, Austria and Germany acquired a 340 km long deep seismic reflection line crossing the Eastern Alps between Munich and Venice. Although the field campaign was split into three different parts, the northernmost 120 km in autumn 1998, the southernmost 50 km in winter 1998/1999 and the central 170 km in autumn 1999, the project gathered for the first time a continuous section enabling consistent data processing from common-midpoint sorting to depth migration including the orogen itself as well as the two adjacent basins.

The Vibroseis survey as the core of the project was designed to accomplish high resolution and depth penetration for the upper crust mainly, thus using the following field parameters:

vibratorpoint spacing 100 m with 4 heavy vibrators, sweep signal 10-48 Hz of 28 s length, recording time 20 s after correlation, geophone group spacing 50 m, spread length 18 km in split spread configuration with 360 recording channels resulting in 90-fold common midpoint coverage. The Vibroseis survey was accompanied by explosive seismic recording using shotpoints of 90 kg charge in 30 m deep boreholes and 5 km spacing. The explosive seismic survey was designed to provide low-fold, but high-energy signals from the deeper parts of the crust. Seven receiver cross-lines, each approx. 20 km long, recorded off-end shotpoints and passively the sources of the main line in order to provide three-dimensional control. All these measurements were performed by contractor companies.

The data processing was done at the universities of Munich and Leoben and at the offices of ENI-AGIP at Milan on different hardware and software platforms. At the beginning of the processing all data of the main Vibroseis line (3841 vibratorpoint records, 27 Gbyte) were combined to form one consistent dataset. A visualisation of the complete processing steps from geometry installation (all coordinates given in UTM-WGS84 system) to Kirchhoff depth migration (poststack) will be shown for a sample portion of the line using a MS-Powerpoint presentation. Static corrections to a datum level (500 m a.m.s.l.) turned out to be a crucial step. A combination of elevation statics, velocity statics based on a tomographic inversion of the first breaks and subsequent residual statics proved to be very efficient for stacking enhancement. This conventional common-midpoint (CMP) processing scheme was complemented for comparison by non-conventional schemes, such as dip-moveout (DMO) processing and pre-stack depth migration with subsequent stacking. The conventional CMP technique proved to be very robust despite of several strongly dipping reflection patterns. For the explosive seismic data a different way was chosen. Because of the large shotpoint interval of 5 km and the low-fold coverage, traces of best quality were selected to form a single-fold section, which was then normal-moveout corrected and (poststack) depth-migrated. The cross lines were processed with the standard CMP technique as well as with a three-dimensional pre-stack migration.

The northernmost and southernmost parts of the 300 km long Vibroseis section (measured along the smoothed CMP-line) display the Molasse basins with the Tertiary base in the Bavarian Molasse as the most prominent reflection. Several hydrocarbon exploration targets can be clearly identified at antithetic normal faults. Thin Mesozoic sediments and the top of the



(European) basement can be seen as subhorizontal reflections beneath the Northern Calcareous Alps (NCA) and the Grauwackenzone (GWZ) with vertical displacements of about 4-5 km each beneath the Alpine front and beneath the Inn valley. The nappes of the NCA can be clearly correlated with southward dipping reflections. The contact between the NCA and the GWZ south of the Inn valley is imaged as a 40-50° , from the surface southward dipping reflection pattern. The Tauern Window is marked by a southward dipping reflection pattern distributed throughout the whole crust, particularly pronounced south of the Periadriatic Fault (PF). The figure shows the upper part of this pattern. Controversial interpretations concerning the trace of the PF are presently debated (compare contributions by CASTELLARIN et al., LAMMERER et al. and NEUBAUER et al.). If it is assumed that the PF itself is seismically non-reflective, that is, there is no impedance contrast across the PF, then one could trace the PF steeply dipping northward separating a highly reflective domain from a non-reflective domain. If the PF exists here at all and is assumed to be reflective, then it must be traced towards South. The base of the crust is imaged by a gently southward bending, relatively thin reflective lower crust on the European side and an Adriatic/African lower crust more than twice as thick. The crustal thickness is asymmetric with 30 km in the North and 45 km in the South, having its peak with about 55 km below the PF where the lower crust appears to be seismically transparent.

The seismic sections will be presented also as posters at different scales. One poster will present a compilation of all seismic sections at the same scale for comparison.

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DEVELOPMENT OF DEFORMATIONAL STRUCTURES DURING ALPINE METAMORPHISM OF THE MESOZOIC COVER ROCKS IN THE VEPORIC UNIT, WESTERN CARPATHIANS

Branislav Lupták, Dusan Plasienka, Marian Janák & Rastislav Vojtko

The Veporic superunit is the middle of three thick-skinned basement thrust sheets of the Central Western Carpathians. The imbricated crustal structure originated during the Cretaceous continental collision after the Late Jurassic closure of the Meliata ocean. As a consequence of collisional thickening, the Veporic basement and its Permian-Mesozoic cover suffered regional Alpine metamorphism (Janák et al., 2001).

Triassic metaquartzites, metacarbonates and metapelites are the main lithological varieties of studied metasedimentary Mesozoic cover rocks. Phyllosilicate crystallinity data (illite-muscovite and chlorite basal reflections) and chemical composition of metamorphic newly formed minerals suggest the upper anchizonal and epizonal (greenschist facies) metamorphic overprint (Lupták et al., 1999). Alpine metamorphism caused recrystallization of former clay minerals and the growth of new authigenic white mica, chlorite, albite and potassium feldspar.

This study presents the main deformational macro-, meso- and microstructures, representing the oldest ductile structural elements developed during Alpine D1 deformation stage in metacarbonates and metaquartzites of the Mesozoic cover.

The D1 structures represent a large-scale subhorizontal ductile shear zone. This shear zone is interpreted as a low-angle detachment fault zone that parallels the basement/cover interface and lithological boundaries within the Veporic cover (Plasienka, 1993; Plasienka et al., 1999; Hók et al., 1993). This detachment fault was active during the Late Cretaceous exhumation of the Veporic metamorphic core complex. Orogen-parallel extension was accompanied and followed by orogen-normal contraction producing superimposed deformation stages (Plasienka, 1993).

For studied rocks a penetrative, flat-laying subhorizontal or moderately NE to SE-dipping metamorphic/mylonitic foliation S1 is characteristic, which is mostly parallel to the original sedimentary bedding. S1 originated mainly by intensive flattening where the pressure solution and dynamic recrystallization took part. The foliation planes bear a distinct stretching and/or mineral lineation L1 trending generally W-E. In many cases, studied rocks exhibit moderately E to NE-dipping shear bands which are mesoscopically penetrative.

Entirely recrystallized quartzite shows strong preferred orientation of mica foliae. Original detrital quartz grains are flattened and stretched and show undulose extinction in the most deformed rocks. Quartz recrystallized grain size in mica-poor layers is larger than in mica-rich layers because in the latter the grain growth was limited by mica grains pinning at the quartz grain boundaries. Some quartz porphyroclasts show shape preferred orientation due to dissolution along boundaries parallel to the foliation. The extent of the pressure solution has been enhanced in some cases by the presence of deformation resistant magnetite grains. Both the face and displacement controlled pyrite-type quartz fibres formed in the pressure shadows.

Marbles exhibit various grain sizes and microstructures. Foliation planes are defined by elongated coarse-grained relic calcite porphyroclasts and dynamically recrystallized fine-grained calcite matrix, both showing the shape preferred orientation. For the first set of grains the clockwise and anticlockwise twins are dominant which become subparallel with respect to the foliation with increasing strain intensity. Dolomite porphyroclasts behave as rigid bodies and are concentrated with other insoluble material on the zig-zag stylolitic boundaries. The authigenic white mica and chlorite concentrate in thin layers together with quartz but are also widespread as single flakes in the marble oriented subparallel to the main foliation plane.

The Veporic cover rocks are overlain by various rock complexes of several large-scale nappe units (better extensional allochthons in the present state). Carboniferous low-grade metasediments of the Gemeric superunit display the same structural association as the Veporic cover, though the strain intensity is weaker. Overlying Murán nappe is built dominantly of the Triassic carbonate platform complexes, which are not affected by ductile deformation. However, slices of very low-grade metamorphosed sediments occur in places between the Veporic cover and the Murán nappe, which might belong to the Meliatic and Turnaic cover nappe systems (VOJTKO, 2000).

The variable microstructures and step-wise, but rapid upward decreasing strain intensity and metamorphic grade within the extensional low-angle detachment fault indicate significant vertical thinning and telescoping of metamorphic isograds. The fault nucleated along the rheologically weak horizons of quartzites and marbles of the Veporic cover during the initial phases of exhumation. Later on, its activity was controlled by changing deformation mechanisms (hardening and softening) due to decreasing P-T conditions in rock units of different composition. The principal displacement plane relocated several times, finally producing lens-shaped extensional allochthons bounded by low-grade ductile/brittle, or basically brittle shear zones.

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A GEOLOGICAL SECTION ACROSS THE "GRAND SAINT BERNARD NAPPE" IN THE SOUTHERN AOSTA VALLEY (WESTERN ALPS, ITALY)

Marco Malusà, Silvana Martin, Pietro Mosca, Riccardo Polino & Alessio Schiavo

The results of detailed geological mapping carried out on the southern side of the Aosta valley (Valgrisenche, Val di Rhemes, Valsavarenche and Val di Cogne) allow to outline the setting of the Penninic nappe pile exposed in this area.

The present structural setting through the southern Aosta Valley cross-section is the result of a complex and polyphasic evolution: basement units described in the literature as belonging to the Grand Saint Bernard nappe have followed independent PT paths during the Alpine orogenesis and now they are juxtaposed in the nappe stack and sandwiched between ophiolitic units.

The lowest structural element of the investigated area is the ophiolitic Gran Vaudala tectono-metamorphic unit (TMU, *sensu* SPALLA et al., 1998), which is characterized by a blueschist facies metamorphism of Alpine age. It is the footwall of the Grand Saint Bernard nappe and it is tectonically overlaid by the Gran Nomenon basement unit along the Entrelor thrust, an important shear zone involving slices of both basement and cover rocks recrystallized under greenschist facies conditions (FREEMAN et al., 1997).

Moving towards the higher and more external Grand Saint Bernard nappe portions exposed along the Valgrisenche – Val di Cogne transect, it is possible to distinguish other basement units: the Pra d'Amont TMU, which overlays the Gran Nomenon TMU by means of the Feleumaz shear zone, and the Leverogne and Ruitor TMU's, that are separated by means of the Avise shear zone. These shear zones consist of west-dipping low-angle tectonic contacts in which basement, cover and ophiolitic rock elements are preserved. Kinematic data are consistent with a tectonic transport direction towards east.

Therefore, the actual setting of the Grand Saint Bernard nappe and the "Piedmont zone" in the southern Aosta Valley is more complicated respect to the picture usually described in the literature. On the basis of the new stratigraphic, structural and metamorphic data collected in the part of Grand Saint Bernard nappe exposed on the southern side of the Aosta Valley, it is possible to recognize the following tectono-metamorphic units:

the Ruitor TMU, a polymetamorphic basement unit comprising metasedimentary rocks and metagranitoids of Ordovician age (460–470 Ma, BERTRAND et al., 2000b) with eclogite facies relics and blueschist facies overprinting of Alpine age

the Leverogne TMU, consisting of metasedimentary rocks with minor metabasites, which differs from the Ruitor TMU for the lack of metagranitoids and for the pervasive blueschist and greenschist facies metamorphic overprinting of Alpine age

the Pra d'Amont TMU, which contains albite-rich micaschists with minor metagranophyres of Cambrian age (511 Ma, BERTRAND et al., 2000a), characterized by a blueschist facies metamorphism of Alpine age followed by a re-equilibration under greenschist facies conditions the polymetamorphic Gran Nomenon TMU, constituted by metagranodiorites of lower Devonian age

(363 Ma, Bertrand et al., 2000b) intruded in a basement mainly consisting of metasedimentary rocks, which shows a slight greenschist facies metamorphic imprint of Alpine age.

In this area, the TMU's classically ascribed to the "Piedmont zone" form shear zones of variable thickness which separate different basement units. They are characterized by metamorphic assemblages of both greenschist facies (Entrelor and Feleumaz shear zones) and blueschist facies metamorphism (Avise shear zone).

As a consequence the juxtaposition of the Grand Saint Bernard basement TMU's has occured at different structural sites and at different times during the Alpine orogenesis. Therefore the present tectonic setting of the southern Aosta Valley transect could be the result of complex uplift trajectories occurred inside the orogenic wedge developed on the Apulian margin.

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MESOZOIC COOLING IN THE ADRIA CRUST (ULTEN UNIT)

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The Ulten unit (central eastern Italian Alps, Adria crust) is formed by stromatic gneisses including eclogites and spinel-garnet peridotites of Paleozoic age. They have been intruded by trondhjemitic magma during Carboniferous and have suffered a slow cooling through Permian (302- 251 Ma, Rb-Sr ages on white mica) and Jurassic (187–160 Ma, Rb-Sr on biotite).

The existing data in the Ulten unit confirm a retrogressive path between ~391 Ma (Sm-Nd internal isochron on gt-cpx, peak age on eclogites) and ~357 Ma (Ar-Ar cooling age on hornblende from eclogitic metagabbros) interpreted as an exhumation path of subducted continental crust incorporating exotic slices of mantle peridotite. After the exhumation from eclogitic conditions, in the period 330–160 Ma, the Ulten basement went from conditions of P ~1 Gpa, T ~600° C at 330 Ma to P ~0.3 Gpa (z ~10 km) and T ~300° C at 160 Ma. In this period, we can recognize two substages: a first fast decompression between Late Carboniferous and Permian (0.3 Gpa, 500° C at 250 Ma), and a second substage with isobaric cooling at constant depth since 250 until 160 Ma.

Data supporting relationships with Mid Triassic thermal events well documented in the Southalpine basement and cover (Eastern Dolomites, Val Rendena schists, Lake Como Dervio-Olgiasca schists) are rare in the Ulten zone. Differently, most biotite cooling data seem to be consistent with the time of the rifting tectonics in the Lake Como-Lake Lugano area and in the Brenta Dolomites (Norian-Lias time). Besides, the biotite Rb-Sr datings of the Ulten gneisses support a metamorphic evolution comparable to that observed in other Adriatic basement domains located at the borders of the Ligurian-Piedmont ocean during Mesozoic as the Austroalpine Margna and the Southalpine Monte Muggio units. As the Ulten unit, these do not show clear evidence for the Triassic thermal anomaly but registered the Jurassic time cooling interpreted as due to the opening of the Ligurian-Piedmont ocean.

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MIOCENE EXHUMATION OF THE SOUTHERN PENNINIC AND NORTHERN AUSTROALPINE BELTS ALONG THE TRANSALP PROFILE

Silvana Martin, Massimiliano Zattin, Alberto Castellarin

This work provides new apatite fission-track data to constrain exhumation of the southern margin of the Tauern window and the overlying Austroalpine basement. Samples have been collected close to the TRANSALP profile which, in this area, runs along the Ahrn valley.

The southern margin of the Tauern window is made by the steep dipping Tux gneisses. Some samples have been collected along the vertical profile of the Sasso Nero peak from 1600 m to 2300 m. The obtained ages range around 10 Ma and confirm the ages of GRUNDMANN & MORTEANI (1985) some kilometres to the east.

The Austroalpine basement south of the Tauern window and north of the DAV fault underwent intense early Alpine deformation, cooled below about 330 °C in the late Oligocene and below the closure temperature of zircon fission tracks only few million years later (STÖCKHERT et al., 1999). New samples have been collected from the "Filladi di Cima Dura" unit, just south of the contact with the Penninic oceanic nappe. Apatite fission-track ages are in the 11–13 Ma range, whereas some samples dated by GRUNDMANN & MORTEANI (1985) are close to 9 Ma. The apparent gap can be explained taking into account the sample elevation difference (the younger samples have been collected at an elevation of about 600 metres lower than the oldest samples). Relationships between age and elevation and between zircon and apatite ages give an exhumation rate of less than 0.3 mm/a, confirming the decrease of uplifting rates in the last 20 Ma described by BLANCKENBURG et al. (1989).

The substantial similarity in the apatite fission-track ages obtained from the Penninic and Austroalpine basements suggest that no major vertical throw at shallow level in the crust has taken along the southern margin of the Tauern window.

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ALPINE EXHUMATION DETERMINED BY FISSION-TRACKS ANALYSIS AND PETROGRAPHY OF TERTIARY SANDSTONES OF THE VENETO FORELAND ALONG THE TRANSALP PROFILE

Silvana Martin, Massimiliano Zattin, Cristina Stefani, Paolo Grandesso & Matthias Bernet

Orogenic sediments provide much information about uplift and erosion of the adjacent mountainous belts. As necessary requirement, burial temperatures reached by the investigated sedimentary successions have to be significantly lower than the total annealing temperatures (about 120° C for apatite and more than 250° C for zircon). In this study, the arenite petrography has been integrated with detrital fission-track geochronology, which utilizes the fission-track ages of single detrital grains (mainly apatite and zircon) to identify the source region and to quantify its thermochronological evolution.

The southern end of the TRANSALP profile crosses the Oligo-Miocene succession of the venetian foreland basin. According to MASSARI et al. (1986), the basin fill history can be divided into two stages: from Chattian to Langhian, the basin represents the foreland of the NW-SE-trending Dinaric chain; from Serravallian to Recent, it was incorporated into the south-vergent South-Alpine chain. The first stage is characterized by the presence of a wide terrigenous shelf and the unconformities recognized have been regarded as dominantly eustatic (MELLERE et al., 2000). In the second stage, as a response of the South-Alpine uplift, there is an abrupt increase in subsidence rate and the shallowing upward of the stratigraphic succession attests the rapid filling of the foredeep. Whereas the Chattian-Langhian succession is up to 800 m thick, the uppermost stage is represented by 3000 m of sediments. These estimates have been confirmed by analysis of organic matter (FANTONI et al., this volume) and by apatite fission-track data, which show a low degree of annealing for the oldest investigated sample (Langhian).

Petrographic and fission-track data confirm the two-phase evolution of the Venetian foreland basin. The Chattian to Langhian samples are predominantly quartzolithic, with some minerals typical of medium-grade and low-grade metamorphic rocks. Apatite fission-track data show distinct sources but most of the ages range in the Paleogene. These data suggest that main source rocks were represented by Penninic and Austroalpine nappes. Minor input comes from the South-Alpine chain which was probably submerged. From the Serravallian onwards, active thrusting, uplift and erosion of the South-Alpine chain are marked by a change of the arenite composition, with an abrupt increase of dolostone grains. Apatite fission-track data again suggest the presence of more sources but most of the ages are Mesozoic, indicating a source region not affected by Alpine metamorphism. A similar age pattern has been revealed by zircon fission-track analysis from modern sediments collected in the Brenta and Piave rivers. These data demonstrate that no major paleographic variations occurred from the Late Miocene onwards in this sector of the South-Alpine chain.

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THREE DIMENSIONAL GEOMETRY OF THE LEPONTINE NAPPES IN THE MAGGIA REGION, CENTRAL ALPS

Michael Maxelon & Neil Mancktelow

The Lepontine Alps represent the classic region for fold nappe development in mid-crustal levels and for the overprinting geometry of multiple deformation phases on all scales. Recently they have also become critical for models of burial to great depths and subsequent very rapid exhumation. Before any such model can really be applied or critically assessed, the geometry of the units involved must be accurately known in three dimensions and combined with the fourth dimension of time to establish a consistent history. However, the three-dimensional geometry of the Lepontine nappes is not unequivocally established because detailed modern structural mapping is incomplete and there are inconsistencies and contradictions between adjacent areas. This project combines new structural mapping of critical and/or contradictory areas with existing observations to develop a testable three-dimensional model of the geometry of the Lepontine nappes in the Maggia region. A consistent regional model must incorporate a great deal of information on the location of unit boundaries relative to topography and on the orientation and kinematics of up to five distinguishable phases of deformation. Assimilating and integrating this complex information into an internally consistent model, together with the problem of its effective visualization, has been a major hurdle to our understanding. It is only very recently that computer-based tools for handling large amounts of geological/geographical data and their three-dimensional representation have become available. In this project, a model is being developed using a computer-aided earth modelling system (CAEM, e.g. Gocad) for visualization and analysis and a Geographical Information System (ARC/INFO, ArcView) as the data repository. The possibilities for $2^1/_2$-dimensional visualisation in GIS allow preliminary assessment of geometrically intricate and ambiguous zones. The Maggia region has been chosen because many of the major nappes and the complete range of deformation phases are exposed in a compact region. The high topographic relief and limited subsurface information available from hydroelectric tunnels also aid three-dimensional reconstruction. The computer modelling system provides a powerful tool to aid in the storage, retrieval and interpretation of field data. It also helps target the critical areas for more detailed structural mapping, namely those where there are inconsistencies or where the location and orientation of structures have a critical influence on the three-dimensional interpretation. Clearly without very extensive subsurface information (e.g. from boreholes, tunnels, reflection seismic etc.), there can be no unique solution. However, the model developed will at least represent an internally consistent solution in accord with available data and geological experience. Such a model can then be critically evaluated and modified in the future as additional surface and subsurface data become available.

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LINKING LITHOFACIES TO GROUNDWATER PROVENANCE – EXAMPLES FROM THE NORTHERN CALCAREOUS ALPS, AUSTRIA, USING THE STABLE SULPHUR ISOTOPE AND TRACE ELEMENT ANTIMONY

Bernard Millen & Rainer Brandner

Keywords: applied hydrogeology, groundwater provenance, natural springs, geochemistry, hydrochemistry, sulphur isotope ($\delta^{34}S$), antimony, geogenic contaminant source, engineering geology, water supply

Presented are applied examples of linking lithofacies (geochemistry) to groundwater provenance (hydrochemistry) and its use in engineering geology and regional water supply investigations.

Using the values of the stable sulphur isotopes ($\delta^{34}S$) for the dating and distinguishing of sulphur bearing rocks has been applied for some time (e.g. NIELSEN et al. 1969, CLAYPOOL et al. 1980, PAK et al. 1981, SPÖTL 1988). Within the Northern Calcareous Alps, Austria, the sulphur bearing evaporitic rocks of the Raibl (Carnian) and Reichenhaller (Scythian/Anisian) Formations occur. By combining whole rock sulphur isotope dating results with those of the hydrochemistry, it is possible to determine the source rocks of sulphur bearing groundwater occurring within the Northern Calcareous Alps.

In 1999, trace element analyses of spring water used for the public supply, occurring within the Palaeozoic Rocks (Schwaz Dolomite and Wildschönau Phyllites) at Schwaz, Tirol, revealed an extremely high content of antimony (up to 3 mg/l). The World Health Organisation's recommended value for antimony in drinking water is <0,005 mg/l. The source of this geogenic contaminant was determined to be the silver bearing "Fahlerz" (Schwazit, Tetraedrit) which has been mined in the region. Presented are hydro- and geochemical data from Schwaz and a prognosis of the possible extent of this geogenic contaminant based on regional mapping results.

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THERMOCHRONOLOGICAL INVESTIGATIONS FROM THE PELAGONIAN AND SUBPELAGONIAN ZONE (REPUBLIC OF MACEDONIA AND NORTHERN GREECE). NEW K/AR, ZIRCON AND APATITE FISSION TRACK DATA

Thomas Most, István Dunkl & Wolfgang Frisch

The northern Pelagonian crystalline zone (NPCZ) is part of the NNW-SSE trending Pelagonian zone (PZ) which extends from Skopje (Macedonia) to northern Evvia (Greece) covering a ca. 420 km long and 60 km wide area. Mesozoic cover rocks overlay the crystalline rocks, which crop out in tectonic windows (e.g. Olympus-Ossa, Pelion, Kranea).

For the southern part of the Pelagonian crystalline zone early Cretaceous nappe stacking and a Tertiary extensional phase is proven by numerous authors (e.g., Schermer et al., 1990; Walcott, 1998; Lips et al., 1998, 1999). From the northern part of the Pelagonian zone practically no modern structural geological, petrological and thermochronological data are available. First petrogenetic characteristics of the rocks and some structural data have been presented by Kossmat, 1924; Medwenitsch, 1956; Jancev et al., 1977 and Dumurdzanov, 1985. An unspecified K/Ar age of 800–1000 Ma for a Pelagonian granite had been presented by Deleon, 1966.

The Pelagonian crystalline zone can be separated into a lower unit (I) consisting of gneisses, micaschists, granitoides, migmatites and amphibolites and an upper unit (II) comprising a mixed series of micaschists, gneisses and marbles. The metamorphic gradient increases from greenschists facies conditions at the margin of the Pelagonian crystalline to amphibolite facies conditions in the central part. The high pressure / low temperature paragenesis of crossite + epidote + white mica + albite + quartz represents a metamorphic event under blueschist facies conditions at the northern margin of the Pelagonian crystalline zone (Mt. Vodno near Skopje).

Ongoing structural geological investigations document a polyphase deformation history of the Pelagonian zone and the adjacent tectonic units of the Vardar- and Subpelagonian zone.

Some 40 biotite and white mica mineral concentrates from more than 30 samples have been analysed by the K/Ar technique.

(I) The first group comprises ages from biotite and white mica derived from unfoliated granitoids and amphibolites of the Pelagonian zone. They range from 447±17 Ma to 267±10 Ma and show that relics of a Hercynian basement are present.

(IIa) Eohellenic ages between 148±6 Ma and 111±4 Ma of the second group representing Late Jurassic to Early Cretaceous nappe stacking associated with the development of the dominating fabrics and structures in the rocks of the Pelagonian crystalline zone. All micas of this group have been separated from strongly foliated paragneisses, orthogneisses (foliated granites), micaschists, cipollinos and blueschists.

(IIb) Three K/Ar ages between 102±4 Ma and 86±3 Ma were gained from micaschists and gneisses from the southern part (Kaimaczalan), overlain by Mesozoic cover rocks and micaschists of the Vardar zone.

(III) Tertiary white mica ages around 64 Ma were obtained from rocks of the Mesozoic sequence from the SE part of the study area.

Westward movement along a mylonitic shear zone in the western part of the studied area (near Brod) is documented by an Upper Eocene to Lower Oligocene K/Ar white mica fabric age (36±1 Ma).

Zircons from the central part of the Pelagonian crystalline zone yield fission track ages between 84±3 Ma and 68±4 Ma. These ages indicate cooling after the Eohellenic tectonometamorphic cycle and lack of Cenozoic resetting. In the Subpelagonian zone the zircons show slightly younger ages around 56 Ma.

The apatite fission track ages are systematically younger than the zircon fission track ages and range around 30 Ma in the central part of the crystalline zone. An apatite fission track age of 45 Ma was obtained near its eastern margin.

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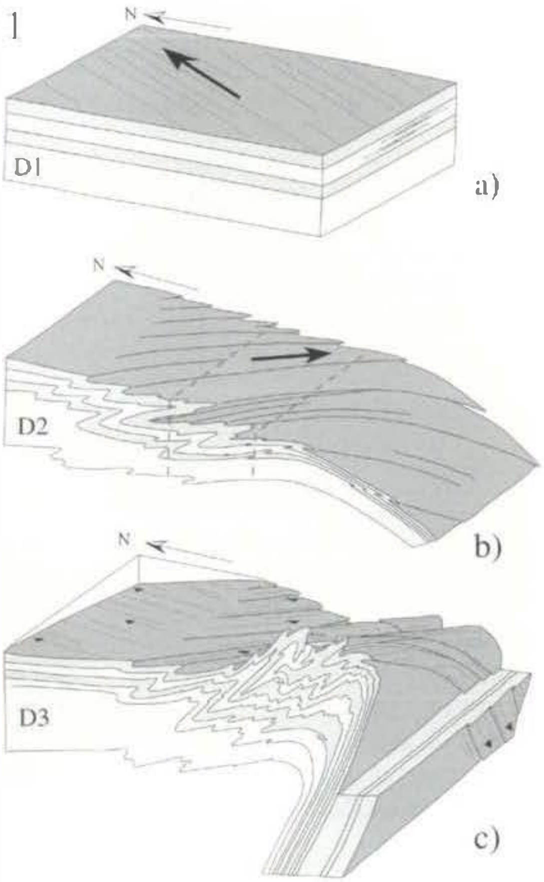
CONSTRAINTS ON THE EXHUMATION OF THE ADULA NAPPE (PART 2): OLIGOCENE UNROOFING OF THE LEPONTINE CORE COMPLEX

Thorsten Nagel & Stefan M. Schmid

After initial exhumation from eclogite facies conditions the Adula nappe was affected by intense amphibolite facies overprint at deep to mid crustal levels. Isograds of this stage clearly crosscut nappe boundaries and hence postdate nappe stacking of the Lower Penninic nappes. The exposure area of amphibolite facies conditions, the so called Lepontine Dome, shows a strongly asymmetric distribution of metamorphic grade. From north to south metamorphic conditions increase continuously from upper greenshist to high amphibolite facies conditions within the gently northeastwards dipping nappe pile. At its southern border the whole nappe pile is reoriented into a vertical to even overturned position by a series of huge backfolds. The southern limb of these backfolds, the Southern steep belt, is a complex high strain zone which also represents the abrupt southern border of alpine metamorphism. Recently the contribution of Miocene orogen parallel extension to the exhumation of the Lepontine has been emphasized. However the overall geometry of the Lepontine as well as the distribution of metamorphism clearly points to a dominant exhumation along the southern steep belt (see Schmid et al., 1987).

Fig. 1



In the southern Adula nappe three ductile deformation phases under progressively decreasing pressures can be distinguished (see also Grond et al., 1995). The first phase D1 (Zapport phase, Fig.1a) is associated with tight to isoclinal folds, an intense axial planar foliation, and a NNE-SSW-trending stretching lineation parallel to fold axes. Shear sense indicators denote TopN directed transport related to D1. Deformation ceased at conditions of 600-650 °C/ 11-13 kbar in the middle Adula nappe. Structures of the second phase D2 (Fig.1b) overprint the established nappe boundary between the Adula and the underlying Simano nappe. D2 leads to the formation of narrow to tight southwestverging folds at different scales associated with TopSE directed shearing. Where D2-deformation is intense a new axial planar foliation S2 is developed. Synkinematic microstructures indicate decompression at conditions of 650-700 °C/ 9-12 kbar during D2 in the vicinity of the backfolds. Large scale folds of the third phase D3 lead over from flat lying nappes in the north into the Southern Steep Belt (Fig.1c). In the lower Val Mesolcina intense D3 folding is associated with an E-W-trending stretching lineation parallel to fold axes, however no axial planar foliation is developed. At this place conditions of 650-750 °C/4-6 kbar were reached during backfolding D3. From north to south dominant pervasive deformation becomes progressively younger. In the north NNE-SSW trending structures are related to D1. Towards South they become overprinted by D2, which leads to a southward anticlockwise rotation of the dominant finite stretching lineation in mapview.

The foliation in the northern part of the Southern Steep Belt is affected by D3-folds and seems to belong to the second deformation phase. We infer that the Southern Steep Belt was active as a south dipping fault zone with a normal sense of shear during D2. From a purely geometric point of view D2 can best be attributed to the upper Oligocene Niemet-Beverin phase in the higher middle Penninic units.

We conclude that major exhumation of the Central Alps along the present Southern Steep Belt occurred in Oligocene time. During the upper Oligocene the Central Alps were exhumed mainly tectonically by orogen-oblique movement along a southdipping shearzone. In mid Oligocene time this shear zone was folded into an upright position and exhumation continued by backthrusting and erosion probably accompanied by E-W extension.

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PRELIMINARY GEOLOGICAL INTERPRETATION OF THE CENTRAL TRANSALP SECTION: INVERTED EXTENSIONAL STRUCTURES AND EXHUMATION OF THE TAUERN WINDOW

Franz Neubauer, Karl Millahn, Gerfried Grassl & TRANSALP Working Group

The Eastern Alps represent the classical example of a double-vergent orogen with an exhumed metamorphic core complex in the centre. The Eastern Alps involves the S-ward subducted European continental lithosphere in a lower plate position and the Adriatic plate in the upper plate position. The Eastern Alps nappe complex comprises from footwall to hangingwall the allochthonous Central Gneis unit, the Penninic oceanic unit and the Austroalpine continental unit, and the Southalpine unit to the south of the Periadriatic fault. The TRANSALP deep seimic line investigated, among other problems, the deep structure of the antiformal Tauern metamorphic core complex within internal zones of the orogen. Recent discussions on the structure of central sectors of orogens focused on double-vergent thrusting leading to vertical extrusion of central, metamorphic sectors of the orogen (e. g. BEAUMONT et al. 1996; BONINI et al., 1998). The principal goal of this study is tconcerned with the crustal structure of the central portion of the Eastern Alps and to elucidate how the structure was formed by processes of convergence and collision and to search for structures inherited from pre-orogenic extension.

The results clearly show a double-vergent orogen with continuous crustal thickening towards the centre of the orogen, with thickest crust beneath the Tauern window (TW). The European basement-to-cover contact can be traced, with some interruptions, from the Molasse zone to beneath the northern TW. This contact displays three major extensional structures, flexures and normal faults, interpreted to represent inherited structures from the extensional stage. The northern margin of the Folded Molasse zone coincides with a sedimentary halfgraben with onlap features of younger sediments. A second halfgraben is supposedly beneath the Inn valley. The contact is gently S-dipping beneath the Inn valley and nearly subhorizontal beneath the Austroalpine basement with traces of possible European sediments in a depth of ca. 13-14 km beneath the Graywacke zone. A major ramp (reflective zone from 15 km, with several breaks, down to ca. 35 km) appears to delimit the continuous European basement beneath ca. the northern edge of the TW. This ramp is likely an inverted normal fault, too, because of the presence of imbricated sedimentary piles along its northern limit. Two major gently S-dipping reflective zones can be traced from beneath the central TW (ca. 20 resp. 30 km) to beneath the Southalpine unit (SA) (ca. 25 resp. 35 km). These structures together are interpreted to represent a major crustal-scale forethrust with several major splays along which basement-cover nappes were stacked towards north.

The TW area display several reflective zones in shallow and intermediate structural levels. These are interpreted to represent basement-cover duplexes. The northern shallow gently N-dipping reflective zones can be interpreted to represent cover schists along the upper margins of the window. A central shallow reflective zone may represent a synform. Major portions in shallow southern levels are transparent (?Variscan Central Gneiss). Some gently north-dipping reflectors occur in ca. 20 km depth (vibroseis) and coincides there with the orientation of the Periadriatic Fault. These are possible buried European sediments. Consequently, the TW Penninic units form a duplex-type structure which is wedged into the Austroalpine units by northward thrusting.

The PF can be traced by a sharp northern, medium-angle N-dipping delimitation of several prominent, gently S-dipping reflectors within the SA. Consequently, the PF has in this interpretation a pronounced component of back-thrusting.

Taking the shallow N-dipping delimitation of the SA, the PF, and the gently S-dipping reflective zones beneath the TW, the SA forms a wedge which caused detachment of the Penninic continental basement from previously extended European continental crust. Together, all these features are interpreted to represent a major crustal-scale fore-thrust with several major splays along which major crustal sectors were transported and stacked towards north.

The European crust is flexured due to thrust loading of the entire Alpine nappe stack onto the European crust. The middle and lower European crust is remarkably unaffected by shortening (except possible duplication of layered lower crust what needs further confirmation). The Alpine nappe stack to the north of the Periadriatic fault shows internally all characteristics of north-directed thrusting with a pronounced ramp-flat geometry where ramps are the loci for major splays and duplex structures which complicate the internal structure of the Alpine nappe edifice, specifically within the Northern Calcareous Alps (see, e.g. EISBACHER & BRANDNER, 1996; ORTNER & REITER, 1999). Among these the duplex-structure of Penninic units exposed within the Tauern window is of particular importance because it shows that the Tauern culmination includes a strong component of N-S shortening, including formation of a flake which intruded into the northern nappe stack ("crocodile structure") (see LAMMERER & WEGER, 1998; NEUBAUER et al., 1999). The overall structure is in clear support of present models of double-vergent orogens where an uniformly subducting slab delaminates and causes back-thrusting starting from a point of singularity (BEAUMONT et al. 1996; BONINI et al. 1998).

As relatively thin sedimentary layers can be followed on the European continental crust, this feature argues that no oceanic rift is present to the N of the Central Gneiss unit. This argument is in line with the recent notion that no separate North Penninic ocean may have existed as recently proposed by WORTMANN et al. (2001). Moreover, the relationships between sediments and basement, and the northward thickening of cover sediments seems to support the presence of a moderately extended passive continental margin. Splays of thrust faults evolved above the tip of previous normal fault structures which controlled, therefore, the structural style of the orogen.

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HALFGRABEN FORMATION PERPENDICULAR TO EXTRUSION: THE NEOGENE WALDHEIMAT BASIN IN THE EASTERN ALPS

Franz Neubauer & Wolfgang Unzog

The Neogene Waldheimat basin (Early-Middle Miocene) is characterized by an asymmetric basin fill along a major, ENE-trending normal fault which is oriented subparallel to the northern boundary of the Neogene extrusional wedge in the Eastern Alps. The Waldheimat basin include the St. Kathrein (W) and Kogl (NE) subbasins. Considering all available surface and subsurface (former mining) information, we subdivide several lithofacies. These include from the base to the top: (1) **Basal breccia/sand lithofacies**: A thin veneer of fine breccia and grits covers the basement. These lithotypes were mainly found during mining in the St. Kathrein subbasin. (2) **Sand/coal facies**: Mica-rich sands and silts are intercalated by three coal seams. The coal seams are together ca. 10.5 meters thick and include some whitish vitric and phenocrystic tuffs. (3) **Sand/clay lithofacies**: The section above the sand/coal lithofacies is composed of bituminous, often laminated clay which yield plant fossils, brown and gray clay followed by well-bedded coarse sand. Basal portions of the sand/clay lithofacies within the St. Kathrein subbasin comprise some tuffaceous material mostly within the bituminous clay. (4) **Gravel facies**: A thick sequence of well-rounded gravels within a yellowish, clayey matrix represents the most prominent formation exposed at the surface. The thickness of these gravels reaches 170 meters within wells. The clasts have a diameter of 10 to 40 cm in average, with a maximum diameter of ca. one meter suggesting a very short transport distance. A broad range of clasts have been observed which include the following sources: (a) Light greenish quartzite, deformed metaconglomerates and paraconglomerates within a foliated, sericite-rich matrix are most likely derived from the Alpine Verrucano Fm. which is exposed to the east within the upper part of the Wechsel window. These comprise major portions of the entire boulder spectrum. (b) Augen orthogneiss, paragneiss are exposed within the Stuhleck-Kirchberg nappe in the surroundings of the basin. (c) Vein quartz is common, micaschist clasts are rare. (5) **Unsorted gravel facies**: At the northeastern corner of the Kathrein subbasin, unsorted gravels with blocks and boulders of a diameter of ca. one meter are exposed. All clasts are angular to subangular. The clasts are mostly quartzphyllite, augen gneiss and quartzitic micaschist to light-brownish quartzite which all strongly resemble to rocks of the Stuhleck-Kirchberg nappe as exposed at the ridge to the north of the Waldheimat basin.

The basin fill displays a uniform, coarsening upward depositional cycle. The lower lithofacies types (1–3) are interpreted to represent a marsh and lake environment which is later replaced by fluvial and alluvial deposits. Sections based on mining data display that basal formations are thick along northern sectors and thin towards south. The presence of a normal fault with a minimum vertical displacement of 300 meters along the northern margin and the internal discordance between sand/clay and gravel lithofacies suggest a rollover structure. The near-base coal seams are folded according to published sections from the mining period.

The ENE-trending master normal fault suggests ca. NNW-SSE extension. This fault is overprinted by N-trending sinistral strike-slip faults and NE-trending reverse faults. Slickenside and striation data were collected at 33 sites between Alpl and Retenegg in order to evaluate fault kinematics. In many outcrops, superimposed sets of slickensides and striations indicate a polyphase reactivation of these faults. Note that along fault traces outcrop conditions are poor and therefore only a few reasonably large exposures have been found along major faults. We observed four sets of paleostress tensor groups deduced from fault patterns.

(1) **Deformation stage D_1**: The dominant pattern, including more than 70 percent of all measured mesoscale faults, records N-S to NNW-SSE extension. The pattern includes predominant gently S- to SE-dipping normal faults with dip-slip sense of displacement.

(2) **Deformation stage D_2**: The normal faults are overprinted by E-W (to subordinate NE-SW) extension patterns which include ca. N-trending normal faults. The basement high separating the St. Kathrein and Kogl basin was initially delimited by such faults.

(3) **Deformation stage D_3**: Extensional patterns are overprinted by N-S to NNW-SSE oriented compressional structures. The pattern is obviously related to compressional structures, folds and reverse faults as found in the subsurface.

(4) **Deformation stage D_4**: The final event is ca. E-W to NE-SW strike-slip compression which formed a conjugate set of strike-slip faults.

The data presented above show that formation of the Waldheimat basin was initiated by a major normal fault along northern margin of the basin. Both map-scale fault geometry and paleostress orientations consistently argue for a predominantly normal sense of movement which resulted in at least 300 meters vertical offset after map data. Both the missing faults along the southern margin of the St. Kathrein subbasin and the internal structure argue for an essentially halfgraben-type structure in the St. Kathrein subbasin which was later modified by minor reverse faults and some internal folding forming ca. ENE-trending folds. We interpret these structures to record two stages of basin evolution: (1) Basin formation during a tensional stage of faulting with a top to the SSE dip-slip throw leading to NNW-SSE extension (D_1) and subsequent E-W extension (D_2); (2) basin inversion during a late-stage N-S to NNW-SSE (D_3) and subsequent E-W (D_4) contractional stages.

The basin fill records the structural evolution. In a first step fine breccias and grits were deposited. The relative fine grain size and sediment composition indicate an only minor relief, short distances of transport and a local source. Deposition of these clastics was followed by sedimention of organic material within a calm aquatic environment in a lake without a major relief in the surroundings. A later increasing amount of coarse clastic material came into the depocenter with a river from the northeast (Wechsel window area). The relief rapidly increased with deposition of rocks comprising the gravel lithofacies. The composition of clastics within the gravel lithofacies argues for a eastern source within the Wechsel window which was uplifted during the Miocene. This argues for a longitudinal sediment transport parallel to the basin axis typical for rift settings. Finally, supply of sediments from the eastern source stopped and lateral sediment supply along the northern basin flank with mass flows replaced it. This resulted in the deposition of unsorted gravel lithofacies along the northern basin margin.

The extensional nature of the Waldheimat basin contrasts with other intramontane basins of the the Eastern Alps which are generally interpreted to represent pull-apart- and transcurrent basins along major strike-slip faults. In this sense, the Waldheimat basin belongs to a group of basins which formed internal to the northern lateral margin of the extrusional wedge. The basin is obviously not controlled by strike-slip faults but by normal faults which indicate extension perpendicular to the motion direction of the escaping block. The Waldheimat basin is, therefore, an example of an extensional basin that formed in response to the widening of the escaping block during progressive eastward extrusion. The succession of deformation events is similar to those found to the north along the Mur-Mürz wrench corridor.

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HIGH DIAGENESIS AND ANCHIMETAMORPHISM IN PERMOTRIASIC SEDIMENTS OF THE SOUTH WESTERN PART OF THE KARWENDEL MOUNTAINS PRELIMINARY RESULTS

Petra Nittel & Marc Ostermann

Location: Our research area is part of the Austroalpine and lies in the Northern Calcareous Alps, in the southern part of the Karwendel Mountains between Innsbruck and Zirl, Tirol, Austria.

Anisian to Ladinian sedimentary rocks of the Northern Calcareous Alps from the area between the Höttingergraben in the east and the Ehnbachklamm in the west have been sampled in several stratigraphic sections, recorded in great detail.

In the Inntal Nappe in the vicinity of Innsbruck the sediments underwent high-grade burial diagenesis with maximum temperatures of about 180° C (KÜRMANN 1993).

According to KRUMM (1984) there is a broad margin of "anchimetamorphic" influence within the southern part of the Northern Calcareous Alps, in the area of the Mieminger and Wetterstein mountains showing even a strong extension towards the north (reaching the area of Garmisch-Partenkirchen).

The target of our analysis is to gain more information about the genesis and dimension of the Middle Triassic sediments through an sedimental-petrographical description and to get an survey of their locally distribution. The thermal overprint raises two questions: is the whole statigraphic succession influenced in the same dimension and is it possible to make a time correlation?

To gain new informations we use the following three methods:

1) The illite crystallinity combines several parallel occurring maturity processes of the potassic white mica and allows to draw conclusion about the grade of anchimetamorphism. With increasing diagenesis neomorphic potassic white mica develop increasingly sharper inflexion maximums in the X-ray diffraction diagram. This effect is called "sharpness ratio" by WEAVER (1960). To minimise errors caused through the input of detritic potassic white mica WEAVER (1960) suggests the analysis of fractions below 2 micron. In these fractions neomorphical potassic white mica dominates over detritic minerals. To reach more precise results KUBLER et al. (1967) suggest to evaluate the half width. With increasing grade of diagenesis the half of the reflection width value (in mm) decreases due to increasing crystallinity. The (silicate) mineral residue, fraction below 2 micron, resulting from solution in formic acid, is examined mineralogically. Its mica content proved to be markedly homogeneous, containing mainly di-octahedral illite minerals. X-ray diffraction analysis furnishes reliable information about the compositional and structural properties of authigenic clay minerals even in polyphase mixtures.

2) Through vitrinite reflexion analyses of the Raibl beds between Thaur in the East and Zirl in the West we want to observe paleogeothermic influences in detail, especially of the reflectance data and by stratigraphical assignment of the samples. The predominant region-

al tendency is a general increase of the maturity from north to south (PETSCHICK 1989).

3) The conodont alteration index which also indicates the thermal overprint, is already proved in some limestones of the Triassic succession through our own preliminary analyses (personal communication KRYSTYN, Vienna).

The results of these analyses will be compared and correlated as far as possible.

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THRUST SEQUENCES IN THE EASTERN ALPS – CONSTRAINTS FOR INTERPRETATION OF THE TRANSALP SEISMIC SECTION

Hugo Ortner

The thrust architecture of the Eastern Alps is a result of polyphase shortening and normal faulting in different directions. In the northwestern part of the Eastern Alps, thrusting was accompanied by synorogenic sedimentation. In the Northern Calcareous Alps, a complete sedimentary column from the Jurassic to the end of the Oligocene is present. For a particular location, the youngest deposits below a thrust plane give the approximate age for thrusting.

The Middle to Upper Cretaceous active continental margin in the Alps was located in the western part of the Eastern Alps and is documented by slices of Flysch sediments and ophiolites (Arosa zone imbricates) within and below the Northern Calcareous Alps and along the western margin of the Austroalpine nappes. Thrusting propagated from more internal parts of the orogen to external parts of the orogen. In the area south and west of Salzburg, thrusting is documented by progradation of submarine fans from the Hauterivian (Rossfeld Fm; DECKER et al. 1987) to the Albian (Lackbach Fm.; DARGA & WEIDICH 1986). In the western part of the Northern Calcareous Alps, stacking of the Lechtal nappe onto the Allgäu nappe ended sedimentation of the Losenstein Fm., whereas sedimentation continued on the northernmost part of the Lechtal nappe and the Cenoman-Randschuppe with the Branderfleck Fm (GAUPP 1982). Sedimentation of the Branderfleck Fm. continues to the Turonian on the Cenoman-Randschuppe. The Inntal Nappe was thrust onto the Lechtal Nappe after deposition of the Aptian to Cenomanian Lech Fm. ("Lechtaler Kreideschiefer"; VON EYNATTEN 1996). A sedimentary development comparable to the Lech Fm. is the Triazza Fm. on top of the Silvretta basement complex (CARON et al. 1982, MADER 1987). The sedimentary succession of the Arosa zone reaches into the Turonian. The Arosa zone in the western part of the Northern Calcareous Alps seems to be a lateral equivalent of the Cenoman-Randschuppe further to the east. The most frontal slices of the Cretaceous Alpine orogen were incorporated during or after the Turonian. At least in the western part of the orogen, post-Turonian shortening resulted mainly in fold growth inside the nappes (ORTNER 2001). Middle to Upper Cretaceous shortening was W- to NW-directed.

Renewed north-directed thrusting with frontal accretion started during Eocene continental collision, resulting in frontal accretion of Flysch and Helvetic units. The nappes of the Rhenodanubic flysch became part of the Alpine orogen after the Early Eocene, the Helvetic nappes after the Middle or Late Eocene. This event is associated with the subduction of the Penninc ocean.

During the Early Oligocene an important new thrust formed within the Alpine orogen. The Inn Valley fault is, according to the preliminary results of the TRANSALP seismic section, a prominent thrust plane. Movement along this major out-of-sequence thrust led to subsidence in the front of the thrust and formation of the Molasse basin north of the present day Inn Valley, which formed the southern margin of the Molasse basin during the Early Oligocene. The Oligocene sedimentary succession in the Inn Valley is in fact closely related to the Molasse basin in terms of subsidence and sequence stratigraphy (Inn valley: ORTNER & SACHSENHOFER 1996, ORTNER & STINGL (in press); Molasse basin: ZWEIGEL 1998). Thrusting propagated successively into the foreland, with two other thrust planes cutting the Northern Calcareous Alps out of sequence, until thrusting stopped in the Middle Miocene at the front of the Alpine orogen. Around the Middle Miocene, the thrust in the Inn Valley became active again, leading to uplift of the Augenstein surface in the hangingwall of the thrust.

In conclusion, three independent foreland-propagating thrust systems dominate the north-western Eastern Alps: An older system of Early to Late Cretaceous age might be related to oceanic subduction of the Penninic ocean. This thin-skinned system led to formation of the Allgäu-, Lechtal and Inntal-Nappes in the western Northern Calcareous Alps and to stacking of the Juvavic nappe units on top of the (younger) Tirolic unit. An Eocene thrust system is related to closure of the Penninic ocean. Postcollisional shortening from Oligocene onwards led to formation of major thick-skinned out of sequence thrusts cutting the previously deformed nappe stack. The Molasse basin, originally reaching south to the Inn Valley, was segmented by progressively younger thrusts propagating towards the foreland. The Oligocene Inntal thrust led to the separation of the Bajuvaric and Tirolic nappe complexes.

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RECENT FAULTS IN THE EASTERN SWISS ALPS IN RELATION TO LITHOLOGY

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The present tectonic activity of the Alps is expressed by recent (post-glacial) faulting, seismic activity and recent uplift. The study area in Graubünden, eastern Switzerland is a region with relatively high seismicity uplift rates are high in the internal parts of the Alps in the South but decrease towards the Molasse basin in the North. Despite the dense vegetation cover (meadows, forests) faults can be mapped on aerial photos and many of them can subsequently be verified in the field. The orientation and morphological appearance of the faults vary with the predominant lithology of the region.

Areas dominated by schists and sandstones with shallowly dipping Alpine foliation, display faults which manifest themselves by slight variations in the micromorphology or small fault scarps. The micromorpho-logical features include aligned sink-holes, variations in slope angle, incisions within otherwise flat surfaces and mountain ridges or slight irregularities in the soil surface. Offsets in an active scree and in post-glacial rock fall areas prove the faults' young age. The fault map shows that, in this area, there are two prominent fault systems, a more or less N-S striking system and an E-W striking one. The observed directions of the faults agree with the directions for strike-slip faults as predicted by focal mechanism data.

In limestone-dominated regions, the faults mainly reactivate old Alpine joints. These reactivated joints are wider than the original joints because reactivation facilitated weathering processes. A few faults in this region trend obliquely to the Alpine joint system and can be recognised by offsets of up to 1 m in the rock surface.

In the crystalline basement, the faults trend ENE-WSW, parallel to the main vertical foliation of the rock. These faults seemingly reactivate old ductile shear zones. Narrow bands of fault gauges that crosscut ductile shear zones are evidence for the reactivation. The faults in the granitoid rocks are the most conspicuous in the study area and often exhibit visible fault scarps.

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DYNAMICS OF JURASSIC RIFTING IN THE WESTERN CARPATHIANS

Dusan Plasienka

The Jurassic period was the time of extensive rifting of the northern, European passive margin of Tethys, which brought about drowning of Triassic carbonate platforms and finally led to disintegration of the European shelf crust into numerous elevated and subsiding domains, some of them presumably floored by a newly-formed oceanic crust. Based on the character and distribution of syn- and post-rift sedimentary sequences, basically three principal rifting phases as climaxes of long-term extensional tectonic regime can be discerned within the Western Carpathian area: (1) the earliest Jurassic uniform "pure-shear" lithospheric stretching and wide-rifting of the epi-Variscan Triassic platform; (2) breakup of the South Penninic-Vahic ocean at the Lias/Dogger boundary; (3) breakup of the North Penninic-Magura ocean at the Jurassic/ Cretaceous boundary.

Lithospheric stretching and crustal heating during the first rifting event at ca 200 Ma is documented by a radiometrically detected thermal event in the Tatric and North Veporic basement (MALUSKI et al., 1993; KRAL et al., 1997), but no volcanism occurred in that time. Broad intracontinental basins were formed (e.g. the Zliechov basin) flanked by uplifted rift shoulders providing terrigenous clastic material for syn-rift strata accumulated in marginal halfgrabens (e.g. the Borinka halfgraben). Comparatively thick hemipelagic marlstones and limy turbidites (Allgäu Fm.) deposited in axial zones of rapidly subsiding basins. For the next 100 Ma, pelagic basins within the Tatric area (Siprun basin) and the Fatric zone (Zliechov basin) of the Slovakocarpathian realm (analogous to the Austroalpine one) were subjected to slow thermal subsidence and calm pelagic sedimentation. Younger rifting and/or lowstand events are recorded by occasional incursions of turbidites (MICHALIK et al., 1996) and emersions on rift shoulders, but no substantial rebuilding of the basin architecture has been recognized. Widespread occurrences of small portions of submarine, mantle-derived, alkaline basaltic lava flows within Lower Cretaceous pelagic successions are interpreted as indications of persisting extensional tectonic regime within these basins (e.g. SPISIAK & HOVORKA, 1997), which were floored by a renewed, probably normal-thickness continental crust.

Zones along the northern edge of the Slovakocarpathian realm and areas north of it (Penninic realm) experienced a substantially different paleotectonic scenario. In addition to the first rift phase, the outermost Austroalpine and Slovakocarpathian units record a strong second rifting event approximately at the Lias/Dogger boundary (ca 180 Ma), which has been interpreted as a breakup phase of the South Penninic-Vahic oceanic zone (e.g. FROITZHEIM & MANATSCHAL, 1996; PLASIENKA, 1998). The north-facing Borinka halfgraben received thick scarp breccias during the Middle Jurassic, but no Upper Jurassic and Lower Cretaceous sediments are known there. This is tentatively ascribed to a thermal uplift of the upper plate due to asymmetric "simple-shear" rifting. The inner (southern) side of the uplifted area (North Tatric ridge) collapsed during the Middle Jurassic, giving rise to a zone with very rugged morphology at the northern flanks of the intra-Tatric Siprun basin. There, restricted basins represented by pelagic sedimentary successions rich in allodaps (often overlapping directly the pre-Alpine basement) alternated with small elevations marked by thin, incomplete and condensed Middle – Upper Jurassic successions (cf. PLASIENKA et al., 1991). It is inferred here, adopting the Alpine oceanic rifting models (e.g. LEMOINE et al., 1987, and many others), that the subcrustal lithospheric mantle was gradually exhumed within the lower plate, creating the floor of the South Penninic ocean, which was designated as the Vahic ocean in the Western Carpathians (see MAHEL, 1981; PLASIENKA, 1995). Although no ophiolites of this presumed oceanic zone participate at the present surface structure of the Western Carpathians, yet several indications of its existence do exist.

The third rifting event affected still more northern areas. Following the first rifting phase that produced system of halfgrabens filled with hemipelagic, often anoxic sediments, the second rifting phase individualized the elevated Oravic ribbon continent in a Middle Penninic position (Czorsztyn pelagic swell – MISIK, 1994). Approximately at the Jurassic/Cretaceous boundary, this swell was emerged and dissected, and subsided again some 50 Ma later in mid-Cretaceous times. The emergence of the Oravic swell is again ascribed to the thermal uplift of the upper plate of an asymmetric breakup zone of the North Penninic-Magura ocean.

The absence of rifting-related volcanism and a persistence of extensional tectonic regime for many tens of Ma indicate a passive rifting mode generated by tensile deviatoric stresses within the European lithosphere. In the Alps, the Jurassic rifting is traditionally interpreted as a consequence of eastward drift of Africa and Adria and opening of the Central Atlantic ocean. In the Eastern Alps and Western Carpathians, however, Adria was separated from Europe by the Triassic Meliata-Hallstatt oceanic trough until the Late Jurassic. This ocean was subducted beneath the distal Adriatic margin during the Jurassic, therefore tensional forces could not be effectively transmitted across the subduction zone towards the eastern sector of the European margin. Therefore it is alternatively presumed that tensile stresses were generated by the subduction slab pull force of the Meliata-Hallstatt oceanic lithosphere operating within the lower, European plate of the convergence system along the NE Adriatic margin.

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IS THERE A HIGH-PRESSURE LOW-TEMPERATURE METAMORPHISM IN THE AUSTROALPINE BASEMENT NORTH OF THE TAUERN WINDOW, EASTERN ALPS?

Andreas Piber & Peter Tropper

This investigation is part of the ongoing project on the tectonometamorphic evolution of the Austroalpine nappes in the northern Zillertal area, Eastern Alps. The two units studied are the Kellerjochgneiss and the Innsbruck quartzphyllite. The former unit is of debated origin, since it has been attributed over the last years to either the lower- or the middle Austroalpine. The latter unit is part of the lower Austroalpine.

The Kellerjochgneis contains the mineral assamblage muscovite + biotite + albite + chlorite + quartz ± stilpnomelane. In addition, a pegmatite sample in the Kellerjochgneiss contains the assamblage garnet$_1$ (Alm_{68} $Spess_{27}$ Pyr_3 Gro_2) + garnet$_2$ ($Gros_{52}$ Alm_{33} $Spess_{15}$) + biotite + stilpnomelane + muscovite + chlorite + albite + quartz. Due to the discontinuous chemical zoning of the garnets this probably represents a remnant of an earlier metamorphic (possibly Permian or Variscan) event. Backscatter images reveal that the muscovites in some of the Kellerjochgneis samples are chemically zoned with newly grown outer rims of ca. 5 mm in diameter. They exhibit a zonation with increasing paragonite- and celadonite component from the core the rim.

Thermobarometry in the samples of the Kellerjochgneiss was performed by calculating invariant points with multi-equilibrium methods such as THERMOCALC v. 2.7 with the data base of Holland & Powell (1998) and TWQ v. 1.02 with the data base of Berman (1988) and Massonne (1997). In addition the empirically calibrated muscovite + chlorite + stilpnomelane + quartz thermobarometer by Currie & van Staal (1999) was also applied. For the quartzphyllite samples only the program THERMOCALC v. 2.7. was used.

The calculations with THERMOCALC v. 2.7. with the assamblage muscovite + biotite + chlorite + albite + quartz ± clinozoisite, constrain an invariant point in the KNaMASH-system, which yields pressures ranging from 9.0 to 11.1 kbar and temperatures ranging from 360 to 390°C. This invariant point also involves H_2O, which is unconstrained yet. Calculations with varying $a(H_2O)$ from 1.0 to 0.1, only result in a slight shift in pressure of ca. 1 kbar. The calculations with the program TWQ 1.02 with the data base of Berman (1988) using the same mineral assemblage but without the celadonite component, which is not included in the data base Berman (1988) yields an additional invariant point. Additional invariant points were also calculated with the data base of Massonne (1997) which also includes Fe-stilpnomelane and phengite. Overall, these calculations yield pressures ranging from 8.3 to 9.5 kbar and temperatures ranging from 380 to 430°C. The results achieved with the empirical thermobarometer of Currie & van Staal (1999) are in good agreement and yield pressures ranging from 5.8 to 7.5 kbar and temperatures ranging from 310 to 400°C.These high pressures are still consistent with the absence of jadeite at temperatures between 350–400°C (Holland 1980).

In the Innsbruck quartzphyllite, due to the absence of biotite, it was only possible to calculate a reaction among muscovite, chlorite and albite. The calculations with THERMOCALC v 2.7 yield the reaction: 6Paragonite + 5Celadonite = 5Muscovite + 6Albite + Clinochlore + 2Quartz

+ $2H_2O$, which was used to estimate the pressures. The obtained pressures vary from 2.5 to 6.4 kbar between 300 - 400 °C.

These data indicate a possible HP-LT metamorphic overprint in the Kellerjochgneiss which is probably the result of early Eo-Alpine metamorphism.

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PERVASIVE REMAGNETIZATIONS IN THE NORTHERN CALCAREOUS ALPS: PRELIMINARY EVIDENCES AND IMPLICATIONS IN THE SALZACH REGION

Emilio L. Pueyo, Hermann J. Mauritsch & Robert Scholger

The Northern Calcareous Alps (NCA) have been the subject of paleomagnetic investigations since the end of the 1950´s until nowadays (e.g. HARGRAVES & FISCHER, 1959; for a reference compilation and review see HAUBOLD et al., 1999). Paleomagnetic data from the NCA are, almost, indispensable to discriminate three different kinds of problems: 1) Paleogeographical reconstructions of the Mesozoic platforms in this margin of the Tethys. 2) Vertical-axis rotations related with the Upper Austroalpine nappes and thrust sheet's configuration. 3) Large-scale orogenic processes like large displacements, lateral extrusion, oroclinal bending, ... Considering the complexity of the problem an intensive paleomagnetic research focus on specific structural units with well-exposed stratigraphical profiles would be the key to differentiate among the above exposed implications. In this sense, more than 60 new sites have been added to 20 previous sites in the Salzach region. These sites are located in two main nappe complexes: a lower unit with Tirolic affinity (Stauffen-Höllengebirge, for convenience is subdivided in North, Central and Southern sectors), and an upper one with Juvavic affinity (Göll-Lammer and Berchtesgaden units). Sampling inside every unit was focused to obtain several fold tests. Stratigraphic position spans from Lower Triassic to Lower Cretaceous.

New paleomagnetic results: Low coercitivity minerals carry the magnetization in most of the samples. Orthogonal demagnetization diagrams from thermal demagnetization procedures reveal the occurrence of two main magnetic components: J1) a pervasive secondary direction which unblocks until 350°C, always displays normal polarity and is present, almost, in any kind of rocks. J2) A higher temperature direction is defined between 350° to 550°C, and it yields two polarities in a few cases. Six successfully significant fold tests have been obtained to constrain the age of J1 and J2 (table 1). Three others also show clear tendencies. These fold tests let clear, with good statistical parameters, a systematic postfolding acquisition for most of the directions except for two high-temperature cases (NSH and CSH) in where two polarities are also present. Accordingly J1 and J2 directions from the three units have been interpreted before any structural corrections ("in situ") except for the above mentioned cases.

Implications: 1) The age of the magnetization can be accurately constrained only in two cases that show evidences of a primary acquisition (NSH & CSH; upper Triassic and Lower Jurassic respectively). In the other cases (postfolding) the age is, as much, equal than the age of the main episode of thrusting and folding of the Juvavic nappes in the area (D2, mid-Cretaceous; SCHWEIGL & NEUBAUER, 1997) but considering the observed inclinations (52° and 53° in average) and the expected ones, from the European or African apparent polar wander paths, they could be easily as young as Lower Eocene. On top of that, the inclination is even more controversial because the remagnetization could have been acquired when the beds where dipped to the North, if so, they would be much younger and would show an apparent shallowing. 2) All cases display the systematic clock-

Unit	Aff	Referenc.	Long	Lat	Tub	s / S	n / N	Pol.	α95	K	Fold test	SIG	%	D&I (fold t.)	
B	J	this work	13,094	47,675	300°C	3 / 3	8 / 8	N	5	183	neg	yes	0%	**89,63**	**R**
		this work			500°C	2 / 3	6 / 6	N	23	118	?	no	0%	**107,59**	**R**
GL	J	this work	13,298	47,587	300°C	2 / 2	12 / 12	N	6	68	neg	no	0%	**46,48**	**R**
		this work			500°C	4 / 5	28 / 28	N	14	47	neg	no	0%	**81,47**	**R**
NSH	T	this work	13,189	47,723	300°C	5 / 6	38 / 40	N	9	75	neg	yes	0%	**49,58**	**R**
		this work			500°C	4 / 5	34 / 37	N+R	23	17	pos	no	100%	**81,43**	**P**
CSH	T	this work	13,271	47,668	300°C	4 / 4	18 / 19	N	8	27	neg	yes	0%	**45,37**	**R**
		M, H, Ch			500°C	19 / 19	- / -	N+R	6	30	pos	yes	100%	**61,55**	**P**
SSH	T	this work	13,233	47,549	300°C	9 / 9	55 / 56	N	8	49	neg	yes	0%	**69,53**	**R**
		this work			500°C	10 / 10	63 / 66	N	5	74	neg	yes	0%	**87,60**	**R**

Table 1: Preliminary results in the Central sector of the Northern Calcareous Alps (Salzach Region): **Unit**: Structural unit; **B**: Berchtesgaden, **GL**: Göll-Lammer, **CSH**: Central sector of Staufen-Höllengebirge, **NSH**; Northern **SSH**; Southern. **Aff**: affinity; **J**: Juvavic and **T**: Tirolic. **References**; **M**: MAURITSCH & FRISCH (1978); **Ch**: CHANNELL et al, (1992) and **H**: HEER (1982) Longitude and Latitude (in average). **Tub**: unblocking temperature (aprox). **s/S**: sites considered /sites analyzed. **n/N**: samples considered/samples analyzed. **Pol**: polarity observed N: normal, **R**: reverse. **a95 & K**: FISHER (1953) statistical parameters. **Fold test**: negative (postfolding; 0%) or positive (prefolding; 100%). **SIG**: statistical significance. **%**: percentage of unfolding for the fold test best fit and the **D&I**: declination and inclination of the paleomagnetic vector that has been interpreted (R: remagnetization, P: supposedly primary).

wise rotation previously reported (see references in table1). If contrasting with a North direction this rotation reaches up to 107° (B). 3) However it is clear that differential rotations exist between the different units and they are higher in the Juvavic ones as well as the northern part of the Höllengebirge unit. 4) The lower temperature components display a systematic smaller value of rotation that reflects the main episode of clockwise rotation in the NCA (45° and 89°, depending upon the structural location). This event succeeds after a pervasive event of remagnetization. The difference in the rotation among the low and high temperature components is quite constant about 20° and would be related with the Upper Austroalpine thrust sheet internal configuration. 5) Surviving primary components (adequately described) have been only found in the northern and central sectors of the Höllengebirge unit. Considering the homogeneity of the magnetic mineralogy this reveals a patent S-N gradient of remagnetization that agrees with the former southernmost situation of the Juvavic nappes as well as the location of possible remagnetization sources.

The exposed results indicate the existence of a pervasive and well-characterised remagnetization component, with important structural and geodynamic implications, that should be adequately dated in the future. This remagnetization could be misinterpreted as prefolding in part of the previous paleomagnetic studies in the NCA.

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VITRINITE REFLECTANCE MAPS OF THE ALPS AND THE DINARIDES IN SLOVENIA

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Slovenia is located in the border region of the Eastern Alps, the Southern Alps, and the Dinarides. The Eastern Alps are situated north of the Periadriatic Lineament in NE Slovenia. The Julian-Savinian Alps and the South Karawanken Mountains south of the Periadriatic Lineament are part of the Southern Alps. The Slovenian Basin and the Sava Folds in central Slovenia form the transition zone between Alpine and Dinaridic tectonic units. The Slovenian Basin formed in Ladinian time, when the Slovenian carbonate platform disintegrated into the Julian Alps in the N and the Adriatic-Dinaridic carbonate platform in the S (BUSER, 1987). Maturation patterns in Paleozoic and Mesozoic sediments from Alpine and Dinaridic units were determined.

Carboniferous sediments, sampled in the Sava Folds and the South Karavanke Mountains, show vitrinite reflectance (VR) of R_{max}= 5,1–6,7% and R_{min}=1,7–3,5%. No difference in the organic maturation of pre-Variscian and post-Variscian Carboniferous sediments was recognized. Therefore the thermal overprint of post-Variscian times was at least as high, as the pre-Variscian one.

Within **Permo-Mesozoic** sediments, a high variability of VR-values can be observed, depending on the geotectonic and stratigraphic position.

Eastern Alps: In the Slovenian part of the Eastern Alps (Mezica area) VR of Triassic (Ladinian / Karnian) sediments is generally in the range of 0,8%R_r to 1.0%R_r, but reaches 1.6%R_r in the vicinity of Mt. Pohorje. Upper Cretaceous coal shows VR of ~0.7%R_r.

Southern Alps: Within the Southern Alps (South Karavanke Mts.) a stratigraphical dependence of VR can be recognized. VR of lowermost Permian shales is ~2,5%R_r and decreases to ~1.6%R_r within Carnian marls. Data from the Savinja Alps (Ladinian) and from the NW part of the Julian Alps (Tamar valley, Martuljek gorge: Karnian, Ladinian), show also values ~ 1.6%R_r. Note that the latter area is located south of the dextral Sava fault. In the northern and central part of the Julian Alps Carnian beds (Predil, Vrata valley, Beli potok) show significantly lower thermal overprint, which is indicated by VR (0,7–0,8%R_r) and Rock Eval data (T_{max} = 430°C), perhaps due to a Mesozoic paleo-high position, resulting in a small Jurassic to Paleogene overburden. A similar scenario was described by GREBER et al. within the Swiss Southern Alps.

Sava Folds / Slovenian basin: The highest thermal maturation occurs in the Sava Folds and the Slovenian basin. Middle Permian sandstones and middle Triassic (Ladinian) shales show VR values of 3.0–5.0%R_r, Jurassic / Cretaceous sediments show VR between 2.5 and 3.6%R_r, Upper Cretaceous marls E of Ljubljana ~2.4% R_r. In the easternmost part of the Sava Folds (E of Sevnica) the thermal maturation of Mesozoic sediments decreases (U.-Triassic: ~2.4%R_r, Lo.-Cretaceous: 1.5–1.8%R_r). Due to the high thermal overprint of Upper Cretaceous sediments in the central Sava

Folds / Slovenian basin and relatively low VR values of Oligocene sediments (0.4–0.6%R_r; SACHSENHOFER et al., 2001), a post-Upper Cretaceous and pre-Oligocene thermal overprint within this area is assumed. Lower maturation occurs SW of dextral, SE trending Idrija fault, where VR Ladinian and Karnian marls reach ~1.6%R_r and Lower Permian siltstones show ~2.3%R_r. The Idrija region is characterized by a complex nappe pile, which overthrusts Eocene sediments of the Adriatic carbonate platform. Eocene flysch is exposed at the surface in the vicinity of Idrija within several tectonic windows. Maturity of these marls is ~0.7%R_r and therefore it can be assumed, that the thermal overprint of the Permo-Mesozoic sediments of the nappes of the Idrija region predates the thrusting on the Eocene flysch.

Adriatic realm: VR of the Eocene flysch sediments in the northern part of Istria is about 0.5–0.7%R_r, Upper Cretaceous coal in that area shows VR of ~1.0%R_r. To the north (Soca valley), the flysch sediments get older (Paleogene, Upper Cretaceous) and the thermal maturation increases to ~1.5%R_r.

Dinaridic carbonate platform: South of the Sava Folds in the Dinaridic carbonate platform Permian sediments show VR between 2.1 and 2.6%R_r. Ladinian marls and Jurassic bituminous limestones (Vhrnika, Kocevlje region) show only slightly higher VR values (~2%R_r) than Upper Cretaceous marls (1.7%R_r). However, there is a break in coalification between the latter sediments and erosional remnants of Eocene age (Kalise area), which are characterized by only 0.7%R_r. This indicates that coalification of Permo-Mesozoic sediments occurred before the Eocene and that a several km thick pile of Upper Cretaceous to Paleocene sediments was removed.

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THERMAL MATURITY OF CARBONIFEROUS TO MESOZOIC SEDIMENTS AS A TOOL FOR PALEOGEOGRAPHIC RECONSTRUCTION IN THE ALPINE-DINARIDIC-PANNONIAN TRIPLE JUNCTION

Thomas Rainer & Gerd Rantitsch

Vitrinite reflectance has become the most widely applied parameter for quantitatively estimation of the thermal maturity of sedimentary rocks. Principles and techniques of vitrinite reflectance were originally developed for use on coal, and have been modified for use on organic matter dispersed in sedimentary rocks. In this study, vitrinite reflectance was performed by measurement of mean random reflectance (%Rr) in Carboniferous to Albian strata of the Southalpine Southern Karawanken Range and the Austroalpine Drau Range. Our purpose is to present a map showing the spatial pattern of vitrinite reflectance in the "Alpine-Dinaridic-Pannonian Triple Junction" (HAAS et al., 2000), involving the data of this study and data from LACZÓ (1982 a, b), IHAROSNÉ LACZÓ & VETÖ (1983), CLAYTON and KONCZ (1994), GREBER et al. (1997) and BALAZS & KONCZ (1999). A comparative interpretation of these data demonstrates the presence of domains characterized by a distinct thermal history. Extension during Norian to Liassic rifting formed an overall N-S trending basin of the South-Alpine realm and its northern prolongation (SCHMIDT et al., 1991) which is divided into a number of asymmetric basins separated by submarine highs. This is documented by abrupt lateral thickness and facies changes in the stratigraphic succession. Thermal maturity of Late Triassic strata is primary dependent on the heat flow and subsidence history. Therefore, thermal basin models can be used to constrain the thickness of Jurassic to Eocene overburden which is now eroded in this area. Consequently, the estimated amount of thickness gives evidence about the paleogeographic position of distinct tectonostratigraphic units.

Vitrinite reflectance values between 1.6% and 1.9%R_r in Carnian strata characterize the Southern Karawanken Range. In contrast, the eastern part of the Gailtal Alps, the western and central part of the Northern Karawanken Range and the northern margin of the Julian Alps show significant lower values between 0.8% and 1.0%. Vitrinite reflectance in the eastern part of the Northern Karawanken Range increases up to 1.6%R_r. Coalification in the Carnian overstep sequences of the Austroalpine Gurktal Range Complex is characterized by a west to east decrease of Rr from 1.2% to 0.8% (RANTITSCH & RUSSEGGER, 2000). This pattern is overprinted by coalification anomalies in the central part of the Gailtal Alps and along a dextral Riedel shear of the Periadriatic Lineament (Hochstuhl fault). These anomalies are attributed to post-tectonic events of strong heating during Oligocene and Miocene times. Vitrinite reflectance values in Late Carboniferous to Albian sediments are used to calibrate a numerical heat flow model of the Drau Range and the Southern Karawanken Range. Thermal alteration within the peripheral segments of the Drau Range (Northern Karawanken Range, eastern segment of the Gailtal Alps and the Dobratsch block and parts of the Lienz Dolomiten Range) is explained by a low heat flow of approx. 60 mW/m^2 during basinal subsidence and a pile of 1400 m Late Cretaceous to Eocene sediments on top of the exposed stratigraphic succession. In contrast, vitrinite reflectance in the Southern Karawanken Range is explained by an eroded overburden of ca. 3000 m Jurassic to Eocene sediments and a heat flow of approx. $60\ mW/m^2$.

Because the reconstructed thermal history of the Southern Karawanken Range is very similar to the thermal history of the northeastern part of the Generoso basin (western Lombardian basin, GREBER et al., 1997), these data give strong evidence for a deep basinal position of the Southern Karawanken Range during Jurassic to Cretaceous times. Furthermore, the model is consistent with the Jurassic to Eocene stratigraphic succession which is exposed within the Transdanubian Range, a Pannonian tectonic unit with facially and stratigraphic affinity to the Southalpine unit (KÁZMÉR, 1987). In the Pannonian realm, low vitrinite reflectance between 0.5% and $0.8\%R_r$ in Middle to Late Triassic strata of the Transdanubian Range and Zala Basin points to a lower thickness of Jurassic to Eocene sediments and therefore, to a platform position of these units. These values are compatible with the thermal model of the Drau Range and indicate a similar paleogeographic position. In contrast, vitrinite reflectance between 1.0 and $1.4\%R_r$ in Late Triassic sediments of the Mecsek Unit may be interpreted by a higher amount of Jurassic to Eocene sediments or by a higher heat flow at the time of maximum subsidence. The map showing the spatial pattern of vitrinite reflectance in the "Alpine-Dinaridic-Pannonian Triple Junction" suggests a paleogeographic relation between the Drau Range (Lienz Dolomiten Range, Gailtal Alps, Northern Karawanken Range), the Transdanubian Range and the Zala Basin during Jurassic to Eocene times. The proposed deep basinal position of the Lienz Dolomiten Range (SCHMIDT et al, 1991) and Zala Basin (KÁZMÉR, 1987) is not reflected by the data of this study. Accepting a close relationship between thermal maturity and sedimentary burial, vitrinite reflectance suggests a paleogeographic position of these units which includes only approx. 1400 m Late Cretaceous to Eocene sediments. In contrast, the Southern Karawanken Range is seen as an exotic block in its present tectonic framework with close affinity to a deep basin (Generoso Basin) of the Lombardian Basin.

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PALEOGENE SEDIMENTATION AND SUBSIDENCE OF THE HELVETIC SHELF (AUSTRIA, BAVARIA)

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The Paleogene Helvetic Shelf in Austria and Bavaria is characterized by a variety of siliciclastic and carbonate, pelagic and shallow water sediments. Especially the shallow water carbonates, which are characterized by ferrugination and glauconitization, are unique in the Eastern Alps. Carbonate particles are represented by coralline algae, nummulitid and orthophragminid foraminifera, ooids, and smaller foraminifera. The estimation of subsidence rates is based mainly on a correlation between the eustatic sea level chart and relative sea level changes, which are reconstructed from facies interpretations obtained from detailed carbonate facies analysis, paleoecological interpretations and literature data.

The Paleocene is characterized by pure siliciclastic Danian to Thanetian sediments, with first ferrugenic particles occurring in the Thanetian. These sediments are overlain by massive Thanetian algal limestones, which are characterized by the presence of glauconitization and the absence of ferrugination; they can grade locally into planktonic foraminifera-bearing limestones. Heavy ferrugination started in the Ypresian. Main ferrugenic particles are larger foraminifera and ooids. Glauconitization is particularly absent during the Ypresian. Only the Lutetian carbonate facies reveals a co-occurrence of glauconitization and ferrugination. The shallow water development is terminated by the end of the Lutetian. Pelagic sedimentation of the 'Stockletten' prevail during Bartonian to Priabonian time.

The described facies pattern can be related to tectonic events, sea-level changes and subsidence. The Paleocene of the Helvetic Zone in Austria and Bavaria is characterized by a low subsidence rate and a relative sea-level fall until the Thanetian. From the Thanetian to the Early Ypresian, a relative sea-level rise occurred, but the subsidence rate is still as low as during the whole Paleocene. Tectonism at the Paleocene/Eocene boundary (known as 'Laramide 3') caused an angular disconformity between Paleocene algal limestones and Eocene ferrugenic foraminiferal limestones. Some uplift is suggested by tectonic subsidence curves. During the Middle Ypresian, another relative sea-level fall and an increasing subsidence rate occurred. This regression is terminated at the Ypresian/Lutetian boundary, which corresponds to a major thrusting event within the Alpine orogen to the south. From the Lutetian to the Priabonian, the relative sea-level rose continuously, with a distinctly increasing subsidence rate starting at the Lutetian/Bartonian boundary. This subsidence event records the formation of a flexural foreland basin due to orogenic loading of the lithosphere.

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THE APPLICATION OF THE GIBBS-METHOD TO GARNETS FROM THE BASEMENT WEST OF THE TAUERN WINDOW (ÖTZTAL-STUBAI CRYSTALLINE COMPLEX, SCHNEEBERG COMPLEX): INFORMATION VERSUS PRECAUTION

Arno Recheis & Peter Tropper

The dominant amphibolite-facies Variscan and eclogite facies Alpine metamorphic event in the Austroalpine Ötztal Stubai basement complex (ÖSBC) and the Schneeberg Complex (SC) was studied on a large scale by means of interpretations of different zonation types in garnets in combination with *P-T* estimates, based on multi-equilibrium methods.

The Variscan metamorphic event can best be studied in the northwestern part of the ÖSBC, because further to the southeast, the grade of the subsequent Alpine metamorphic overprint increases, culminating in eclogite facies conditions in the SC. The investigations of the different types of garnet zoning yields two major groups of zonations: (1) continuous and (2) dicontinuous zoning types. The first type appears in most samples of this investigation, displays the typical "bell-shaped" elemental distribution with Ca- and Mn-rich cores and can clearly be related to the dominant Variscan overprint. The second type only occurs in samples from the southeastern part of the ÖSBC, adjacent to the Schneeberg Complex. This type is clearly related to the polymetamorphic history, thus providing informations about the Variscan and Alpine event. Furthermore almost all garnets display a Mn-enrichment in the rims, related to later retrogression. The Mn enrichment is strongest in the western part of the ÖSBC and decreases towards the southeast, thus samples adjacent to the Schneeberg Complex lack the Mn enrichment in the rims. The depth of this enrichment also shows a positive correlation with the diameter of the garnets.

The investigated metapelites contain the assemblage garnet + staurolite + biotite + muscovite + plagioclase ± kyanite ± sillimanite ± andalusite were used to reconstruct pressure and temperature conditions with multi-equilibrium methods. During the Variscan metamorphic event, kyanite was the stable Al_2SiO_5 polymorph, and conditions of 470–710°C and 4–9 kbar were derived for garnet rim compositions, whereas no regional P-T trend could be found for the Variscan metamorphic overprint. Adjacent to the Schneeberg Complex, pressures increase at 8–9 kbar due to the subsequent eclogite facies Eo-Alpine overprint. Textural and chemical data clearly indicate a continuous pre-Alpine and Alpine metamorphic evolution.

In a metamorphic system mineral composition is a function of pressure and temperature and therefore it is possible to model pressure and temperature by using mass balance considerations within a mineral assemblage and compositional variables. The calculation requires the compositions and modal proportions of the mineral assemblage and a starting condition, which has been obtained by thermobarometry (SPEAR 1993). The computer software GIBBS (SPEAR et al. 1991a) has been applied to six samples with variably zoned garnets so far. The obtained thermobarometric estimates for garnet rim compositions range from 469°C and 4.2 kbar to 630°C and 7.3 kbar and were used as starting conditions. The Mn-enriched rims were excluded from the calculations, when no definitive sign of growth zonation (e.g. decrease in CaO) occurred with the increase in MnO. The P-T path has been modeled with the compositions of the garnets by using X_{Alm}-X_{Gro}, X_{Alm}-X_{Spe} and X_{Sps}-X_{Gro} pairs as compositional variables. The results show no definitive answer. In most samples (Ö-492, Ö-526, 91-3), pressure increases with decreasing temperature in the first steps of the calculated path. Afterwards no general trend could be found. Two samples show an increase in pressure with temperature (II-91, P8-b), which is contrary to the results obtained BY TROPPER & HOINKES (1996), PERGHER (1997) and ZANGERL (1997). Sample 80-77 shows a decrease in pressure with a decrease in temperature, followed by a strong increase in pressure again. Since there is no information on the equilibrium assemblage during garnet growth because of the lack inclusion assemblages, the quantitative information obtained from these calculations must be considered with caution.

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DUCTILE TO BRITTLE FAULTING IN THE FOOTWALL OF THE BRENNER NORMAL FAULT AND ITS CONNECTION TO THE INNTAL STRIKE-SLIP FAULT SYSTEM (THE TYROL, EASTERN ALPS)

Franz Reiter, Rainer Brandner, Kurt Decker, Hugo Ortner & Gerhard Wiesmayr

The data presented derive from a regional structural geology survey covering a complete section through the western Tauern Window and adjacent Austroalpine Units carried out by order of the Brenner Base Tunnel Company (BBT) (compare DECKER et al., this volume).

Brenner fault and Silltal fault: The Neogene orogen-scale Brenner low-angle normal fault at the W margin of the Tauern Window (Fig. 1) is characterized by a several hundred meters thick mylonite zone (BEHRMANN, 1988; SELVERSTONE, 1988). Displacement continuosly decreases from the center of the Tauern Window towards the N and S (FÜGENSCHUH ET AL., 1997). The northern continuation of the mylonite zone between the Lower Austroalpine N of the Tauern Window and the Ötztal Crystalline Basement (OCB) is formed by a discrete brittle fault referred to as Silltal fault (BEHRMANN, 1988). Comparable fully brittle structures can be traced southwards into the Tauern Window (e.g. in the area of Gossensaß). The faults are assumed to operate during the late stage of orogen-parallel extension post-dating fission track cooling ages of about 13Ma (FÜGENSCHUH et al., 1997). Structural investigations at the Silltal fault near Innsbruck revealed that the fault continuously bends to NW-directed strike. Kinematic indicators in ultracataclasites indicate a Top SW normal movement on moderately SW-dipping fault planes. The Silltal fault is displaced by E- and N-striking high angle faults offsetting it by several tens of meters.

Normal faulting and subsequent folding in the footwall of the Brenner fault: The most prominent structures in the footwall of the Brenner fault in the Tauern Window are meso- to macroscale W-directed semi-ductile and brittle normal faults and tension gashes. Subordinate conjugate normal faults indicate E-W extension. Many of these fault sets on the northern limb of the Tux antiform indicate a post-extensional northward tilting in the order of 10-20°. We assume that the conjugates are not older than the zircon fission track ages (10-15 Ma, FÜGENSCHUH et al, 1997). The structures therefore may indicate continued updoming of the Tauern structure during or after the Late Miocene.

NE-striking sinistral ductile to brittle shear zones: Several NE-striking ductile to brittle shear zones with subvertical mylonitic foliation, 5-15° W-plunging stretching lineation and sinistral shear indicators were mapped on the northern limb of the Tux antiform. The shear zones commonly involve rocks of the "Altes Dach"-Complex acting as low-competence zones between the Zentralgneis units. Towards the Brenner normal fault the shear zones link up with SSW-striking oblique normal faults not penetrating the Brenner mylonite zone. Brittle (re-) activation of these shear zones with similar kinematics is indicated by slickensides paralleling the stretching lineation and cataclasites. These brittle faults cause minor displacement of the cover sequences. At this point of the study brittle

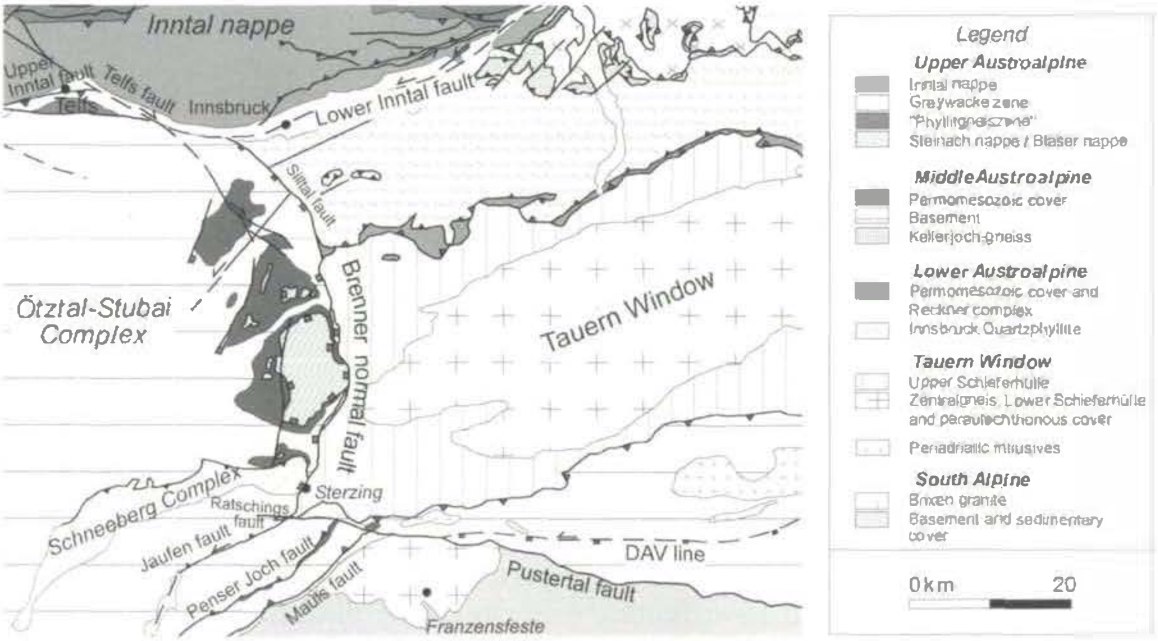

Fig. 1: Tectonic map of the western Tauern Window and surroundings

strike-slip faulting can be interpreted either as resulting from a continuous ductile-brittle deformation process during exhumation of the Tauern Window, or as a later reactivation of ductile shear zones. Due to the consistently W-dipping stretching and slickenside lineations the faults separate zones of higher exhumation in the south from zones of lower exhumation in the north. The ENE striking boundary between the Tauern Window and the Lower Austroalpine is overprinted by semiductile sinistral shear zones, which do not crosscut the Silltal fault. The jump in fission track ages from 16 to 35 Ma across this tectonic contact (FÜGENSCHUH et al., 1997) can be explained by faster eastward exhumation of the Tauern window with respect to the Lower Austroalpine Units. Both units apparently were uncoupeled by the described ENE-striking sinistral shear zones comparable to the "Tauernnordrandstörung" further east.

The Connection between the Silltal and the Inntal fault: Neogene northward movement of the Adriatic indenter caused both N-S contraction of the Tauern Window (which there was coeval with the activity of the Brenner normal fault), N-directed thrusting of the OCB at its northern margin, and S-directed back-thrusting along the southern margin of the OCB. The Upper Inntal fault can be regarded as a steepened thrust of OCB over the southern margin of the Northern Calcareous Alps (NCA). The regional trend and slip direction of the northern Silltal fault supports a kinematic link with post-Oligocene fault movement of the NE-striking sinistral Lower Inntal E of Innsbruck. Ultracataclasites of the Silltal fault are dissected by conjugate E-W-extensional faults and conjugate NNE- and ENE-trending strike slip faults. From the strike-slip faults we infer that the post-13 Ma extension at the Silltal fault (FÜGENSCHUH et al., 1997) was followed by a Late Miocene NE-directed contraction, which might be correlated with an E-W compressional phase at 9 Ma, previously documented for the Vienna basin and Eastern NCA (PERESSON & DECKER, 1997)

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SEMMERING BASE TUNNEL SITE INVESTIGATIONS: NEW INSIGHTS TO THE TECTONICS

Gunter Riedmüller & Peter Pölsler

The alignment of the Semmering base tunnel transects various major geological units at the north-eastern spur of the Eastern Alps. Proceeding from north to south, these units are the nappes of the Upper East Alpine Grauwacken zone, consisting of early and late Paleozoic, very low-grade metamorphosed sediments and volcanic rocks, as well as the nappes of the Lower East Alpine unit, consisting of a polymetamorphic basement with an Alpine metamorphic Permo-Mesozoic sedimentary cover.

The crystalline basement of the Lower East Alpine unit consists mostly of quartzphyllite. Its Permomesozoic sedimentary cover includes phyllite, quartzite, marble and rauhwacke. The Paleozoic sequence of the Upper East Alpine "Grauwackenzone" contains quartzconglomerate, meta-sandstone, greenstone, chloritic and graphitic phyllites with intercalations of anhydrite and gypsum.

Site investigations between 1988 and 1998, which include the evaluation of satellite images, geological mapping, core drilling, geophysical survey and the construction of a pilot tunnel have indicated the existence of two large thick-skinned, basement involved, thrusts within the Lower East Alpine tectonic unit. Each thrust sheet includes a thick inverted sequence of the sedimentary cover in the foot-wall and tectonically reduced, isolated remnants of the sedimentary cover in the hanging wall.

Furthermore, detailed mapping, trenching and core drilling revealed new information on location and tectonic architecture of the "Noric Overthrust".

The transport of the upper thrust sheet occurred along a northerly dipping, low-angle, shear zone which is dominated by clayey gouge, crushed quartzite, marble and rauhwacke.

Of great importance in view of the tunnel project are brittle high-angle faults which have generated gouge and intensely fractured rocks. Outcrop studies coupled with satellite images have shown that the pattern of brittle faults consists of strike-slip duplexes trending NNE-SSW, NE-SW and E-W. The youngest faults seem to be N-S striking extensional oblique-slip faults. Geometry and kinematics of the young brittle faults comply with the Neogene eastward extrusion of the Central Alps.

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EVOLUTION OF THE FRONT OF THE BERCHTESGADEN NAPPE COMPLEX – PRELIMINARY RESULTS

Martin Rittner, Michaela Lukesch & Hugo Ortner

The area of study is located next to Lofer and Unken (Salzburg, Austria), and comprises parts of the Reiter Alm area and Loferer Steinberge, as well as the Loferer Alm area and the Unkenbach valley, where Upper and Lower Juvavic units of the Berchtesgaden Nappe complex are thrust over Tirolic units of the Staufen-Höllengebirgsnappe.

In the Hallstatt limestones of the Lower Juvavic unit, slumping partly led to tilting and folding, which is indicated by geopetal fabrics.

In Aptian times (Early Cretaceous), Juvavic units were thrust upon the Lackbach-basin (correlates to the Roßfeld-basin). A strong argument in favour is the progradation of the submarine fans of the Lackbach Formation and the occurence of Late Jurassic limestone pebbles resedimented in conglomerates of the Lackbach Formation (Darga & Weidich, 1986). The Upper Jurassic Lärchberg limestone overlies the Hallstatt limestones of the Lower Juvavic unit. The Juvavic units continued to be transported and must have reached a position beyond the Unken Syncline. The thrust plane is not preserved due to later tectonics.

The Lower Juvavic units were folded into a large anticline trending SW-NE, but no detailed time constraints about this deformation could be found.

The Upper Juvavic units thrust over the Lower Juvavic units, and thus cut the fold obliquely, which resulted in a wedging out of the latter towards the East.

Pregosauic erosion removed the Late Jurassic shallow marine limestones (Lärchkogel and Plassen limestone) from the Upper Juvavic units in the area.

During Tertiary times, N-S trending normal faulting resulted in a juxtaposition of Lower Juvavic and Tirolic units. Slices of Lackbach Formation mark the fault plane.

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THE BRENNER BASE TUNNEL - GEOLOGY AND GENERAL TECTONICS

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The proposed Brenner Base Tunnel (55 km long) crosses the complete Central Zone of the Eastern Alps. In the north, the tunnel runs through the Lower Austroalpine Innsbruck Quartzphyllitzone, which mainly consists of phyllites with varying quartz contents and interbedded calcareous and dolomitic marbles, iron-rich dolomites, greenschists, graphitic phyllites and porphyroids.

These rocks are overlain by the Tarntal Mesozoic Unit (Triassic and Jurassic) metasediments, comprising quartzites, rauhwackes (karstified evaporites), calcareous and dolomitic marbles, breccias, metasandstones, schists, radiolarites and metamorphosed ophiolites (serpentinites, ophicalcites). The Tarntal Mesozoic Unit is also imbricated with the southern Quartzphyllites. This imbrication zone is, from a geotechnical viewpoint, very difficult; in particular, the serpentinites and rauhwackes will cause problems.

From the Navis valley, the planned tunnel traverses the nappes of the Tauern Window (in our working area, up to Pfitschtal – Val di Vizze). Directly underneath the Innsbruck Quartzphyllitzone is another imbricate zone (the Matrei Zone or Nordrahmenzone). In this zone, the Bündner Schists are imbricated with numerous fragments of Permo-Mesozoic rocks (dolomites, limestones, rauhwackés, phyllites of Keuper age, quartzites and conglomerates; possibly gypsum and serpentinite may also occur). On the one hand the Nordrahmenzone could be interpreted as a tectonical imbrication zone, on the other hand these rock fragments could be interpreted as olistoliths. The northern margin of the Tauern Window and the Innsbruck Quartzphyllitzone are mostly overprinted by very tight folds with steep axial planes, with a axial planar cleavage being the dominant fabric in the rocks.

The Nordrahmenzone terminates in the slopes south of the Navis Valley, and the rocks of the Tauern Window (Obere Schieferhülle - Glockner Nappe) become more and more homogenous. The predominant lithology in the Bündner Schists are calcareous phyllites, calcareous mica schists, black phyllites and some greenschists. However, the typical Glockner Nappe rocks (in Glockner–facies) occur south of the Pfitsch Valley (Val di Vizze); these are prasinites, metamorphic ophiolites and calcareous mica schists.

At the base of the Glockner Nappe, Permo-Triassic tectonic slices (mainly quartzites and carbonates) of different thicknesses occur. In our working area, they are mainly concentrated in the Schmirn Valley (Permo-Triassic of the Schöberspitze) and west of Kematen (Caminata) in the Pfitsch Valley. The Permo-Triassic rocks of the Schöberspitze (Schmirn Valley) dip in an upright south-vergent fold to west. In the south, the Permo-Triassic rocks form the Kalkwandstange (Cma. della Stanga) are striking along (dip steeply down to south) the Pfitsch Valley. This zone, at the base of the Glockner Nappe (possibly with heavily water saturated rocks) is one of the key zones in the Base Tunnel.

The footwall rocks are the Zentralgneiss-cores (various metagranites, migmatites, light and dark dykes) and the hanging wall comprises Permo-

Mesozoic metasediments. The northern core (Tux core) and the southern core (Zillertal core) are separated by the Greiner Syncline (paragneisses, mica schists, Furtschagel Schists, amphibolites, serpentinites, talc schists, carbonate rocks, ...), which is a complex synformal structure overprinted by shear zones.

North of the Tux core and separated from it by the Hochstegen Zone, lies the tectonically lowest Zentralgneiss-core, the Ahorn core. This does not crop out in the working area, because it plunges down to the west from the Tux Valley. However, the metasediments (between Tux and Ahorn core) may appear in the planned tunnel.

The Permo-Mesozoic metasediments of the Zentralgneiss cores mainly consist of quartzites, metaconglomerates, schists (Upper Carboniferous, Permo-Skythian), Triassic carbonates (calcareous marbles, dolomites, rauhwackes), Jurassic metasediments, Liassic black quartzites, Dogger brown marbles, and Malm Hochstegen Marbles) and the Lower Cretaceous Kaserer Series. The latter is a very variably composed succession of breccias, dark quartzites, black shales, calcareous schists and calcareous phyllites. The base is characterized by the occurrence of olistoliths and/or tectonic slices (Limestones, dolostones, rauhwackes, quartzites) of different grain sizes (few centimetres to a few metres). The metasediments are divided into two parts (FRISCH 1974): the lower Hochstegen Zone and the Wolfendorn Nappe. The Hochstegen Zone are more or less autochthonous metasediments overlying the Zentralgneiss cores. Above, separated by Triassic rocks, lies the Wolfendorn Nappe, the only unit containing the Kaserer Series. This series was probably detached from the Zillertal core.

The key zones by this tunnel project (only in the working area north of the Pfitsch Valley, the investigations south of the Pfitsch Valley were made by the working group from Padova) are nappe boundaries and imbrication zones:

- between Lower Austroalpine and the Tauern window,
- the so-called Nordrahmenzone (Matrei Zone),
- the base of the Glockner Nappe with the Permo-Triassic metasediment slices,
- the metasediments of the Hochstegen Zone and the Wolfendorn Nappe,
- and the complex Pfitsch Valley Zone (Greiner syncline and shear-zone) with paragneisses, mica schists, Furtschagel Schists, amphibolites, serpentinites, talc schists, carbonate rocks.

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SPRING TUFAS AND CEMENTED SLOPE DEPOSITS IN GORGES OF THE WESTERN NORTHERN CALCAREOUS ALPS, TYROL: AN INTERIM OVERVIEW

Diethard Sanders

In gorges of the western Northern Calcareous Alps (Tyrol, Austria), local spring tufas and associated cemented slope deposits correlate with both a vegetated drainage area beside the gorge and presence of (quasi-) perennial springs. Within the range of gorges observed, depth and length of gorge incision, drainage area, mineralogy of the carbonate rock substrate, and exposition all do not to exert an influence on tufa formation.

A total of fourteen gorges (status May 2001) incised into Triassic to Jurassic limestones and/or dolomites were checked. Several contained sizeable spring tufa formations and, locally, associated cemented talus or colluvium. A cross-check indicates that, aside the formation of spring waters supersaturated for calcium carbonate, the single most important factor for tufa formation is the presence of a (quasi-) perennial spring or sap. Presence of tufa-precipitating springs appears to be controlled by the permeability of the substrate, combined with conditions favouring the formation of spring waters supersaturated for calcium carbonate, such as water retention within vegetated soil.

Gorges flanked by barren rocky slopes or that bear a thin, patchy soil cover are devoid of tufas, irrespective of slope height. There, near the gorge base, dissolution of rock carbonate is common at saps, and typically produces small half-caves. Gorges with a vegetated, soil-covered flank drainage area, by contrast, are favourable settings for the formation of spring tufas. Tufa-precipitating springs or saps may discharge from soil-covered drainage areas very small, provided that the spring discharges over all or most of the year. The soil cover of vegetated flank drainage areas provides both water retention, enrichment with CO_2 and, as a consequence, enhanced calcite dissolution within the soil and in the underlying carbonate rock. In some of the gorges with spring tufas, glacial diamicton is present in the flank drainage area. The diamicton may promote both retention of water in the soil and provide a source for dissolved calcium carbonate. The tufas and their associated deposits typically are confined to, or dominantly present on, one flank of the gorge; this reflects combined controls such as tectonic structure, local geology and hydrology, and soil/vegetation cover.

The tufas are present as (a) perched spring-line moss tufas and microbial tufas that may be situated well-above the gorge base, and/or (b) as waterfall tufas (phytoclastic tufas, moss tufas, microbial tufas), and (c) as macrophyte tufas and/or moss tufas largely concealed below vegetation cover ("concealed tufas") closely above the water table of the gorge stream. Microbial tufas are characterized by a relatively even to botryoidal to digitate surface covered by organic mucus. Locally, spring tufas at least 1 meter thick are present, and comprise the cement to talus boulders up to a few meters in size. At one location, below a spring formed by excavation in 1966 of an artificial rock wall, moss tufa and microbial tufa precipitated; the moss tufa accreted at a minimum average rate of 5–8 mm/a.

The spring tufas are locally associated with talus or colluvium cemented by isopachous to microstalactitic crusts of calcite. Cemented talus aprons associated with spring tufas may be up to

at least 8 meters thick, and are locally incised by the present gorge stream. Spring tufas and associated cemented slope deposits thus provide a record of Alpine gorge development. Small occurrences of spring tufas are much more common than suggested by literature, but comparatively large tufa formations (including hitherto undescribed occurrences) are rare. All spring tufa formations found within gorges are presently active; no unequivocal example of inactive (subfossil) spring tufa has been found. Comparing documented rates of spring tufa formation with the thickness of the observed tufa formations suggests that at least most of them (and at least part thereof) may be up to only a few hundreds of years old.

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SEQUENCE DEVELOPMENT ON A HIGH-MOUNTAINOUS SUBSTRATE: THE HÖTTING BRECCIA (PLEISTOCENE, INNSBRUCK, AUSTRIA)

Diethard Sanders, Christoph Spötl & Ulrich Obojes

Following a Pleistocene glaciation, north of Innsbruck (Austria) a terrestrial clastic sequence sourced by its local, high-mountainous substrate accumulated, and consists of systems tracts each formed in response to changes in depositional system upon onlap onto and burial of high, steep rocky slopes and cliffs.

The sequence formed during the ?last Interglacial, and is underlain and topped by an unconformity each cut, largely, by glacial erosion. In the distal portions, the sequence locally rests on lodgement till topped by a thin loess layer. At most locations, however, including the medial and proximal parts of the succession, the substrate consists of Triassic carbonates and, at intermediate topographic height, of an outcrop belt of Permo-Triassic redbeds. Nowhere else in the area were redbeds exposed below the Hötting Breccia. The stratigraphically lower part of the sequence consists of an alluvial fan succession of debris-flow breccias and, subordinately, of stratified breccias/conglomerates and cross-laminated sandstones deposited from aqueous flows. In the lower part of the sequence, clasts derived from the redbeds are abundant. The fan succession dips a few degrees towards the south, and contains multiple intercalations of light-brown, carbonate-bearing sands and silts, interpreted as loess deposits. Both the loess intercalations and plant fossils (Murr, 1926; Gams, 1936) suggest an overall cool-temperate climate, possibly shortly after the Inn valley became deglaciated. Towards the east, the lower part of the sequence consists largely of conglomerates and conglomeratic breccias deposited from gravelly streams and, subordinately, of debris-flow breccias; debris-flow deposits similar to the western part (i.e. with a red-coloured matrix from erosion of redbeds) are rare, but become more common upsection. The lower part of the sequence constitutes a laterally continuous apron along the base of the former slope. To date, no depositional geometries or deposits suggesting persistent, stable channels, and no soil profiles have been identified.

The presence of conglomerates, breccias and sandstones deposited from aqueous flow, and their vertical association with debris-flow deposits suggests quasi-perennial to ephemeral (seasonal peak?) surface runoff. The lower part of the sequence was sourced by its immediately adjacent rocky slopes and cliffs, and probably consisted of laterally coalescing, small, unvegetated to scarcely vegetated fans with superposed, ephemeral channels.

Up-slope, both above the belt of Permo-Triassic redbeds and the onlapping fan succession, the sequence consists of a rock-fall megabreccia and/or of thick-bedded rudites (breccias to conglomerates) composed of clasts from the local substrate. The rudites are arranged in amalgamated stratal packages that formed from channelized flow within gullies, from sheet flows and, subordinately, from debris flows. This intermediate succession dips between 5-15°, and in its topmost portion interfingers with lithified talus aprons. In the intermediate succession, with the exception of extremely rare clasts of crystalline rocks (remnants of glacial deposits from the preceeding glaciation), all the clasts are derived from the immediately underlying Triassic substrate, including characteristic brown-weathering dolomitized limestones and cellular dolomites (Reichenhall Fm) and red, nodular lime mudstones (Schusterbergkalk Fm) exposed in the local substrate.

Near the contact with the substrate, both in the lower and middle part of the sequence saproliths, colluvium and small talus accumulations are locally present. Within the lower and middle part of the sequence a few, large clasts of lithified carbonate slope breccias suggest that, either, (local) lithification of breccias proceeded rapidly, or that erosional remnants of an older generation of slope breccias existed. At one location in the middle part of the sequence, in a succession at least a few meters thick of fine-grained deposits below the ruditic succession, a fossil flora is preserved. The composition of the flora is similar to mixed Alpine-deciduous floras that today are locally present, at similar altitudes, on hillslopes with southerly exposure. Two elements of the flora, however, may suggest an overall warmer climate than today (MURR, 1926; GAMS, 1936). The deposits with the plant fossils mainly are cream-coloured, chalky lime mudstones to siltstones. This location is now covered by vegetation.

The intermediate succession of mainly conglomerates and breccias deposited from (quasi-) perennial to ephemeral surface runoff suggests a climate of similar to lower or more seasonally distributed precipitation than today. The composition of the succession of clasts derived from the local substrate, and the vertical association of gully deposits, sheet flow deposits and debris-flow deposits, and the 5–15° dip strongly suggest that the succession accumulated in the basal to lower part of talus aprons that were strongly overprinted by channelized and unchannelized surface runoff. The fine-grained deposits with the plant fossils, if penecontemporaneous with the ruditic succession, may have accumulated in a small lake or pond beside the talus. Similar lake-talus facies associations are locally present at high altitudes in the Northern Calcareous Alps today.

The stratigraphically and topographically highest part of the sequence consists of thick, lithified talus aprons that steepen from 10–15° in their lower part to 35° and, locally, 40° at their head. The downslope part of the talus successions is characterized by extremely poor to poor sorting (gravels to boulders), common presence of matrix, variable bed thickness and, locally, poorly defined bedding, variable bed dip/strike, cut-and-fill structures, and by local large-scale foreset-bedding. Upslope, in the steeper-dipping middle part of the talus, bedding becomes regular and planar. The middle and upper portion of the talus succession is characterized by (a) beds of moderately to well-sorted gravels to cobbles with „openwork“ fabric, cemented by calcite, and (b) fewer beds, commonly poorly to very poorly sorted, of clast-supported gravels to cobbles, with a matrix of mixed carbonate siltstone to mudstone. Upslope, both the openwork beds and, to a lesser degree, the matrix-rich beds are generally better sorted and grade into moderately to well-sorted, coarse to medium gravels; bedding becomes still more regular and even.

The talus succession probably was fed from a periglacial s.l. environment with seasonal freezing. The openwork beds probably formed by dry grain sliding and particle creeping; at least many of the beds with matrix were deposited from debris flows. The talus breccias locally prograded over the underlying succession. “Grèze litée” suggesting deposition of the talus successions by nivational processes and/or from solifluction lobes was not identified.

Each of the described depositional systems from alluvial fans to talus slopes represents a distinct geomorphic stage with a specific position within the sequence, and with specific depositional geometries, stratal dip, stratal packaging and lithologies related to sequence development and, hence, is regarded as a systems tract. When the rocky slopes were largely exposed, during deposition of the lower systems tract of the sequence, debris-flow dominated deposition and deposition from (ephemeral) gravelly streams prevailed near the toe-of-slope ahead. When the Permo-Triassic redbeds were buried by onlap, deposition in ephemeral gullies and from sheet flows prevailed in the basal and lower part of a developing talus apron. This intermediate systems tract, in turn, provided the foundation for the buildup of the aggradational to progradational talus aprons that constitute the upper systems tract of the sequence.

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THE RELEVANCE OF BRITTLE FAULT ZONES IN TUNNEL CONSTRUCTION – LOWER INN VALLEY FEEDER NORTH WITH A VIEW TO THE BRENNER BASE TUNNEL

Thomas Sausgruber & Rainer Brandner

Zones of rock deformed under brittle conditions greatly influence underground construction projects, especially in the case of deep lying tunnels, where they cause large problems, above all when they have a high water permeability. In some cases a further advance is no longer feasible, without measures to reduce the water pressure, from a tunnel engineering point of view or due to an unassessable residual risk. For the geologist, the difficulty is, when using the results of the surface mapping, to predict the geomechanical properties and groundwater conditions to the tunnel level depth.

The Lower Inn Valley in the Tyrol, in the Eastern Alpine region, Austria, contains a major fault zone. The fault zone originated as early as in the Upper Cretaceous in the course of the formation of the Gosau Basin. The ensuing formation of the Lower Inn Valley Tertiary Basin and further sinistral strike-slip faulting in the Miocene, which is cut by local younger dextral strike-slip faulting, characterise the Lower Inn Valley Fault Zone. Also, recent seismic activity in the Zirl – Wörgl area is a proof of ongoing tectonism in the region.

The planned railway project Munich – Brenner – Verona runs approximately 40 km subparallel to the Inn Valley and crosses many faults which constitute the Inn Valley Fault Zone. During the construction of the reconnaissance tunnels in the Lower Inn Valley, geological conditions were encountered which led to serious tunnel engineering problems. Fundamentally, the problems involved fault zones made up of different types of brittle deformed rock. There are two factors of significance when considering the geomechanical properties of the faults:

1. Rheology:
   Depending on the host rock, pure brittle deformation gives rise to breccia, namely kakirites. In the case of rigid carbonates - massive rock with great compressive strength - cohesionless zones of soft rock are formed. When slaty or foliated rock of low compressive strength, such as slates or phyllites are involved, slightly cohesive soft rock is formed.
2. Age of the faults:
   Geologically older fault breccia is in general cemented. Young to recent fault breccia are frequently superficially healed and thus comprise zones which are technically hard to construct in. In principle, it can be stated that the degree of cementation of a kakirite determines its geomechanical and hydrogeological properties.

Examples:
Cataclasites:

In the Vomp East Reconnaissance Tunnel, around Station 670 m, at the southern tectonic margin of the Inn Valley Nappe, in the so called Vomper Bach Imbrication Zone, several cataclasic zones were intersected in Wetterstein Dolomite. It is assumed that these thrust faults date back to the Cretaceous, with a later reactivation of these now steep dipping faults presumably occurring into the Miocene (reconstruction of the

Fault Zone Types	Host Rock	Age of Fault	Geomechanical Characteristics	Groundwater Conditions
Cataclasite	Dolomite	Cretaceous to Miocene	Consolidated, cemented fault breccia	Increased jointing results in increased water ingress
Type 1 Kakirite	Phyllite	Cretaceous to Miocene	unconsolidated fault breccia but with cohesive soft rock character	Fault breccia frequently has an impermeable character
Type 2 Kakirite	Gypsum-bearing carbonates	young or recent	Lixiviated zones + unconsolidated almost cohesionless fault breccia made up of sand and gravel sized grains	Highly permeable fault zones with large water supply under pressure

Table of Fault Zone Types

paleo-stress directions based on movement criteria).

As the mentioned faults are well cemented, there was no significant geomechanical deterioration. Deformation measurements within the tunnel showed no significant increase. There was, however, increased water ingress which was attributed to the increased amount of fractures and joints within the zone.

Kakirites:

Type 1 Kakirites

Tectonically sheared Wildschönau Phyllites, at Station 1050 in the Brixlegg East Reconnaissance Tunnel, comprised a zone of cohesive soft rock. In the zone, groundwater conditions were defined as damp. Due to the composition of the host rock, the fault had an impermeable character. It was possible to knead the material of the fault zone by hand. The rock mechanical behaviour was squeezing, with deformation slowly subsiding after several months. From a geologically point of view it is a normal fault. At the fault boundary, Paleozoic Wildschönau Phyllites are in contact with Mesozoic carbonates of the Partnach Formation.

Type 2 Kakirites

At Station 2274 in the Brixlegg East Reconnaissance Tunnel, a kakirite zone was encountered when drilling an anchor hole in the left-side tunnel wall. A major water ingress (kf~1xE-04 and 5 bar) resulted, with the flushing out of sand and gravel sized material. Consequently, for safety reasons, tunnelling was discontinued. In engineering terms, after a very thorough and costly investigation, it was determined that the fault zone consists of almost cohesionless soft rock. To date, it has not been possible to consolidate the rock using injection methods, while maintaining the water pressure, to such an extent as to be able to resume tunnelling.

The genesis of the fault can be attributed to the ss-parallel leaching in the Raibler strata. As the fault is not cemented, it appears to be of a young age. The formation of the fault is seen as a cataclasis of the lixiviated zones in connection with seismic activity along the Inn Valley Fault, with no large-scale movement occurring.

These examples show that for large engineering projects and especially deep tunnelling projects, knowledge about brittle fault zones and their condition, as consolidated, cohesive or cohesionless zones of soft rock is of the utmost importance and can be decisive for the technical and economic feasibility of a project. With regards to future deep lying tunnels in Austria, and in particular the Brenner Base Tunnel, it is recommended to investigate closely the fault zones by means of direct and indirect methods, after the surface structural geological mapping has been carried out, in order to gain the best possible picture of the geology at the relevant depth.

Cohesionless fault breccia can for instance be expected in the southern section of the Brenner Base Tunnel where recent shearing has led to the displacement of the prominent Puster Valley Fault (part of the Periadriatic Fault; see Bistacchi et al., 2001). The cataclasis zone here consists of the carbonates and the evaporites of the Eastern Alpine Crystalline Basement, the Mauls Tonalite Lamella and the Brixen Granite.

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MASS MOVEMENTS AT THE BORDER BETWEEN THE NORTH-WESTERN TAUERN WINDOW AND THE LOWER AUSTROALPINE UNIT
CASE STUDIES OF GEOTECTONICALLY INDUCED MASS MOVEMENTS

Manfred Scheikl, Lukas Pergher & Ulrich Burger

Introduction

Slope instabilities in the north-western frame of the Tauern Window (Austria) in several locations have damaged infrastructural facilities. Extensive investigations were subsequently conducted to determine the reasons for these recent mass movements. A survey was carried out which not only included geomorphologic analyses, but which furthermore – based upon a structured standard legend (SCHEIKL et al. 2001) – looked into hydrologic/hydrogeologic, petrologic, lithologic aspects especially focusing on tectonic and geotechnic conditions. Features such as the current situation of slope water and the system condition of water courses were explored, and a correlation between the locations of recent slope failure patterns and nappe-tectonic boundaries, including associated faults and resulting geotechnical rock properties was found.

Methods

For the investigation, diverse methods were applied. In a first step stereographic infrared pictures taken by an airplane-based system were used to document slope failure structures of overriding importance. In a next step, extensive fieldwork was done to produce detailed maps, which were post-processed by means of a special CAD-based standard legend, developed for geomorphologic investigations. For each specific situation, maps which thematically combine morphologic, hydrologic, hydrogeologic, petrologic, lithologic and tectonic data were elaborated. Lithostructural data were processed and visualized using the "Tectonics FP" computer program. Additional 3D-visualisations of the mass movement system including all collected data helped to understand the complex situation.

Case studies

The area under investigation lies at the north-western edge of the Tauern Window between the Glockner Nappe and the Lower Austroalpine unit. The Glockner Nappe is thought to be a continuation of the Penninic unit of the Western Alps. In the course of the Tauern Window uplift and associated erosion processes, the Tauern Core complex was exhumed. The rocks of the Tauern window were subject to both ductile (deformation at high differential stress in combination with high ambient pressure) and brittle deformation (NEUBAUER et al. 2000). The deformation process as a whole produced large-scale structures such as dipping folds as well as small-scale structures occurring as isoclinal small folds and micro folds. Microscopic analyses revealed the presence of recrystallisation and crenulation fabrics.

The large-scale structures, which developed in the course of the multi-phase deformation history, are overprinted recent mass movements, which are reflected by prominent sagging structures and crack zones. These processes occur in the form of active hard and soft rock creep bodies, which endanger inhabited and agricultural areas as well as infrastructural facilities (roads, power supply lines, and water pipelines). Analyses of the large-scale tectonic and morphologic structures revealed that the main slope failure zones in the area of the Stinkbach-Lackenbach system (Gerlos valley, Austria) largely correlate with the location of the tectonic boundary between the Glockner Nappe and the Lower Austroalpine unit. The pronounced opening of cracks leads to surface water infiltration, which significantly influences the slope water situation and consequently reduces the slope stability. An impact on the slope or mountain water condition by a nearby, shut-down and structurally weakened water pipe may also not be ruled out.

Another example of a recent mass movement in a comparable area at the north-western edge of the Tauern Window is in the Gerlos valley (Austria), near the "Ötschenwirt" (B165 federal road).

Apart from large-scale tectonic structures, this mass movement is characterized by quaternary sediments, as well as by a sequence of carbonatic middle triassic rocks overlying rocks of the Wustkogelserie and rocks of the Bündnerschieferserie, arranged in a system of hard rocks topping soft rocks known as "System Hart auf Weich" (R. POISEL & W. EPPENSTEINER, 1989).

Following the border between the Penninic Nappe and the Lower Austroalpine unit, the Navis valley is reached. The slope below the "Miesljoch" and the "Mieslkopf" is also subject to current processes of mass movements, endangering a residential area.

Even if the geotectonic situation in this area appears to be far more complex than in the Gerlos valley, the general situation may still be compared from the mass movement and general tectonics point of view.

Summary

In the vicinity of large-scale tectonic structures along the border between the Penninic Nappe and the Lower Austroalpine unit at the northwestern Tauern Window, several mass movements have been observed. A thorough analysis of local scenarios clearly illustrates the close correlation between tectonic boundaries and slope instabilities. Large-scale tectonic structures go hand in hand with rocks exhibiting critical geomechanical properties. Micro-scale and macroscale anisotropies in combination with adverse factors in the given geotectonic setting encourage slope instabilities.

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EO-ALPINE TRANSPRESSION IN THE AUSTROALPINE CAMPO CRYSTALLINE COMPLEX (NORTHERN ITALY)

Dirk Scheuvens, Timo Krass & Oliver Schwarz

In the central Alps, the Austroalpine nappe stack is characterized by large basement exposures (e.g. Ötztal crystalline complex, Campo crystalline complex) and smaller areas with Permomesozoic cover units (Ortler nappe etc.). Kinematic, petrological and geochronological investigations clearly reveal a multi-episodic evolution during Alpine orogeny with Cretaceous high- to medium-pressure metamorphism and nappe stacking, subsequent cooling accompanied by latest Cretaceous low-angle detachment faulting and renewed Oligocene compression with an important backthrusting component in the south. The Cretaceous nappe stack is interpreted as a westward propagating orogenic wedge resulting from collision following subduction of the Meliata-Hallstatt oceanic domain. The presented models for the central Alps mostly result from investigations of the Ötztal crystalline complex and its surroundings whereas the southern Campo crystalline complex has achieved considerable attention only recently.

We have performed detailed mapping in the western part of the Campo crystalline complex (area around Passo di Gavia) to get new insights into the petrostructural evolution of this part of the Austroalpine nappe system. The Austroalpine basement rocks of the study area are positioned immediately below (i.e. in the footwall of) – but are generally unaffected by – the late Cretaceous ductile to brittle Peio fault zone. The low-angle sinistral transtensional Peio fault separates the Campo crystalline complex with Alpine cooling ages in the footwall from the Tonale unit with largely Variscan cooling ages and only a weak Alpine overprint in the hanging wall. Hence, the investigated area represents one of the southernmost Austroalpine areas within the central Alps where deeper crustal processes during eo-Alpine convergence can be studied.

The study area comprises four major units which generally dip moderately to the south. From the base to the top these are a quartz phyllitic unit with abundant lenses of marble, actinolite schist, and acid orthogneiss, a mica schist unit I with conspicuous horizons of albite porphyroblast schists and high amounts of tourmaline, a staurolite-bearing mica schist unit II associated with large bodies of a hornblende-bearing orthogneiss, and a sillimanite-bearing paragneiss unit. The units are variably metamorphosed with metamorphic grade increasing from greenschist facies in the north to amphibolite facies in the south. Both rocks of the lowest and the highest unit of the structural pile exhibit a main foliation S_2 that monotonously dips moderately to shallowl to the S. The main foliation of the quartz phyllites is cut by discordant (?Permian) mafic dykes, whereas the main-foliation of the sillimanite-bearing rocks is cut by partly undeformed pegmatites which have been dated at c. 314 Ma (Thöni 1981). Both magmatic events can be used as time markers and confirm that the main foliation-forming event is Variscan in age (or older). However, mica schist unit I and II show a much more complicated structural record which will be outlined below.

In the area around Passo di Gavia the Variscan foliation S_2 is affected by a folding event D_3. In mica schist unit I, several flexure zones occur where the moderately S dipping foliation S_2 is bent into a steep position. The W-E striking "steep zones" represent high-strain zones that reactivate the main foliation S_2 and show prevailing S>>L fabrics (stretching or mineral lineation largely absent). Outside the shear zones mica-rich layers exhibit a mainly subhorizontal WSW-ENE trending crenulation lineation that is interpreted to be contemporaneous with large-scale bending of the main foliation. The crenulation lineation is locally refolded by cm- to dm-sized tight folds (D_4). In between closely spaced steep zones F_4 fold axes scatter in orientation defining an indistinct small circle with a centre at c. 330/70. Under the microscope, both F_3 and F_4 folds are characterized by dominant subgrain rotation recrystallization of quartz, by polygonization of micas within the hinge zones and a lack of recrystallization of feldspar suggesting upper greenschist facies conditions during D_3 and D_4.

Within mica schist unit II post-D_2 deformation is even more intense. The most conspicuous feature are large-scale non-cylindrical synclines, which are correlated with the D_3 flexure zones further to the N. The synclines are characterized by moderately S dipping long limbs (including parasitic folds with "S" geometries; view to the E), steeply oriented short limbs and undulating but mainly WSW-ENE trending fold axes. Anticlines are generally suppressed by W-E striking steeply dipping zones of intense folding and shearing resembling „flower structure"-like geometries. The steep shear zones exhibit mineral lineations that either show a pitch of more than 80° (type I shear zones) or are oriented subhorizontally and trend W-E (type II shear zones). Shear-sense indicators reveal both S-side-up and S-side-down kinematics for type I shear zones and sinistral kinematics for the type II strike-slip zones. Sinistral shear zones are phyllonitic in appearance and rarely overprint shear zones with a vertical displacement vector. Under the microscope microstructures in both types of shear zones point to (upper) greenschist to lower amphibolite facies deformation conditions.

The age of D_3 and D_4 folding and shearing is younger than the emplacement of late- to post-Variscan intrusives but older than exhumation and cooling of the Campo basement in late Cretaceous times, and therefore can be tentatively attributed to an eo-Alpine orogenic event.

The described tectonic inventory of the western part of the Campo crystalline complex (coherent low-strain blocks with large-scale non-cylindrical N-verging folds and mainly subhorizontal fold axes separated by steeply dipping high-strain zones with variable kinematics) is attributed to pure-shear-dominated transpressional shearing during eo-Alpine convergence. The different kinematics in shear zones with a vertical displacement component and the strong undulation of fold axes are probably the result of vertical extrusion of material and rotation of material lines towards a vertical orientation. The late sinistral shear zones are interpreted to result from an anti-clockwise rotation of the direction of convergence causing a switch from pure-shear-dominated to sinistral wrench-dominated transpression.

Eo-Alpine sinistral transpression within the more southern positioned part of the Austroalpine nappe system (in present-day co-ordinates) is in accordance with the geodynamic model of FROITZHEIM et al. (1996) which proposes a large-scale sinistral wrench fault at the southern edge of the Austroalpine unit separating the westward propagating Austroalpine wedge from the largely undeformed South Alpine unit.

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PERMO-TRIASSIC SEDIMENTARY RECORD AND CONTEMPORANEOUS THERMAL BASEMENT EVOLUTION IN THE DRAUZUG-GOLDECK-KREUZECK AREA (EASTERN ALPS / AUSTRIA)

Ralf Schuster & Peter Faupl

In the Austroalpine unit the primary relationship of the Permo-Triassic cover series to their original middle and lower crustal basement have been widely obliterated during the Alpine orogenetic events. Large parts of the sediments have been stripped off as cover nappes or cover nappes with the upper portions of their basement. These cover nappes experienced only a weak Eo-Alpine thermal imprint, whereas the remaining basement was effected by a metamorphic imprint of various grade.

The Permo-Triassic Tethyan sediments of the Austroalpine unit document an evolution from a fluvial to a shallow marine and, finally, to a carbonate platform environment. The sedimentary piles reach up to more than 3000 m in thickness and argue for a more or less continuous subsidence of the basement. On the other hand, a widespread Permo-Triassic high temperature/low pressure (HT/LP) metamorphic imprint of various grade has been recognised within the Austroalpine crystalline units (SCHUSTER et al., 1999; THÖNI, 1999). The relationship between the sedimentary and subsidence history of the cover successions and the contemporaneous metamorphic and thermal evolution of the crystalline basement has not been worked out until now. In this paper preliminary results from the Kreuzeck-Goldeck-Gailtal area are presented. There a section through a Permo-Triassic middle and upper crust up into the contemporaneous sediments has been preserved. The sediments are represented by the Drauzug Mesozoics, whereas the basement towards the north comprises, from top to the bottom, the Goldeck, Gaugen and Strieden Complexes.

The Gailtaler Alpen are a segment of the Permo-Mesozoic Drauzug (LEIN et al., 1997). An idealised section through the sediments is 3250 ± 250 m in thickness (BECHSTÄDT et al., 1976). The fluvial part is about 170 m thick and comprises the Permian sediments (Werchzirm and Griffen Formation) which contains layers of Permian quartzporphyric volcanic rocks, and the Skythian Buntsandstein Formation. The marine environment of the clastic Werfen Formation established at c. 245 Ma. In the Anisian a restricted shallow water environment is indicated by the Alpine Muschelkalk Formation. The Werfen and the Alpine Muschelkalk Formation together are ca. 500 m in thickness. The development of the Wetterstein carbonate platforms and intraplatform basins starts in the Ladinian (c. 235 Ma) indicating an open marine environment. These platforms comprise c. 1200 m of shallow water sediments. After a regressive phase in the Carnian, which is expressed by the terrigenous influence in the Raibl Formation, a second carbonate platform stage can be recognised. In the Gailtaler Alpen it is represented by the lagoonal Hauptdolomit, Plattenkalk, Kössen and Oberrhätriffkalk Formations. The thickness of the Norian and Rhaetian carbonates is about 1400 m.

The Permo-Mesozoic sediments transgressed unconformably onto the Gailtal Crystalline basement in the south and onto the Goldeck Complex in the north. The latter consists of phyllites with intercalations of chlorite schists and marbles that exhibit a prograde Variscan lower greenschist facies imprint (DEUTSCH, 1977). The underlying Gaugen Complex is dominated by coarse-grained micaschists and biotite-plagioclase gneisses with minor orthogneisses, amphibolites and marbles. It experienced a prograde Variscan medium-grade imprint and a retrograde overprint of very low to low-grade conditions. In the Strieden Complex two pre-Alpine metamorphic events can be identified: (1) A Variscan imprint reached upper greenschist facies conditions in the structural upper part and amphibolite facies conditions at medium pressures in the lower part. (2) The overprinting Permo-Triassic event shows HT/LP characteristics and a zonation with structural depth. In the uppermost part of the section features of the second imprint are scarce. Below an andalusite-zone, an upper sillimanite zone and a lower sillimanite-zone zone with partial anatexis can be observed (HOKE, 1990). Pegmatites are obviously related to this thermal event because they occur only in the lowermost andalusite zone and within the sillimanite zone. Peak metamorphic conditions occurred at 260 ± 20 Ma. Based on metamorphic grids peak conditions of 550 ± 50°C at 0.35 ± 0.1 GPa and 650 ± 50°C at 0.45 ± 0.1 GPa can be expected for the andalusite-zone and the sillimanite-zone respectively. The cooling history of the rock pile was investigated by Ar-Ar and Rb-Sr ages on muscovite and biotite. The Ar-Ar plateau ages on muscovite, which are interpreted as cooling ages below c. 400°C exhibit Variscan ages (RS7/00: 316 ± 4 Ma; RS8/00: 311 ± 3 Ma; RS24/00: 312 ± 3 Ma) below the transgressive Permo-Mesozoic sediments and decrease with structural depth. From the garnet-muscovite-schists 287 ± 2 Ma (RS55/99) and 286 ± 2 Ma (RS58/00) were determined. Staurolite-garnet micaschists yielded 225 ± 3 Ma (RS4/00) and 210 ± 2 Ma (RS14/97), whereas 212 ± 2 Ma (RS69/00) and 205 ± 2 Ma (RS13/97) have been measured for the andalusite-zone. The lowest age of 193 ± 2 Ma (RS43/00) has been found in the sillimanite-zone.

Based on these data an idealised rock column from the surface to about 15 km crustal depth and its evolution can be reconstructed: The Variscan metamorphic rocks cooled down below 400°C at about **310 Ma**. During the Permian, extension of the lithosphere caused condensation of the isotherms and a HT/LP metamorphic imprint. Peak metamorphic conditions occurred at c. **260 Ma** at an elevated geothermal gradient of c. 40°C/km. This gradient implies that the normal MOHO temperature of c. 800°C has already been reached at about 20 km depth. Heating caused intense magmatic activity expressed in pegmatites and volcanic rocks. Subsequently the rock column started to cool down to the steady state geotherm. At c. **245 Ma** a marine environment developed, indicating an isostatic equilibration of the lithosphere at sea level. After that a more or less continuous subsidence is indicated by the sedimentation of c. 3000 m of shallow water sediments. Ongoing extension, cooling of the lithosphere and thickening of the lithospheric mantle have been responsible for this subsidence, whereas loading with sediments had an opposite effect. At c. **200 Ma** a geothermal gradient of about 25°C/km has been reached and the rocks of the former andalusite and sillimanite zone cooled down below 400°C.

The crustal sequence described is not a unique situation, it represents the typical evolution of the southern part of the Austroalpine unit. This is indicated by comparable thicknesses of the sedimentary piles and by the widespread occurrence of the Permo-Triassic thermal imprint.

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INDICATIONS FOR A PERMO-TRIASSIC METAMORPHIC IMPRINT IN THE AUSTROALPINE SILVRETTA NAPPE (EASTERN / ALPS)

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In the past years a widespread Permo-Triassic high temperature/low pressure (HT/LP) event of various grade has been recognised within crystalline rocks of the Austroalpine unit (SCHUSTER et al., 1999). In this abstract we discuss indications for this event in the Austroalpine Silvretta Nappe. The study is based on data from the literature and new Ar-Ar age determinations which demonstrate striking analogies to the Austroalpine unit in the Kreuzeck-Goldeck-Drauzug section c. 50 km in the east.

In the Kreuzeck-Goldeck-Drauzug section a more or less continuous section through a Permo-Triassic middle and upper crust, up into the contemporaneous sediments has been preserved (SCHUSTER & FAUPL, 2001). The HT/LP imprint shows a characteristic zonation expressed in mineral assemblages, the occurrence of pegmatites and typical cooling ages for different structural levels. From the petrological point of view a sillimanite-zone with local anatexis, an andalusite-zone and a zone of preserved Variscan assemblages can be distinguished from bottom to the top (HOKE, 1990). Synmetamorphic pegmatites are frequent in the sillimanite-zone and die out in the andalusite-zone, where andalusite-quartz veins occur within staurolite and garnet-rich layers. With respect to ductile deformations of the magmatic feldspars the pegmatites exhibit syn- to postintrusive deformation at temperatures of more than 500°C. Formation ages of the pegmatites, are 260 ± 30 Ma. Ar-Ar cooling ages on muscovite from the pegmatites and the surrounding schists, which are interpreted as cooling ages below c. 400°C, yield plateau ages of 190 ± 10 Ma. Those from the andalusite zone are 210 ± 10 Ma. Going upward in the section plateau-type Ar-Ar cooling ages increase up to c. 270 Ma until saddle-shaped age spectra with total gas ages of 270 to 310 Ma occur. Rocks below the transgressive Permo-Mesozoic sequences of the Drauzug experienced less than c. 400°C during the Permo-Triassic thermal event and exhibit Variscan Ar-Ar plateau ages of c. 310 Ma. The sequence is interpreted as the result of Permo-Triassic lithospheric extension, subsequent thermal relaxation and sedimentation of the cover series (SCHUSTER & FAUPL, 2001).

For the Silvretta Nappe literature with important implications for this study and/or geochronological cooling ages exist from HOERNES (1971), GRAUERT (1969), THÖNI (1981), KRECZY (1981), AMMAN (1985), FLISCH (1986) and SPIESS (1987). Based on the literature pegmatites postdating the Variscian structures occur along the eastern limit of the unit. They are embedded within sillimanite-bearing gneisses and micaschists. Sillimanite in this eastern part is younger than Variscan kyanite, postkinematic with respect to the Variscian deformation and growing by the breakdown of pre-existing garnet and staurolite (AMMAN, 1985). At present no reliable formation ages of the pegmatites are available. Ductile deformation of magmatic feldspars indicates deformation at temperatures of more than 500°C. K-Ar cooling ages of muscovites from the pegmatites and the surrounding schists are 144, 160, 174, 184, 199 and 207 Ma. New Ar-Ar ages yielded 191 ± 2 and 189 ± 2 Ma. Towards tectonically higher levels in the north and west, no more pegmatites can be observed and the K-Ar and Ar-Ar cooling ages are increasing. E.g.

northwest of Galtür an Ar-Ar plateau age of 246 ± 2 Ma was determined on an orthogneiss muscovite. However data of this zone are scarce. In the southwest and in the north the Silvretta Nappe is locally transgressed by Carboniferous and the widely developed Permo-Triassic sedimentary piles of the Ducan and Langwasser synclines and the Northern Calcareous Alps. Ar-Ar ages on muscovite and Rb-Sr ages on biotite from the crystalline basement below the transgressional contacts yield Variscan cooling ages of about 310 ± 5 Ma respectively 290 ± 15 Ma.

Until now geochronological ages below 280 Ma have been interpreted as Variscan ages partly reset by an Alpine overprint. Several arguments argue against this interpretation: If the muscovite K-Ar and Ar-Ar ages represent Alpine overprinted ages, a stepwise pattern with low-temperature ages close to the overprinting event would be expected. However even the Triassic and Jurassic Ar-Ar cooling ages exhibit plateau-type pattern without steps of Alpine ages of c. 90 Ma. On the other hand if the Ar-Ar system of the muscovites would be partially reset, temperatures close to 400 °C, would be indicated for the Alpine overprint. In this case totally or nearly totally reset Rb-Sr ages of biotites would be expected because of the lower closure temperature of about 300°C for this isotopic system. However from thirtyone age data the five lowest are 124, 173, 181, 182 and 196 Ma.

Conclusions: The Silvretta Nappe represents a crustal block with a prominent Variscian structural and metamorphic imprint (e.g. HOERNES, 1971; GRAUERT, 1969). During Permo-Triassic times (at 260 ± 30 Ma) an elevated geothermal gradient caused a HT-LP imprint. At middle crustal levels sillimanite-bearing assemblages developed and pegmatites were emplaced. Subsequent cooling to the steady state geotherm produced a characteristic pattern of Ar-Ar muscovite ages. They are ca. 190 Ma in the sillimanite-zone and increase up to 310 Ma below the Permo-Triassic sediments. The Alpine temperatures did not exceed 400°C and were most probable just below 300°C in the main parts of the Silvretta Nappe. Late Alpine tectonics caused a large scale tilting of the Silvretta Nappe and exhumation of the structurally deepest parts in the southeast.

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PERMO-TRIASSIC DUCTILE DEFORMATION IN THE AUSTROALPINE STRIEDEN COMPLEX (KREUZECK MOUNTAINS/ AUSTRIA)

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During Permo-Triassic time the Austroalpine – Southalpine realm was affected by an extensional event (BERTOTTI, et al., 1993; SCHUSTER et al., 1999). This extensional regime caused a high temperature/low pressure (HT/LP) metamorphic imprint and the formation of extensional structures. In the Kreuzeck-Goldeck-Drauzug area a more or less continuous section through a Permo-Triassic middle and upper crust up into the contemporaneous sediments is preserved. Metapelites of the Strieden Complex show distinct metamorphic zonation, indicating increasing temperatures with increasing structural depth (HOKE, 1990). They range from sillimanite-bearing schists with evidence for partial melting at the base, to low-grade phyllites at structural higher levels. This succession is transgressed by the Permo-Mesozoic Drauzug sequence. For the Strieden Complex a polyphase metamorphic and structural evolution, with at least four pre-Alpine (D_l – D_o) and two Alpine (D_p – D_q) ductile deformations have been discovered by HOKE (1990). New structural and geochronological data mostly confirm this deformation history but indicate a much more prominent deformational event D_o under HT/LP conditions which is Permo-Triassic in age.

Remnants of the earliest visible deformation phase D_l are a segregation layering S_l and concordant quartz mobilisate layers. During D_m the main schistosity (S_m) of the rocks developed. In amphibolites and marbles S_l defines tight to isoclinal folds (F_m) with dm to m-scale wave lenghts. In metapelites F_m is preserved as dismembered isoclinal fold hinges, which form quartz rods aligned with the foliation S_m. Syndeformative garnets were rotated and pressure shadows formed within the S_m foliation. F_n folding caused the repetition of amphibolites and marbles within the metapelites on a 10–100 m scale. The folds are open to tight with wave lenghts up to 100 m, their axes are dipping to the SE. A medium-grade assemblage including staurolite, kyanite and garnet formed syn to postdeformative to D_n. Hornblende and staurolite porphyroblasts are orientated within the NW-SE directed stretching lineation (L_n). A Sm-Nd garnet-whole rock isochron of 342 ± 3 Ma (SCHUSTER et al., 1999) defines D_m and D_n as Variscan in age.

Subsequently the Variscan assemblages are overgrown by andalusite, sillimanite and biotite respectively clinopyroxenes in amphibolites. In the sillimanite zone the steeply SSW dipping S_m was overprinted by a subparallel penetrative foliation (S_o) and a stretching lineation (L_o) defined by the high-temperature mineral assemblage and neosom layers. Pegmatitic intrusions that are interpreted as metamorphic mobilisates from the sillimanite-bearing schists are mostly concordant and show a variable grade of deformation. Some exhibit magmatic textures, whereas others are foliated or mylonitized. Core and mantle structures and grain boundary migration in feldspar indicate deformation at temperatures of more than 500°C. Discordant pegmatite veins are folded by open to tight folds (F_o) with E –W trending axes. The axial planes of the folded pegmatites correspond to the S_o foliation of the surrounding schists. Shear sense indicators are scarce and give no clear sense of shear. This might indicate plain strain as the dominant deformation mechanism.

As the intensity of D_0 is rapidly decreasing above the sillimanite-zone S_0 is most probably induced by thermal softening of the rocks in the zone of partial melting. Within the overlying andalusite zone irregular-shaped pods and veins of andalusite + quartz + muscovite are crosscutting S_m and S_n. According to HOKE (1990) and new Sm-Nd isochron ages on magmatic garnets the pegmatites are Permo-Triassic in age. The isochron from a coarse grained sample (RS35/00) yields 261 ± 3 Ma whereas a mylonitised pegmatite vein (RS43/99) yields 228 ± 4 Ma. The muscovite of the latter sample shows an Ar-Ar cooling age of 193 ± 2 Ma. As Ar-Ar ages on muscovite are interpreted as cooling ages below c. 400°C and as the high-temperature ductile deformation of the feldspars occurred at more than 500°C, D_0 has to be Permo-Triassic in age.

In Eo-Alpine time (100–80 Ma) the base of the Strieden Complex was affected by a high strain and plastic deformation (D_p) under lower greenschist-facies conditions (HOKE, 1990). The main mylonite zone is presumed to be responsible for the primary exhumation of the eclogite-bearing Polinik Complex which borders the Strieden Komplex in the north. D_p structures are overprinted by the deformation D_q which caused a km-scale folding with WNW–ESE trending axes, as a consequence of N–S shortening.

In the Oligocene the dextral E - W Ragga-Teuchl fault zone developed in continuation of the Defereggen-Antholz-Vals lineament. This fault represents the present day contact of the Strieden and Polinik Complex. Contemporaneously basic and intermediate dikes aligned to the Periadriatic plutonism (30–40 Ma) intruded. They are subvertical and show no ductile deformation.

During the exhumation of the Tauern Window (c. 20 Ma) a system of brittle faults developed. In the northern part of the Strieden Complex the most prominent fault set is dextral, NW–SE orientated and aligned to the Mölltal fault. In the area W of the Möllkopf these faults crosscut the Ragga-Teuchl fault zone and induced up to 10 m deep gorges with cataclastic crystalline rocks and pseudotachylites at the base.

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THE WINNEBACH MIGMATITE (ÖTZ-STUBAI CRYSTALLINE UNIT) – EVIDENCE FOR A PAN-AFRICAN METAMORPHISM IN AN OVERTHRUST NAPPE SEQUENCE IN THE EASTERN ALPS (AUSTRIA)

Frank Söllner

The Winnebach migmatite is part of the Ötz-Stubai crystalline unit, a metamorphic nappe unit which forms the basement of the Mesozoic cover (middle Eastern Alpine unit) of the Eastern Alps. This unit can be divided into two series, the Ötztal Peri-Gondwana complex (ÖPC) which represent supra-crustal metamorphic rocks and the Ötztal ophiolite complex (ÖOC)which has formed in an oceanic crustal regime. In the northern part of the Ötz-Stubai crystalline unit and in tectonic contact to the ÖOC, in addition, a nappe can be separated (Ötztal Gondwana complex, ÖGC) which is characterized by local phenomena of anatexis. This complex borders to the ÖOC by a major shear zone (Sulztal shear zone, Söllner et al. this volume) which is exposed near Längenfeld (northern Ötztal valley) and can be traced back over several kilometers to the southeast.

The Winnebach migmatite denote the largest anatectic area (7 to 3.5 km) among others within the ÖGC, e.g. the outcrop near the Regensburger Hütte (Stubai valley, Ranalt village). Despite the widespread distribution of supra-crustal rocks in the ÖPC, which built up the overall southern part of the Ötz-Stubai crystalline unit beyond it, anatectic rocks are lacking.

The Winnebach migmatite is formed by homogeneous diatexites with numerous xenolites ("Schollenmigmatite"), which passes gradually into an inhomogeneous migmatite (xenolites dominate molten parts) and finally into a foliated biotite-plagioclase-gneiss and biotite-quartz-schist. The central part reveals only a very weak deformation thus, prior to age determinations the migmatite forming process was ascribed to the last fundamental thermal event in this area.

Age determinations on zircons of the homogeneous migmatite (Söllner & Hansen 1987) provide a very complex pattern in the Concordia diagram. This can be attributed to the multi-stage crystallisation history of the zircons. Cathodoluminescence (CL) investigations denote three to four different zircon growth phases. Bulk zircon analyses therefore, can always record mixing ages only, without the possibility to detect the real crystallization age of the numerous growth phases.

The only way, to avoid such mixing ages was to use SHRIMP analyses (Sensitive High Resolution Ion Micro Probe). This method allows to focus the analysing beam to a single zircon growth zone an thus, to record real crystallization ages.

In general, the investigated zircons display a detrital core which is positioned asymmetrically and bordered to the rim by rupture or abrasion surfaces. Normally, oscillatory zoning points at the igneous origin of the detrital cores. Ages inferred from these cores vary from Archean to Late Proterozoic. The oldest core age is dated at 2.6 ± 0.02 Ga. Several data concentrate between 1.96 and 2.3 Ga. The most surprising result in core ages denotes a high quantity of Grenville ages (3 of 12 analyses, mean 1 ± 0.04 Ga). This, in addition, implicates a nearby position of the sedimentation area to northern Gondwana **and** a continent which suffered Grenville thermal overprint. Nearly half of the core ages characterize a Panafrican igneous zircon crystallization, separated in different phases. These growth stages coincide well with phases, known from Panafrican orogenic events in northern Gondwana (summarized in SÖLLNER et al. 1997). Ages can be assorted to Pharusian I (818 ± 36 Ma), Pharusian II (677 ± 17 Ma) and Pan-African I with focal points at 639 ± 22 Ma and 610 ± 14 Ma. The large errors, conditional on limited SHRIMP count rates on Late Proterozoic zircons prevent a more exact separation of the igneous phases during Panafrican thermal event.

The detrital cores are all surrounded by a rim which results in the euhedral outer shape of the zircons. The quantity of the rim varies from small to volumetrically dominant. The presence of rims in all zircons clearly demonstrates the in situ growth. This zircon growth can be related to the anatectic event. The inhomogeneous growth conditions may be attributed to a dispersion of the fluid phase during anatexis. This phenomenon may also account for variations in luminescence as sector zoning or irregularly, cloudy to spotted, dark and light domains. In some cases, the anatectic zircon phase is overgrown itself by a very thin rim (up to 5µm) which may be attributed to a final metamorphic thermal overprint in Caledonian [or Variscan?] times.

Age determinations carried out on the anatectic rim display a mean value of 607 ± 13 Ma. Therefore, the anatexis in the Winnebach area has to be attributed to a Panafrican thermal event. Conventional zircon analyses of the migmatite, in any case supply mixing ages. The smaller the crystals are and the more they are metamict, caused by an anomal high U content (up to 1700 ppm U), the more dominates the influence of the Caledonian thermal heating effect in the zircons (SÖLLNER & HANSEN 1987, KLÖTZLI 1999). The Caledonian metamorphic influence on zircons is profound as well, in the surrounding precursor rocks (biotite-plagioclase-gneisses) and in granite-gneiss veins cross-cutting the migmatite (remolten migmatite).

In consequence, the unit named Ötztal Gondwana complex (ÖGC) has to be regarded as a nappe, originated from Gondwana itself or a terrane split from there and subsequently thrust over the sequence of Peri-Gondwana metasediments (ÖPC) and metabasites (ÖOC) in Variscan times (SÖLLNER et al. this volume). The thrust plane is exposed in the Sulztal shear zone. The southwestern to western front of the nappe is well documented in the outcrop of mylonitic biotite-augengneisses.

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THE SULZTAL SHEAR ZONE, A VARISCAN THRUST PLANE SEPARATES PERI-GONDWANA METAMORPHIC SEQUENCES FROM A GONDWANA NAPPE ON TOP OF THE ÖTZ-STUBAI CRYSTALLINE UNIT (AUSTRIA)

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The Sulztal shear zone (SSZ) is a long lasting lineament which crops out near Längenfeld (Ötz valley) and can be traced to the ESE over several kilometers up to the village of Ranalt in the Stubai valley. There it turns to the NW in acute angle and is cut off by the intrusion of the Alpeiner granodiorite-gneiss. The continuation of the shear zone in Längenfeld is not quite clear, it tends more to the north than to the west. The shear zone, dipping 60° to 80° NE is folded and faulted by younger Alpidic tectonic processes.

The SSZ separates two major sequences of the Ötz-Stubai crystalline unit which are totally different in origin, age and metamorphic history. (1) The lower sequence can be divided into supra-crustal rocks of the so-called Ötztal Peri-Gondwana complex (ÖPC) and in rocks from an oceanic crustal regime, the so-called Ötztal ophiolithe complex (ÖOC). Both complexes originate from post Panafrican times, formed during Paleozoic opening of the Mid-European Sea. (2) The hanging sequence is a nappe, thrusted on the younger metamorphic rocks of ÖPC and ÖOC and composed solely of supra-crustal rocks of Panafrican age. It has to be regarded as part of the Gondwana continent (so-called Ötztal-Gondwana complex, ÖGC; SÖLLNER, this volume). Near Längenfeld at the Burgstein, tectonic microstructures clearly demonstrate the inverse layering of the hanging wall. The front of the nappe therefore is formed like an overturned fold.

In 1997 a geological project has been started to investigate the major rock units accompaning the Sulztal shear zone. As a result, a geological map from the surrounding area of the Amberger Hütte/Gries im Sulztal is presented here. The course of the Sulztal shear zone (SSZ) is often cut by younger traverse faults. The most significant is the SW-NE trending, sinistral Längental fault with a dislocation of about 4 km. Mylonites of the SSZ are dragged into the fault zone.

The rocks involved in the shear zone are strongly deformed and recrystallized. Transpressive deformation has not only concentrated on the thrust plane itself but tension has also relieved within the adjacent rocks. The rock, mainly deformed is a biotite-augengneis. Within this augengneiss mylonitic zones and distinct shear bands are developed. These zones of high prolate deformation ("Stengelgneise") are parallel to the foliation (direction of shear N/45°), several decimeter wide and sharply separated from lower deformed ranges. The subjacent layer of the shear zone, a coarse-grained metagabbro shows gneissic textures and lamination, as well.

To get an idea of the time of the tectonic activity along the Sulztal shear zone, age determinations were carried out on the deformed biotite-augengneiss. U-Pb zircon dating should mark the crystallization age of the rock and Rb-Sr investigations on thin slabs and minerals should be able to limit the time interval of the deformation.

U-Pb investigations on zircons of the biotite-augengneiss (SUL) provide a lower Concordia intersept age of 501 ± 4 Ma which can be interpreted as the crystallization of the precursor rock. Abraded zircon fractions trace back to an upper intersection of about 2.6 Ga. The inheritance of detrital zircon cores, the typological zircon classification as S6 and S11 types, as well as the $^{87}Sr/^{86}Sr$-initial ratio of 0.7095 point to an acid igneous rock of mainly crustal origin.

Thin slabs of a well deformed biotite-augengneiss (KB) characterizes alternating layers, dominant in biotite and quartz+feldspar, respectively. Rb-Sr isotopic analyses of these slabs do not yield the favoured results. Data points are wildly scattering in the isochron diagram and thus, demonstrate incomplete multiphase isotopic exchange. Dark biotite-rich layers may point to an Alpidic age (86 ± 8 Ma) which is identical with that, determined on the biotite itself (85.5 ± 2.1 Ma), as well as that on chlorite (85.3 ± 2.5). The oldest biotite age stems from the most deformed, but also the most dense and fine-grained biotite-augengneis (98.9 ± 2.2 Ma). Mucovite-whole rock ages vary between 292 and 299 Ma and denote cooling ages subsequent to the Variscan thermal event. Alpidic metamorphism in this area, therefore, didn't reach muscovite equilibration temperatures of about 500°C. The last fundamental thermal overprint has happened in Variscan times. Sm-Nd garnet-whole rock data on eclogite lenses, intercalated in basic metamorphic rocks of the ÖOC, which are integrated in the Sulztal shear zone yield ages of 350 to 360 Ma (MILLER & THÖNI 1995). This high grade eclogite facies metamorphism should has happened prior to the tectonic movements along the shear zone, because of the contact of quite different precursor rock types and the degree of metamorphism, not exceeding amphibolite facies conditions in the supra-crustal rocks of the overlying Ötztal Gondwana complex. Dynamic recrystallization of muscovite and amphibole in mylonitic and ultramylonitic biotite-augengneisses and metagabbros of the shear zone, respectively presume temperatures above 500°C (PASCHIER & TROUW 1996). Therefore, movements along the Sulztal shear zone are limited to the time interval of about 350 to 292 ± 8 Ma, trending more to the lower age.

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POST-COLLISIONAL EXHUMATION HISTORY AND SURFACE EVOLUTION OF THE CENTRAL ALPS

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The Oligo-Miocene is an important period for the geomorphological evolution of the Alps. After the Eocene-Oligocene collision and nappe stacking, the Central Alps started to develop a significant relief in Oligocene times. Miocene lateral extrusion caused an east-west stretching of more than 300 km and led to the collapse of the relief. This collapse is reflected by a drastic decrease of sediment accumulation rates in the foreland basins of the Central Alps at 21 Ma. The aim of this study was a detailed reconstruction of the exhumation history and the surface evolution of the Central Alps in Oligo-Miocene times. Geochronological, geochemical and isotope studies on the foreland basin sediments give evidence for the first exposures of certain tectonic units and their cooling rates. Moreover, the paleodrainage system of the Central Alps in Oligo-Miocene times can be reconstructed. To summarize, the following can be concluded: During Oligocene times only sedimentary cover nappes (flysch and carbonates) and basement nappes of the Austroalpine mega-unit were exposed on the northern flank of the Central Alps. The eroded part of the Austroalpine basement in the Central Alps consisted of large areas, which experienced only weak or even no Eo-Alpine metamorphic overprint. It was the direct western continuation of the Ötztal and Silvretta block of the western Eastern Alps. Austroalpine basement exposed on the southern flank of the Central Alps experienced slightly higher temperatures (~240–300°C) during Cretaceous metamorphism. The main drainage divide was situated north of a volcanic chain which was positioned in the area of the Periadriatic lineament. Contemporaneous with the collapse of the relief units of the Penninic lower plate became exposed over large areas of the Central Alps (21 Ma). While in the hinterland of the Kronberg-Gäbris and Hörnli fan only upper parts of the Pennninc nappe pile were eroded, the Honegg-Napf and Pfänder system rooted in deeper levels of the Penninic sequence. Geochronological data reveal an average cooling rate of ~20°C/Ma in Late-Oligocene to Early Miocene times for these Penninic units. The Pfänder river system rooted in the Lepontine area of the Central Alps. The Pfänder fan itself was situated in the area of the recent Lake Constance. Therefore, the catchment area was similar to the present-day Rhine river and the Pfänder system might be called 'Paleo-Rhine'. In Middle Miocene times Lower Penninic units of the Lepontine Dome were exhumed to the surface, contemporaneously with the opening of the Tauern window in the Eastern Alps.

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NEW CONSTRAINTS ON QUATERNARY CLIMATE AND LANDSCAPE EVOLUTION IN THE EASTERN ALPS FROM CAVE DEPOSITS

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Data of environmental change in the Alps are confined largely to the Late Glacial and Postglacial, because repeated glacial advances effectively obliterated most older surface sedimentary records. Cave calcites (speleothem) hold a high promise of providing critically needed paleoenvironmental information that can complement the record from lacustrine and glacial deposits and extend it back in time up to several hundreds of thousands of years. The reasons for this high expectation are twofold. First, caves are natural shelters that are much less affected by large-scale erosion processes than sedimentary deposits on the Earth's surface. This is particularly true for mountainous regions such as the Alps. Second, calcite can be precisely dated using the uranium-series disequilibrium technique, provided that the material has a sufficiently high uranium concentration coupled with a low abundance of detrital thorium, and has not been diagenetically altered. The typical dating limit of the mass spectrometric Th-U method is approximately 400 ka, but may be extended back to c. 600 ka in the case of excellent sample material.

Results from some 140 Th-U determinations performed on approximately 52 individual samples show that Alpine caves host both Holocene (and in many cases still active) and older, mostly inactive speleothems, some of which are older than the limit of the method. These results underscore the potential of the speleothem "archive" given the fact that there is no "absolute" chronology for the vast majority of the Quaternary surface sediments in the Alps prior to isotope stage 3 (i.e. older than the radiocarbon dating limit).

Our results suggest that many Alpine speleothems are useful recorders of major environmental change simply because calcite deposition ceases under fully glacial conditions. This "on/off switch" provides new constraints on major climatic changes, e.g., the onset of speleothem accretion at 131 ka BP at approximately 2300 m a.s.l. in the Zillertal Alps, requiring essentially ice-free conditions in the accumulation area of the former stage 6 ("Riss") glacier network during Termination II. Likewise, a stalagmite from the same area in the Central Alps grew between 57 ka and 47 ka BP, i.e. during the early part of stage 3 at some 2200 m a.s.l. This places constraints on the extent of alpine glaciers during this long time interval of the Würm glaciation and strongly argues against the presence of a significant ice cover during stage 3. A third example pertains to calcitic flowstone present as fracture-lining deposit in the famous Hötting Breccia near Innsbruck. A sample from this locality yielded a Th-U age of 73 ka and for the first time allows us to state that the central Inn valley was ice-free during the critical stage 5/4 transition.

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THE ALPS: A PRODUCT OF THE LITHOSPHERIC WEATHER

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The success of the application of the plate tectonic theory is obvious worldwide, except some places, where no clear plate boundaries can be defined. "... Where plate boundaries adjoin continents, matters often become very complex and have demanded an ever denser thicket of ad hoc modifications and amendments to the theory and practice of plate tectonics in the form of microplates, obscure plate boundaries, and exotic terranes. A good example is the Mediterranean, where the collisions between Africa and a swarm of microcontinents have produced a tectonic nightmare that is far from resolved." states Encyclopaedia Britannica.

Recently SZÉKELY (2001) proposed a comprehensive model for tectonically complex regions like the Apenninic-Alpine-Carpathian system, the Indonesian archipelago and the Hunter ridge-Fiji-Lau ridge system: these features are interpreted as products of a widely present lithospheric weather, an analogous phenomenon to the meteorological evolution of air masses. The aforementioned systems are found to be analogous to meteorological low pressure zones both in kinematical and dynamical sense (SZÉKELY 2001). Here we present an overview of the Alpine geological phenomena from the point of view of this model.

The Apenninic-Alpine-Carpathian multiple orogenic loop is a nice example of a geological "cyclone" system termed as geovortex. Because of the extensive set of available data the observations can be arranged into a comprehensive model: for the Apenninic-Alpine segment of the orogen, it is found that the cyclonal center situated NW of Genova separates a warm-front-like part and a cold-front-like part represented by the Alps and the Apennines, respectively.

The crustal thickness (GIESE & BUNESS, 1992; HORVÁTH, 1993) beneath the region is strikingly similar to a meteorological cyclone: the crustal depth pattern forms two steeply (cold) and moderately (warm) dipping, arcuate zones separated by sudden horizontal changes appearing as warm and cold fronts. Considering the two systems analogous, the dynamic behaviour explains several phenomena and fits to plate tectonic reconstructions.

The geological evolution of the front system (e.g. DOGLIONI et al. 1999, KUHLEMANN 2000) is ambivalent: the Alpine flank (representing the warm front) is moving relatively slowly towards N with slightly rotating trend and with decreasing rate, while the fast moving and accelerating Apenninic flank introduces rotation: Corsica and Sardinia are the first testimonies and in the last 10 Ma the fast opening of the Tyrrhenian basin shows similar characteristics to meteorological cold fronts.

The fact that earthquake distribution of the geoveortex center is very similar to the cloud pattern of an occluded cyclone demonstrates that the process can be validated even in recent times on short timescales as well.

Although the physical background of the phenomenon is difficult to discuss at the present level of knowledge, some basic properties can be mentioned. The meteorological thermal instability (hot and less dense material below, cooled and more dense material on the top) exists also in the mantle, while the non-dimensional scaling is similar, if we take into account the different viscosity and moving speeds. It seems that the cyclonal development also influences the rheological pattern in details: the spatial distribution of the earthquakes suggests, that like in the case of the cloud production in a low pressure zone, the slight differences in p and T in consequence of the mixing of rock masses (analogous to air masses) are responsible for different rheology: some areas produce earthquakes (i.e., at least in part brittle deformation), while some other, horizontally interfingered areas are seismologically more silent indicating ductile deformation.

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THE METAMORHPIC FIELD GRADIENT OF THE KORALPE

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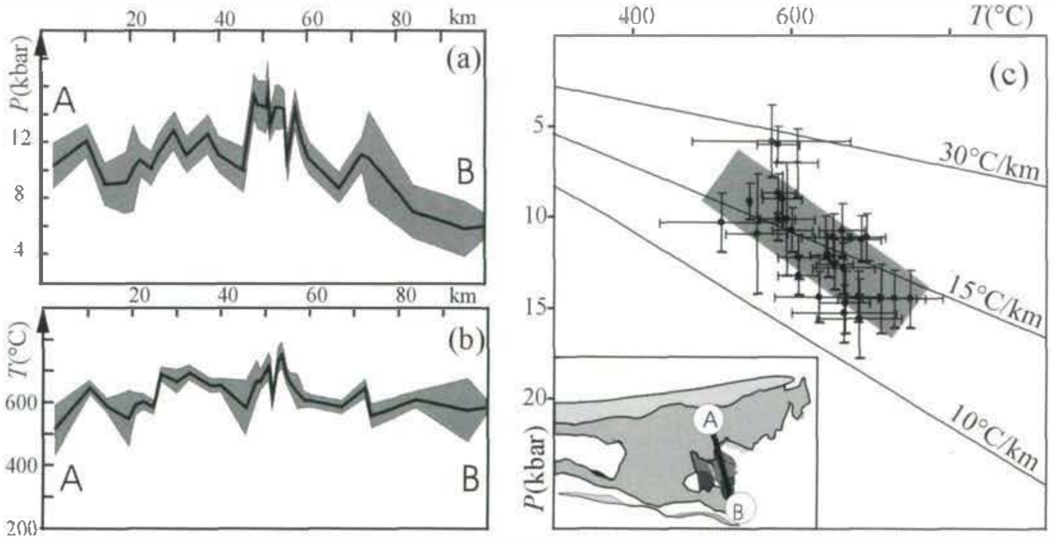
The Koralpe, which contains the eclogite type locality, is the largest region of the Alps preserving high grade metamorphic rocks from the early part of the Alpine orogenic cycle: the Eoalpine event in the Cretaceous. Here we present a detailed documentation of the metamorphic field gradient of the Koralpe along a transsect from north to south (shown in the inset in fig. c)

The principal characteristics of the region are: (1) The gradient of Eoalpine metamorphism in the Koralpe is inverted. It increases from North (A in fig. c) to South (B in fig. c)over a distance of 50 km from greenschist to amphibolite and eclogite facies conditions along a structurally south-dipping sequence. This sequence consists of predominately metapelitic rocks containing metre to kilometre sized mafic bodies that are amphibolites in the north and eclogites in the south. (2) South of the highest grade rocks, the gradient drops symmetrically to the north, back down to lower grade conditions. (3) The structure is controlled by the flat-lying Plattengneiss shear zone, which is the largest shear zone in the Eastern Alps and covers the central part of the transsect, where the metamorphic grade is the highest. (4) Eoalpine deformation occurred synchronous with the metamorphic peak and age of metamorphism decreases with increasing grade. (5) Despite the high grade, Eoalpine parageneses show relics of previous metamorphic events, indicating very heterogeneous equilibration and possibly short duration of the event.

We show that, in the northern half of the profile, both pressure (fig. a, bold line; grey shaded area indicates the error estimates) and temperature (fig. b) increase constantly from north to south across all boundaries that have been assigned tectonic significance by previous authors over a length of about 60 km. However, while pressure increases from 9 kbar to at least



15 kbar, temperatures increase only from 550°C to 700°C over the same distance. A comparable continuous decrease of the PT conditions can be seen in the southern part of the profile where pressure decreases from 15 kbar to 6 kbar over about 40 km. The results raise the question whether the metamorphic field gradient (indicated by the grey shading in fig. c) of the Koralpe follows a metamorphic geotherm (three possible linear geotherms are outlined in fig. c as straight lines) with considerably high perturbation of the lower grade rocks, or a piezotherm during Eoalpine times that does not follow traditional piezotherms of regional metamorphic terrains. Both interpretations are not completely consistent with traditional interpretations of the region. Finally, we discuss the tectonic settings that allow the formation of this significant metamorphic field gradient by rapid exhumation of deep seated rocks.

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CRETACEOUS EMPLACEMENT OF THE AUSTROALPINE SCHNEEBERG COMPLEX?

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The Schneeberg complex (SC) is located in the SE part of the Austroalpine Ötztal-Stubai basement complex (ÖSC) and is regarded as a separate unit within the ÖSC based on lithological constraints. The age of deformation and metamorphism in the SC has always been a subject of discussion. New garnet Sm/Nd crystallization ages (mineral-whole rock ages of 93.1 ± 4.7 Ma and 90.9 ± 4.1 Ma) and Biotite Rb/Sr cooling ages (mineral-whole rock ages between 84 –73 Ma) from the SC indicate an eo-Alpine age for the tectono-metamorphic evolution.

Based on field mapping and structural data, as well as thin section analysis and first microprobe investigations, two ductile deformation phases (D1-D2) can be differentiated. Deformation phase D1 defines a mylonitic foliation (metamorphic layering) with a well developed stretching lineation (L1) trending to NW-WSW. The monocline symmetry of some clasts points to a strong non-coaxial component of deformation. Isoclinal folds (F1) with fold axes strictly parallel to the stretching lineation L1 are related to D1, the axial plane of F1 corresponds to S1.

D2 is characterized by S-vergent fold trains with W-E oriented fold axes, forming the major synforms of the Schneeberg complex ("Schneeberger Hauptmulde"). The D1-deformation can be correlated with the pressure peak at (maximum time span 98-86 Ma; interpreted as main period of garnet crystallization). Amphibolite facies conditions outlasted deformation and led to static mineral growth, which has variously overprinted all ductile structures related to D1 and D2.

Concluding, the rocks of the SC record a polyphase ductile deformation history during one single eo-Alpine metamorphic event. The microstructural relationships and Sm/Nd ages of garnet document that both ductile deformation phases (D1, D2) are an integral part of one, rather short-lived tectono-metamorphic sequence. Permo-Mesozoic rocks (Brenner Mesozoic), exposed at the northern border of the SC show the same structures (D1 and D2) and an eo-Alpine medium-grade metamorphic imprint (DIETRICH 1983), thus providing a further evidence for the eo-Alpine age of the main tectono-metamorphic evolution in this area.

Considering the absence of pre-Alpine structures or relic minerals in the whole SC, the clear change in the microstructural pattern at the western contact between SC and ÖSC, the different tectonic history of SC and ÖSC farther NW, might best be explained with an Alpine emplacement of the SC at medium grade conditions, together with some basement rocks to the SE of the SC, i.e. the eo-Alpine eclogites, showing rather similar structural, petrological and geochronological patterns.

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HOW MUCH TIME INFORMATION DO METAMORPHIC MINERALS RECORD? AGE DISCORDANCE BETWEEN „ROBUST“ ISOTOPE SYSTEMS AND THEIR LINK WITH P-T-D DATA IN ALPINE HIGH-P ROCKS

Martin Thöni

Exact knowledge of the timing of different stages related to a metamorphic PT path is indispensable for calculating reliable exhumation and/or cooling rates in metamorphic rocks. However, the evaluation of radiogenic isotope data from metamorphic minerals to establish their strict time significance needs to address, first of all, the following basic problems:

a) isotopic (dis-)equilibrium within the analyzed system;
b) the influence of (probably unequilibrated) inclusions in the "clean" mineral separates used for dating;
c) the effects of any possible post-peak perturbation (open system behaviour) of the isotopic systems, due to late active processes, such as thermally controlled diffusive loss of radiogenic isotopes, selective deformation-induced (re-)crystallization, fluid activity, or a combination thereof.

Although an apparent age scatter from samples with a common tectono-metamorphic history might well be explained in some cases by processes a) and b), age discordance, even between the so-called „robust“ systems (U-Pb, Lu-Hf, Sm-Nd), can also result from heterochronous chemical processes operating at different stages of metamorphic (re-)crystallization and/or isothermal decompression and exhumation of deeply buried rocks. This means that, depending on bulk chemistry and pre-existing metamorphic history (mineralogy, microstructure) of the rocks involved as well as inhomogeneous distribution of deformation in an accretionary or exhuming wedge, different isotopic systems may be influenced by different processes.

Examples from Alpine eclogite- to amphibolite-facies-grade areas of the Austroalpine basement are used to illustrate the above discussed problematics.

In the Koralpe and Saualpe (KS) area of the SE Austroalpine units Sm-Nd ages from pyropic high-P garnets in meta-acidic lithologies (mainly metapelites) cluster within a narrow time range between 91±2 and 86±2 Ma. Sm-Nd garnet ages from the Schneeberg garnet mica schist complex in the southeastern Ötztal basement (western part of the Austroalpine unit) are roughly similar, ranging between 93–90 Ma for the final stage of garnet crystallization. All these ages are interpreted to trace final peak pressure conditions for the "high-P metamorphic belt" (THÖNI & JAGOUTZ, 1993) that characterizes considerable portions of the southern Austroalpine basement units. The data imply that exhumation of eo-Alpine high-P rocks in the Austroalpines initiated almost contemporaneously, within the rather narrow time window of c. 89±3 Ma. This date correlates in time with the oldest portion of the Gosau Group sediments in the Northern Calcareous Alps (WAGREICH & FAUPL, 1994). Together with mica cooling ages, the above age data allow the mean exhumation rates for the southern Austroalpine sheet to be constrained on a regional scale. The calculated values are 4-6 km/Ma for the time interval of roughly 89 (±3) to 78 (±3) Ma (corresponding to cooling rates of 25–40 °C/Ma, respectively) (EXNER et al., 2001).

On the other hand, mineral-mineral and mineral-whole rock ages from metabasic rocks of the KS, calculated on the basis of the Sm-Nd and Lu-Hf isotope systems, scatter more widely, yielding ages of between 109±9 and 87±5 Ma. In combination with microstructural and microchemical data, these somewhat older dates from more competent, Ca-rich lithologies may be interpreted to reflect earlier steps of the same eo-Alpine high-P evolution.

Interestingly, U-Pb SHRIMP ages for zircons from the same metabasites range among the youngest age figures (THÖNI et al., 2001). Since some of these zircons show inclusions of high-P garnet and omphacite, late-metamorphic zircon crystallization (82±4 Ma) is independently proven by microstructural criteria.

It may be inferred, therefore, that the so-called "robust" chronometers – generally thought to date peak PT conditions – may yield internally discordant, but valuable age results, being able to record basically different processes operating along a coherent subduction/exhumation path of one single continuous metamorphic evolution. The above results are also compared with "robust" isotope data from other HP-UHP areas of the Alpine chain and implications for their interpretation are discussed.

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EARLY CRETACEOUS TO TERTIARY THRUSTING IN THE THIERSEE STRUCTURE: RESULTS FROM STRATIGRAPHIC AND PALEOMAGNETIC INVESTIGATIONS

Wolfgang Thöny & Hugo Ortner

The Thiersee syncline is an E-W-trending structure stretching for about 30km in the western part of the Northern Calcareous Alps. The Thiersee structure has traditionally been interpreted as a simple syncline with an overturned southern limb and a normal northern limb. The TRANSALP seimic line revealed the presence of a deep-reaching thrust plane inside the structure (Thiersee thrust).

In the Achensee region, the thrust plane is exposed at the surface. Measuring the distance between hanging- and footwall cutoff, 7 km of shortening within the structure can be deduced (SAUSGRUBER 1994). Several stages of thrust activity can be distinguished:

Sedimentation in the Thiersee syncline ends with middle Albian carbonate sandstones (RISCH 1985). No Upper Cretaceous deposits are known from the Thiersee structure west of Thiersee. If the structure had not been closed by thrusting, Upper Cretaceous deposits should be present.

Upper Cretaceous deposits are present at the northern flank of the southerly adjacent Guffert-Pendling anticline. Onlap of Turonian alluvial fan sediments indicate a (pre-) Turonian growth of the anticline, presumably above a thrust plane reaching the surface in the Thiersee structure.

Tertiary thrust activity along the Thiersee thrust is indicated by paleomagnetic investigation of the Ampelsbach section in the Achensee area in the overturned southern limb of the Thiersee structure. Upper Triassic to Lower Cretaceous rocks were sampled; no primary magnetisations were encountered. The remagnetisations are interpreted to be caused by Tertiary overprint. The interpretation is based on the inclination of the characteristic remanent magnetisation. The paleomagnetic vectors are arranged along a small circle indicating a synfolding magnetisation (Fig. 1, inset c). The magnetisation was aquired when the beds were in a north-dipping to overturned position. Minor clockwise rotation of 20° postdating the magnetisation brought the trace of the Thiersee thrust into an E-W-trending position. Before rotation, it was NW-directed.

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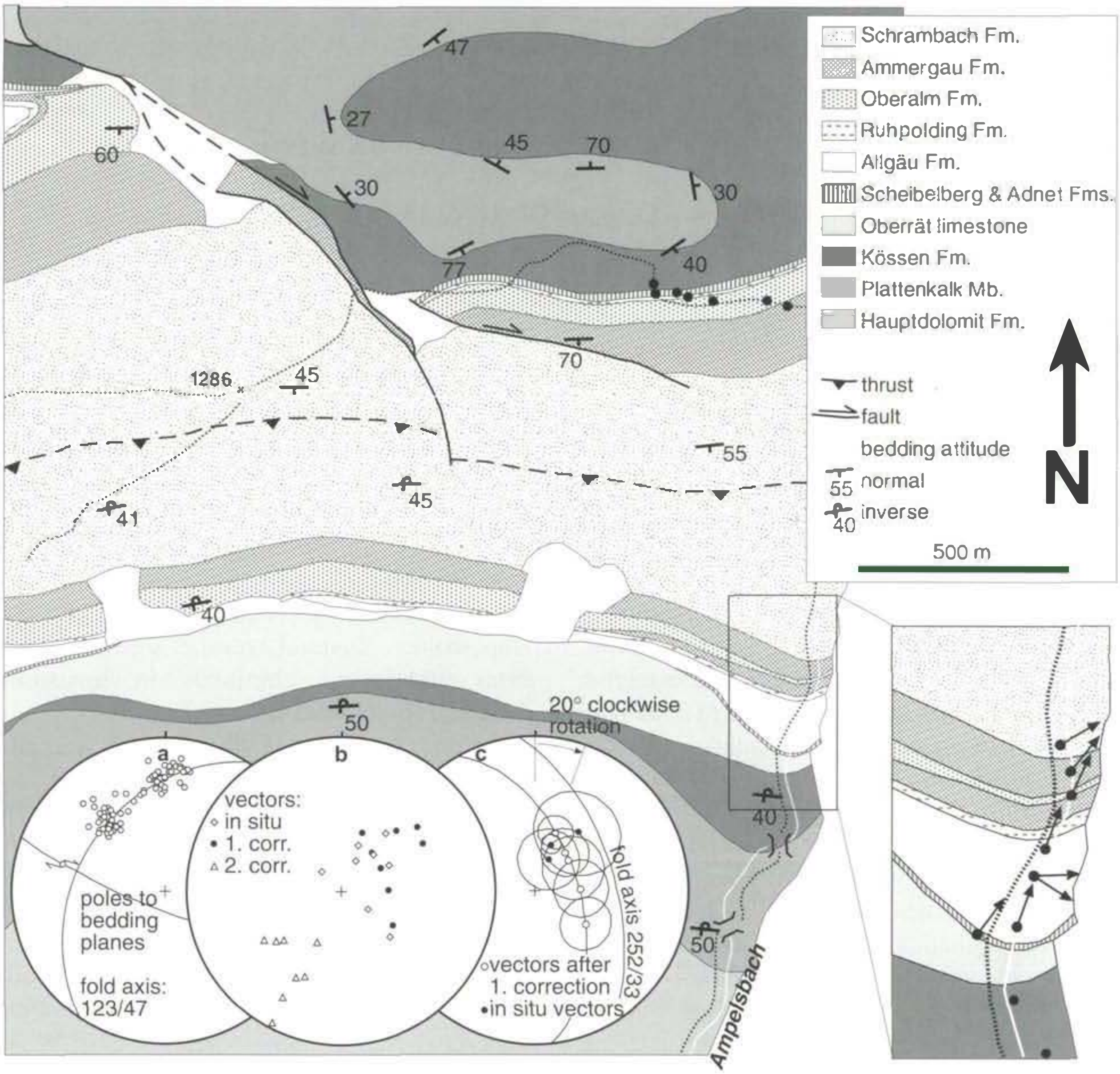

Fig. 1: Geological sketch of the Ampelsbach area. Geology redrawn from Sausgruber 1994. Declinations of magnetisation are indicated by arrows. Inset a) local fold axes related to fault activity calculated from bedding planes. Inset b) Orientation of paleomagnetic vectors. Inset c) Orientations of paleomagnetic vectors with cones of confidence arranged along a small circle. This is interpreted to be the result of a remagnetisation aquired during folding.

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GEOLOGY OF THE HIGH AHRNTAL, SW TAUERN WINDOW (ITALY)

Giovanni Toffolon, Giovanni Cortiana, Giorgio V. Dal Piaz & Paola Tartarotti

A new geologic map of the High Ahrn Valley (Ahrntal, South-Western Tauern Window) at the scale of 1:25.000 is presented. The field work was performed at the scale of 1:10.000, in the frame of the CARG-PAB (Provincia Autonoma di Bolzano) project (Geologic Map of Italy, scale 1:50.000, Sheet Nb. 003 "Vetta d'Italia"). The eastern part of this sheet was carefully mapped by Bianchi & Dal Piaz (1930). The Ahrntal is located in the SW part of the Tauern Window, where the Penninic nappe stack and the overlying Austroalpine units are exposed, due to updoming and tectonic denudation. The Penninic units consist of (see review in Kurz et al. 1998): 1) the (structurally lower) pre-Variscan *Venediger Nappe /Wolfendorn Nappe*, intruded by Late Paleozoic granitic plutons (*Zentralgneis*), covered by Mesozoic sequences (*Hochstegen* and *Kaserer* formations); 2) the Variscan *Storz Nappe,* and the *Greiner Series/Murtörl Group* (quartzites and metapelites of Late-Paleozoic? or Cretaceous? age); 3) the *Eclogite Zone* made up of mafic eclogites intercalated with metasediments showing high pressure peak metamorphic conditions (Dachs, 1986) and a later retrogression into garnet-amphibolite/greenschist facies conditions; 4) the *Rote Wand-Modereck Nappe* built-up of thin gneissic units (*Lamellae*) and a Mesozoic metasedimentary-metavolcanic unit; 5) the *Glockner Nappe*, consists of metabasites and serpentinites covered by metacherts, quartzites, micaceous marbles and calcareous schists intercalated with MORB-type metabasalts of Jurassic to Cretaceous (?) age; 6) the *Matrei Zone* is made-up of metamorphic flysch sediments, breccias and olistholites (or tectonic slices) mainly of Austroalpine derivation. In the study area, only Penninc units crop out, with the exception of the Matrei Zone. In our study we refer to the nomenclature adopted by Dal Piaz (1934), who recognized in the Ahrntal the following nappes: 1) the *Gran-Veneziano Nappe* (Grosse Venediger-Zentralgneis Auct.), consisting of Late Carboniferous-Permian granitoids transformed into gneiss during the Alpine orogenic cycle, and by pre-granitic paragneiss and amphibolites. Textural types of gneisses range from undefomed granitoids in low-strain domains, to sheared, mica-rich gneiss in high-strain domains. Biotite-rich schists are also present. The Alpine metamorphic imprint is mainly characterized by greenschist facies conditions in the southern sectors, whereas increasing T conditions are shown to the north. The Gran-Veneziano Nappe crops out along the northern side of the Ahrntal. 2) The *Dreiherrnspitz-Greiner Nappe* crops out in the south-eastern side of the valley. To the north, it overthrusts the Gran Veneziano Nappe, along a straight ENE-WSW trending contact, going along the valley bottom and crossing through the Birnlucke pass to the Austrian side. The Dreiherrnspitz-Greiner Nappe is mostly made-up of paraschists, enclosing layers and boudins of mafic (garnet)-amphibolite, orthogneiss and marbles of pre-Triassic age?. The paraschists are of various types. A preliminary distinction (work in progress) was tentatively made on the basis of lithological assemblages and on the occurrence of garnet and graphitic matter, with the aim of recognizing the pre-granitic metamorphic basement (i.e., "Unterste Schieferhülle" Auct.) from the younger "Untere Schieferhülle" (post-Variscan), as it has been done in other parts of the Tauern Window, where the Alpine imprint is less pervasive than in the Ahrntal. 3) The *Glockner Nappe* was divided in the study area into the Ophiolite Unit ("Obere Schieferhülle" Auct.) and the Continental Margin Unit. The Ophiolite Unit crops out along the southern side of the valley, to the south of the Windtal. It consists of calcareous schists intercalated with greenschists and amphibolites, and of scarce serpentinite slices. Near the village of St. Peter, the tectonic contact between the Glockner and the Gran-Veneziano nappes is outlined by a 400-500m-thick tectonic imbrication of calcschists from the Ophiolite Units, and Triassic marbles and dolostones from the Continental Margin Unit. Structural analysis suggests that in this sector of the Ahrntal the main thrust surface has been re-activated by a sinistral trascurrent fault system. In the south-eastern side of the Ahrntal, between the Windtal and the Röttal, the north-vergent Glockner Nappe overthrusts the Dreiherrnspitz-Greiner Nappe. Here the tectonic contact is complicated by an imbrication of slices of ophiolites, paraschists from the Grainer Nappe and Triassic quartzites, dolostones and marbles from the Continental Margin Unit. At least three main ductile structures of Alpine age were recognized on the field: D1 structures consist of rootless isoclinal folds observed within cm-thick quartz-rich layers, relict in the penetrative regional schistosity (S2). D2 structures are isoclinal folds with a penetrative S2 axial plane foliation (regional schistosity). D3 structures are asymmetrical folds (mostly S-saped looking eastwards), with no axial foliation and dipping 30°-60° westwards. D3 stage locally developed crenulation cleavage in calcschists. Anyhow, coherent structures at the meso-scale are not widespread, due to the vicinity of the main thrust surface between the Gran Veneziano Nappe and the Dreiherrnspitz-Greiner Nappe and the Glockner Nappe, where ductile deformation is penetrative and overprinted by later faulting. A noticeable improvement with respect to previous works on this area was done in Quaternary geology. Quaternary deposits were revised and various units were distinguished according to allostratigraphic criteria. The Postglacial Unit (Ahrntal Alloformation) includes all quaternary sediments deposited from the Last Glacial Maximum (LGM) to the Present. It includes the Dreiherrnspitz Allomember consisting of Quaternary deposits related to the Little Ice Age. The Garda Allofm. includes all glacial and fluvial deposits related to the L.G.M., and the Kasern and the St. Jakob Allomembers, both consisting of stadial deposits not correlable each other. The introduction of the Garda Allofm. allows the correlation among all deposits referable to the L.G.M. from the whole Adige-Garda basin.

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SHALLOW HIGH-RESOLUTION SEISMICS – A LINK FROM QUATERNARY TO TERTIARY ALONG THE TRANSALP PROFILE IN SOUTHERN BAVARIA

Rüdiger Thomas, Kurt Bram, Jürgen Fertig & Klaus Schwerd

Introduction

In its northern part the east-alpine reflection seismic traverse TRANSALP crosses the complicated transition zones from the Foreland Molasse to the Folded Molasse and from the Folded Molasse to the tectonically superposed alpidic thrust units. The contact zones are covered totally by Quaternary sediments. The deep-reflection seismics of the TRANSALP project and the exploration seismic profiles (THOMAS et al., 2001) do not provide any information from surface down to about 300 to 500 ms two-way travel time (TWT).

Acquisition and Processing

Three high-resolution reflection seismic profiles were surveyed to explore the near-surface structures in the transition zones. During the survey the acquisition parameters of geophone spread, spacing and frequency range were particularly adjusted to reflectors which are expected to dip steeply southwards. A high-frequency vibrator was used (BUNESS et al., 1997; VAN DER VEEN et al., 2000), designed for shallow reflection surveys.

An end-on spread configuration was selected. In case of southward dipping layers the vibration points have been positioned south of the geophone array. With this a favourable angle of incident for p-wave registration of steeply dipping events at the geophone was assumed.

The common problem of the Quaternary cover with glacial deposits complicates the data processing to a large extent. To this the complicated geological/tectonical conditions and the unfortunate circumstances for energy distribution are added. The consequences are that in most cases evaluation of reflection hyperbolic functions is not possible in raw data. Only after a time-demanding prestack processing, reflections with a travel-time up to 300 ms TWT can be interpreted in unstacked sections.

Consequently, that part of the hyperbolic reflection function next to the first arrival is vital for an optimum stacking result. Therefore, refraction energy has been carefully muted as close as possible to the first arrivals. In order to enlarge and optimally use the effective window between first arrival of refraction and surface waves all available techniques regarding noise suppression have been applied. This affords a sensitive combination of air blast attenuation, spectral balancing, bandpass filtering and amplitude scaling. This combination proved to work successfully when permanently adjusted to the quickly changing data quality along the profile. The muting zone has to be estimated for each vibration location separately, so that in addition, small spatial and near-surface velocity variations could be taken into account.

The main aspect of data processing can be seen in the determination of velocities. They play a distinctive role in computing static corrections, the NMO-correction for CMP-stacking and, finally, in migration.

The data of this project shall redress the lack of interpretation of deep and exploration seismics at the uppermost 300-500 ms TWT. To connect the overlapping interpretations it is necessary, however, to include larger travel times as good as possible, too. Combining refraction statics and residual static corrections has shown to be best suited. Thereby, the usable band-width of the signal as well as the stacking velocity was improved iteratively.

Results

This project of high-resolution reflection seismics in complicated geological transition zones of the Bavarian alp rim shows, that even in areas, which are strongly folded and faulted by imbricate thrusts, seismic information can be gained. Three high-resolution seismic profiles reveal a detailed image of the transition zones from the unfolded Foreland Molasse to the Folded Molasse as well as from the Folded Molasse to the Helveticum/Flysch zone. Even the Quaternary cover in the vicinity of the Foreland Molasse and the Folded Molasse could not only be (seismically) observed, but also seismic information could be gained down to 1.3 s TWT in this area. The dipping events of the transition zone Folded Molasse/Helveticum/Rhenodanubian Flysch are much lesser than expected.

Data processing had to be attentive to steeply dipping structures. For this all means of noise suppression had to be employed in order to enlarge the effective window between refraction events and surface waves and to use this most effectively. Hence, a precise processing of single traces was necessary, yielding the best results.

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COMPARING ANALOGUE AND DIGITAL 3D MODELS: RECONSTRUCTION OF A TRANSFER ZONE FROM SOUTHERN ALPS

Giovanni Toscani, Antonio Ravaglia, Silvio Seno & Francesco Zucca

Comprehension of various geological contests necessary implies 3D visualisation. But, besides the visualisation, a valid 3D model also represents a validation tool of the consistency of the informations used to realise it. In fact, features and data that are compatible in two dimensions may be unfounded in the third one; thus, the model construction leads to reconsider both the collected data and the related kinematic evolution previously suggested.

Two different kind of tools may be useful to represent geological contexts in 3D:

- 3D digital models (based on 2D data set) showing surfaces and volumes;
- analogue models (sandbox).

In this work we present an integration between both tools, showing a 3D reconstruction of a natural example and the related analogue model. Analogue models, giving an easy and helpful vision of the entire spatial evolution of the structures, are used also to check "sensitivity" and reliability of a 3D digital model against the type and the number of data that have been employed, thus identifying the minimal threshold of data needed to reach a valid outcome.

Analogue sandbox models are geometrically correct and spatially continuous, so that we can use them to check sensitivity and reliability of the digital representation against the type and the number of data that have been employed, thus identifying the minimal threshold of data needed to reach a valid outcome.

Geological context – We used as a natural example a sector of the Southern Alps thrust belt, the Vette Feltrine thrust sheets (D'ALBERTO ET AL., 1995). In map view, thrust sheets located in the area show undulations reflecting lateral heterogeneities due to:

- pre-existing geological structures;
- facies variation;
- thickness variations of the sedimentary cover.

The Vette Feltrine structures represent a typical non cylindrical case not completely imaged in 2D only. A 3D model gives an exhaustive representation of the whole geometry. The Vette Feltrine geological cross sections published by D'ALBERTO ET AL., (1995) are tightly spaced and balanced, for these reasons they are suitable to an interpolation and a 3D reconstruction.

Analogue model – Sandbox analogue model has been built to reproduce this geological situation. A glass microbeads layer has been introduced in the sand package to simulate a detachment horizon in a non homogeneous stratigraphy. We imposed lateral heterogeneity on the base of the model to force along strike variations in the thrusted anticline geometries. As a result we obtained different wavelength thrust sheets connected each other by an oblique transfer zone.

3D digital model – Sandbox analogue model has been tightly sectioned, not considering lateral slices affected by wall side effect. The sections have been digitised to reconstruct the surface of some key horizons and fault planes.

The same process has been followed for the Vette Feltrine cross sections.

Comparison between the analogue model and the real case shows along strike variations of structural parameters, such as:

- thrust sheets wavelength and geometry;
- thrust sheets horizontal displacement;
- topographic slope angle;

Some of these aspects are particularly evident in the 3D reconstruction and visualization; furthermore we can highlight them using structure contour maps.

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THE EFFECT OF CHEMICAL AND ISOTOPIC EXCHANGE ON MICA RB-SR AGES IN SLOWLY COOLED ROCKS.

Hannah Townley, Gawen Jenkin & Randy Parrish

The determination of cooling and exhumation rates of metamorphic terranes depends on knowing closure temperatures for different geochronological systems. Ages measured for geochronological systems are plotted against their closure temperatures to produce cooling curves. If a geothermal gradient is assumed the exhumation rate can be calculated, telling us about the tectonic behaviour of metamorphic rocks. Closure temperatures have conventionally been assumed to relate to the effective cessation of isotopic exchange (for example, Sr isotopes in the Rb-Sr system) during cooling. However, we suggest that the down-temperature chemical exchange of elements involved in dating schemes may also be important in controlling the closure temperatures of radiometric systems.

JENKIN et al. (1995) have suggested down-temperature exchange of Sr isotopes among minerals and this has been shown in JENKIN *et al.* (2001). In geochronological systems there is the potential for both isotopic (^{87}Sr with ^{86}Sr, investigated in this study using laser ablation ICP-MS) and chemical (Rb with K or Sr with Ca, investigated using an ion microprobe) exchange as the rock cools that will cause variations in measured ages. Understanding what these variations mean will give better constraints on closure temperature ages and therefore, the cooling and exhumation rates of mountain belts.

Simple calcite marbles, containing mica bands were used in this study. Two point phlogopite-calcite isochrons of samples from Lago del Narèt, Central Swiss Alps (where the metamorphic peak was attained at 25 Ma, after Steiner, 1984) produce ages of 17-18 Ma (^{87}Sr/^{86}Sr ~ 0.8 and ^{87}Rb/^{86}Sr ~ 290). These ages suggest 7 Ma of ^{87}Sr has been lost from the phlogopites during cooling, indicating isotopic exchange. Stable isotope data suggests no fluid flow has occurred during cooling, implying exchange via grain boundary and volume diffusion.

Laser ablation ICP-MS results suggest ^{87}Sr lost from the mica has entered the surrounding calcite, giving increased ^{87}Sr/^{86}Sr ratios in the calcite near the mica band, which decrease over a distance of a few centimetres (which varies with grain size, mineral mode and Sr concentration). Modelling of these results suggests a combination of grain boundary and volume diffusion is a suitable mechanism for the exchange.

The results of the ion microprobe study indicate chemical exchange is occurring among grains within this rock sample. Sr concentration profiles across calcite and K-feldspar grains show that K-feldspar is gaining and calcite is losing Sr at the rims of grains. The phlogopite in these samples has low total strontium concentrations and the Sr profiles are inconclusive.

The ion probe traverses, in conjunction with laser ablation ICP-MS results, show that both elements and isotopes of those elements are mobile during cooling. Strontium isotopic exchange occurs between the mica and the calcite with ^{87}Sr diffusing from the mica into the carbonate. However, the ion microprobe traverses suggest Sr chemical exchange occurs in the opposite sense, with net strontium movement out of the calcite and into other minerals, such as K-feldspar. This implies other Sr isotopes are mobile during cooling, a factor not previously considered in closure temperature models.

Combining the effects of both isotopic and chemical exchange, measured ages will decrease and the closure temperatures will be lowered compared to those calculated for only strontium isotopic exchange. Models of the chemical exchange suggest if Rb is increased in phlogopite, the measured ages will decrease and the closure temperature will be lowered compared to those calculated without chemical exchange, enhancing the mode effect (described in this paper and JENKIN et al. 1995). Using the Sr isotope traverse modelling, it may be possible to develop an independent method of estimating the cooling rate.

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GEODYNAMIC EVOLUTION OF THE EASTERN ALPS: EVIDENCES FROM FISSION-TRACK GEOCHRONOLOGY IN THE RHENODANUBIAN FLYSCH ZONE

Britta Trautwein, István Dunkl, Joachim Kuhlemann & Wolfgang Frisch

The geodynamic evolution of the Eastern Alps is reconstructed by studying the provenance and thermotectonic history of the Rhenodanubian flysch and Ybbsitz klippen zone. The fission-track geochronology on zircon and apatite gives the opportunity to decipher these processes.

The study shows that from Cenomanian till Eocene times, two different depositional realms existed, the Main Flysch basin and the Laab basin. The origin of the sediments was deciphered with zircon fission-track geochronology and by classifying the zircons after their external morphology (Pupin method). The Laab basin received sediments from the European continental margin. A northern position relative to the Main Flysch basin is therefore attributed to the Laab basin. The source area delivering the Main Flysch basin were the evolving Alps with detritus from Austroalpine units. The zircon fission-track ages point to thermotectonic events affecting the hinterland of the basins. The Cretaceous ages reflect the cooling after Eoalpine metamorphism in the Austroalpine realm. The Permian to Jurassic ages are the result of thermotectonic processes due to the disintegration of Pangea. Paleogeographically spoken, three different situations are possible: (1) the Main Flysch basin belongs to the South Penninic realm and the Laab basin to the North Penninic realm, (2) both basins belong to the North Penninic realm, or (3) North and South Penninicum were no separated depositional areas in the Eastern Alps.

The Rhenodanubian flysch zone (RDFZ) represents an accretionary wedge with a rather complex thermal history due to successive and differential accretion and exhumation. The sedimentary sequence was deposited along a convergent margin. According to the apatite fission-track data accretion started before the Maastrichtian and lasted until the Miocene. The accretion prograded from a central area (Salzburg-Ybbsitz) to the west and east. In the west, the accretion continued in Middle Eocene to Early Oligocene times reflecting the underplating of the RDFZ by the European continental margin sediments. In the east, where three nappes (Greifenstein, Kahlenberg and Laab nappes) can be distinguished, the exhumation started in Late Oligocene to Early Miocene time. The Kahlenberg and Laab nappes suffered total resetting, and the Greifenstein nappe partial resetting. According to the new paleogeographic reconstructions, the Kahlenberg and Laab nappes were placed on top of the Greifenstein nappe by an out-of-sequence thrust.

The apatite fission-track data give evidence for a burial depth of at least 6 km for the samples, which experienced total resetting, but not deeper than 11 km, since the zircon fission-track data do not show resetting.

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OLIGO-MIOCENE WNW-DIRECTED THRUSTING IN THE WESTERN ALPS NORTH AND SOUTH OF THE PELVOUX MASSIF: A COMBINED TECTONIC AND MICRO STRUCTURAL STUDY

Ghislain Trullenque, Stefano Ceriani,
Bernhard Fügenschuh, Renée Heilbronner & Stefan M. Schmid

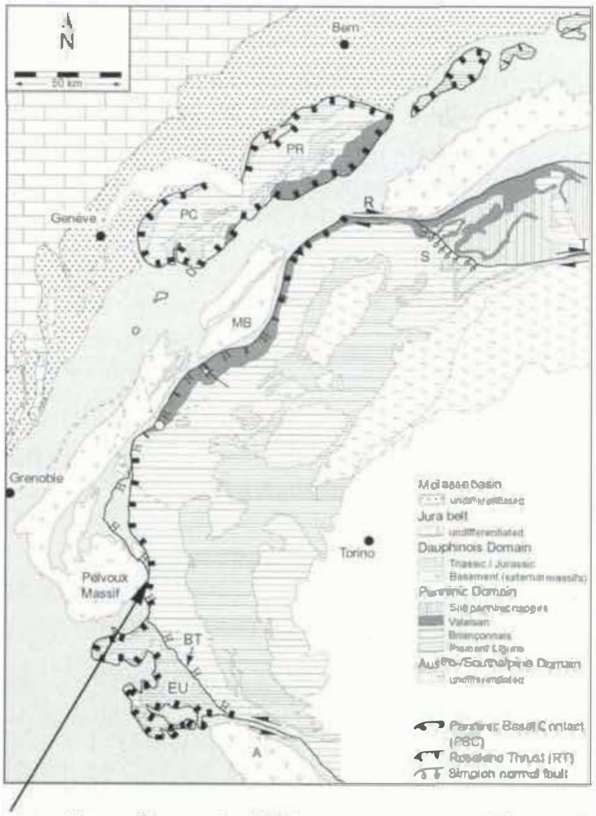
In the Alps, the contact between the Helvetic (or Dauphinois) paleogeographic domain and the internal Penninic domain is the result of a multistage tectonic evolution.

N-S shortening in the Eocene led to collision between these two domains as well as the emplacement of detached and unmetamorphosed Penninic nappes. In the western Alps, the end of this collision phase is marked by the transgression of detrital flysch formations, the Priabonian Aiguilles d'Arves and Cheval Noir flysch units (CERIANI et al. 2001).

In the Oligocene the whole pattern of convergence changed dramatically from N-S to WNW-ESE. The earlier formed contact between Penninic and Helvetic units, i.e. the Penninic Basal Contact (PBC), was partly reactivated and WNW-directed thrusting occurred along the Roselend thrust (RT, cf Figure 1). Along strike, from the Mont Blanc to south of the Pelvoux massif different units can be observed on either side of the RT. In the Mont Blanc area the RT reactivates the PBC and carried North Penninic units onto Helvetic units. In the Maurienne area, the RT could be traced within the Helvetic domain, separating Ultradauphinois from Dauphinois units (CERIANI et al. 2001). Immediately to the SE of the Pelvoux massif, the Roselend Thrust carried Briançonnais units over the Dauphinois domain. Further to the South, this same structure, reactivates the so-called "Briançonnais Front" (TRICART, P. 1986) in form of an out-of-sequence thrust which carries the Briançonnais units on top of the Embrunais Ubaye nappe stack.

Stretching lineations and related shear sense indicators consistently yielded top to the WNW directed thrusting along the studied portion of the RT from the Mont Blanc massif in the north to south of the Pelvoux massif.

Late Neogene to present NW-SE directed extension affected the whole Western Alps and partly reactivated earlier tectonic contacts (SUE et al. 1999).



Locality of sample 203

Figure 1

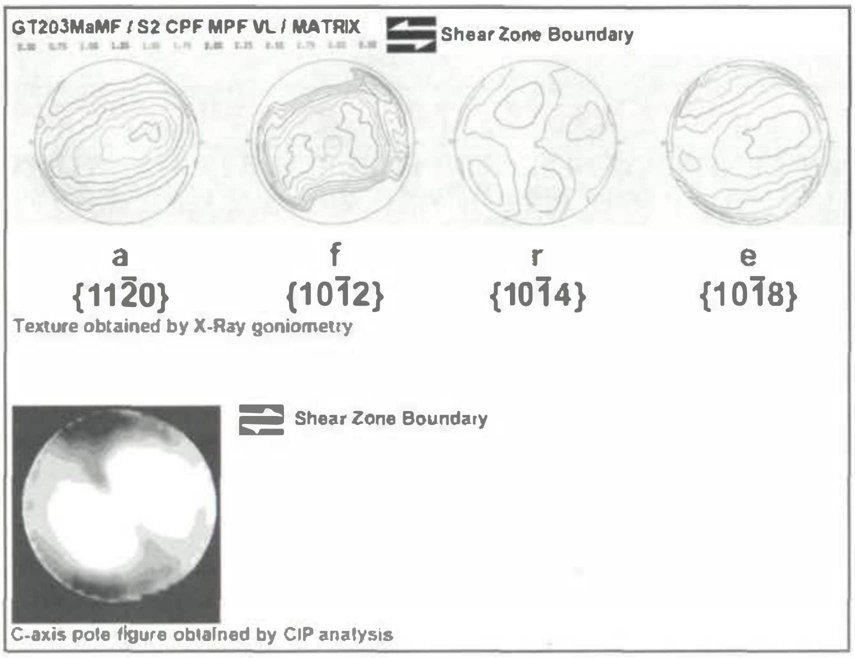


Figure 2

South of the Pelvoux massif, movements along the RT have induced intense shearing of mylonitized sediments. Textures and microstructures of calcite ultramylonites (grain size distribution from 10 to 100 mm) sampled in the autochthonous cover of the Pelvoux massif have been studied using Computer Integrated Polarisation microscopy (CIP) and X-Ray texture goniometry.

Preliminary results (cf Figure 2) indicate a combined contribution of twinning and basal <a>-glide deformation to the pole figures.

It remains unclear so far whether this is due to superposition of different deformation phases or to domains displaying distinct grain-size dependent deformation mechanisms.

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EXPERIMENTAL AND TEXTURE-DERIVED ELASTIC PROPERTIES OF PRINCIPAL ROCKS FROM THE TRANSALP SEISMIC TRAVERSE

Klaus Ullemeyer, Siegfried Siegesmund & Patrick N.J. Rasolofosaon

The TRANSALP research program includes seismological investigations along a traverse across the Eastern Alps. Most effort was put on the recording of a 340 km long near-vertical reflection seismic profile between Munich and Venice. For the understanding of the observed seismic structures, accompanying laboratory investigations of the elastic rock properties are required. The elastic properties of rocks have been confirmed to be anisotropic in the general case (see review by SIEGESMUND, 1996), they mainly depend on the lattice preferred orientations (textures) of the rock-forming minerals and the crack fabric (porosity). In order to obtain the most complete information on elastic rock anisotropy and its controlling parameters, the following experiments have been performed on various rock samples from the central part of the seismic profile:

- Complete compressional (P-, V_p-) wave velocity measurements at various confining pressures up to $P_{conf} = 200$ MPa. A better approximation of the crustal conditions can be achieved since cracks are more or less competely closed.
- Complete compressional wave velocity measurements on dry and water-saturated samples at atmospheric pressure. Since the compressional wave propagation velocities in air and water are diffent, the difference patterns represent a quantitative measure of the crack (pore space) distribution.
- Neutron texture measurements on the same specimens in order to calculate the compressional wave distributions from the mineral textures. The modelled velocity distributions are not affected by the other fabric parameters (like porosity) and therefore represent an upper velocity limit.

The P-wave velocity distributions measured at $P_{conf} = 200$ MPa approximate the texture-derived patterns, however, the velocities are generally lower at $P_{conf} = 200$ MPa (~ 0.3 km/s). The observed anisotropies $A = (V_{p\,max} - V_{p\,min})/V_{p\,max}$ range from 1% ~ 9% (texture-derived) and 5% ~ 16% ($P_{conf} = 200$ MPa). Highest anisotropy values are observed for monophase carbonate samples, whereas the P-wave anisotropies of polyphase gneisses are very low. The differences between both these velocity distributions confirm, that the P-wave anisotropies are not only texture-controlled. Since in most cases the minimum velocities parallel the normal to the main rock foliation, it seems that the observed velocity differences are somehow related to the foliation. The difference patterns between dry and water-saturated samples show a maximum parallel to the foliation normal, *i.e.*, the foliation plane represents the preferred plane of crack generation (accumulation of pore space). If any fluid-filled pore space should be possible at large depths, it is expected that the rock foliation controls its spatial distribution.

Seismic reflections originate from contrasts of acoustic impedance $Z = V_p r$ (r: density) between adjacent rocks and may be described by the reflection coefficient $R_c = (Z_1 - Z_2)/(Z_1 + Z_2)$. Considering mean velocities of the velocity distributions (*i.e.*, neglecting anisotropy), the maximal possible reflection coefficients are $R_{c\ max}$ = 0.11 (texture-derived) and $R_{c\ max}$ = 0.13 (P_{conf} = 200 MPa). Assuming that the foliations of adjacent rocks run parallel to the geological interface, the minimal velocities should be used for the calculations. In this case, the maximal possible reflection coefficients are $R_{c\ max}$ = 0.11 (texture-derived) and $R_{c\ max}$ = 0.14 (P_{conf}= 200 MPa), *i.e.*, changes are minor. Geological interfaces with such high reflection coefficients are easily visible in seismic cross sections. However, most hypothetical interfaces are characterized by much lower reflection coefficients and the question arises, whether they are sufficiently large to cause detectable reflections or not. From the anisotropy data presented, it may be inferred that discordant layering at the interface should produce stronger reflections, although the observed P-wave anisotropy is rather weak. It may be also speculated, whether fluids may be responsible for pronounced reflectors in the seismic sections.

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DATING TRANSPRESSIONAL DEFORMATION ALONG THE SALZACHTAL-FAULT (AUSTRIA): NEW IMPLICATIONS FOR THE EXHUMATION HISTORY OF THE TAUERN WINDOW

Christoph Urbanek, Wolfgang Frank & Kurt Decker

The Salzachtal-Ennstal fault zone (SEMP) is a major crustal-scale transpressional shear zone, which developed at the northern border of the Tauern Window during Tertiary lateral extrusion and unroofing of the Tauern Window (LINZER et al. 1997; NEUBAUER et al., 1999; Fig. 1). In the research area between Zell am See and the Rauriser Ache the Salzachtal-Fault juxtaposes rocks of the Paleozoic Upper Austroalpine Greywacke Unit and the Penninic Units of the Tauern Window. Both units show distinct deformational and cooling histories, which are described using new ***kinematic*** data and ***geochronological*** Ar/Ar age datings.

(A) The Penninic Units of the northernmost Tauern Window are part of a transpressional shear zone accomodating sinistral ***ductile shear*** and ***NNE/SSW compression*** along the E-W-striking shear zone. Kinematic data are mainly obtained from mylonitic marbles. Formation ages of synkinematic minerals from ***28 Ma to 35 Ma (Late Eocene to Early Oligocene)*** constrain the age of sinistral transpression at the northern border of the Tauern window. These ages are well

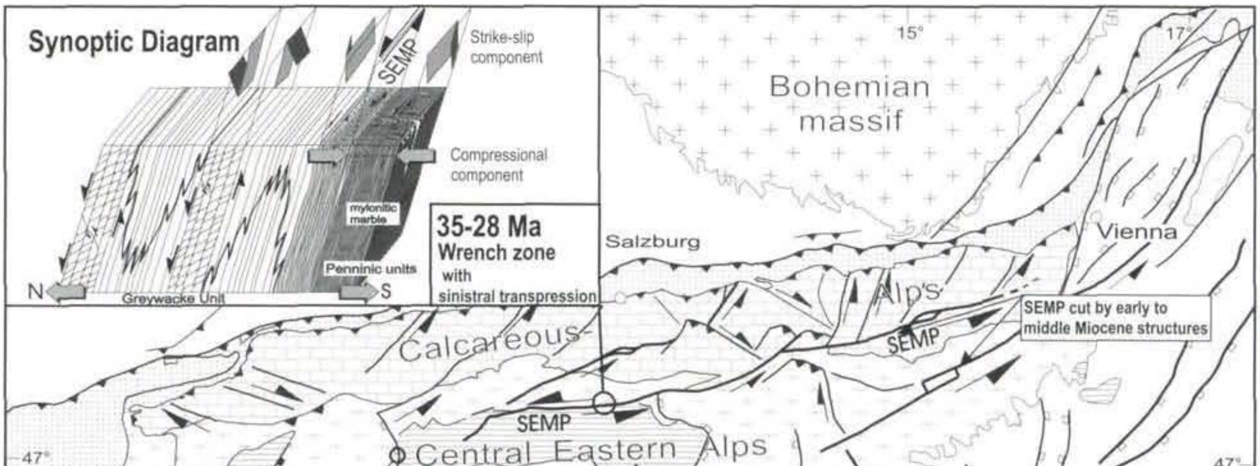

Fig. 1

Ar/Ar - Data Penninic Unit

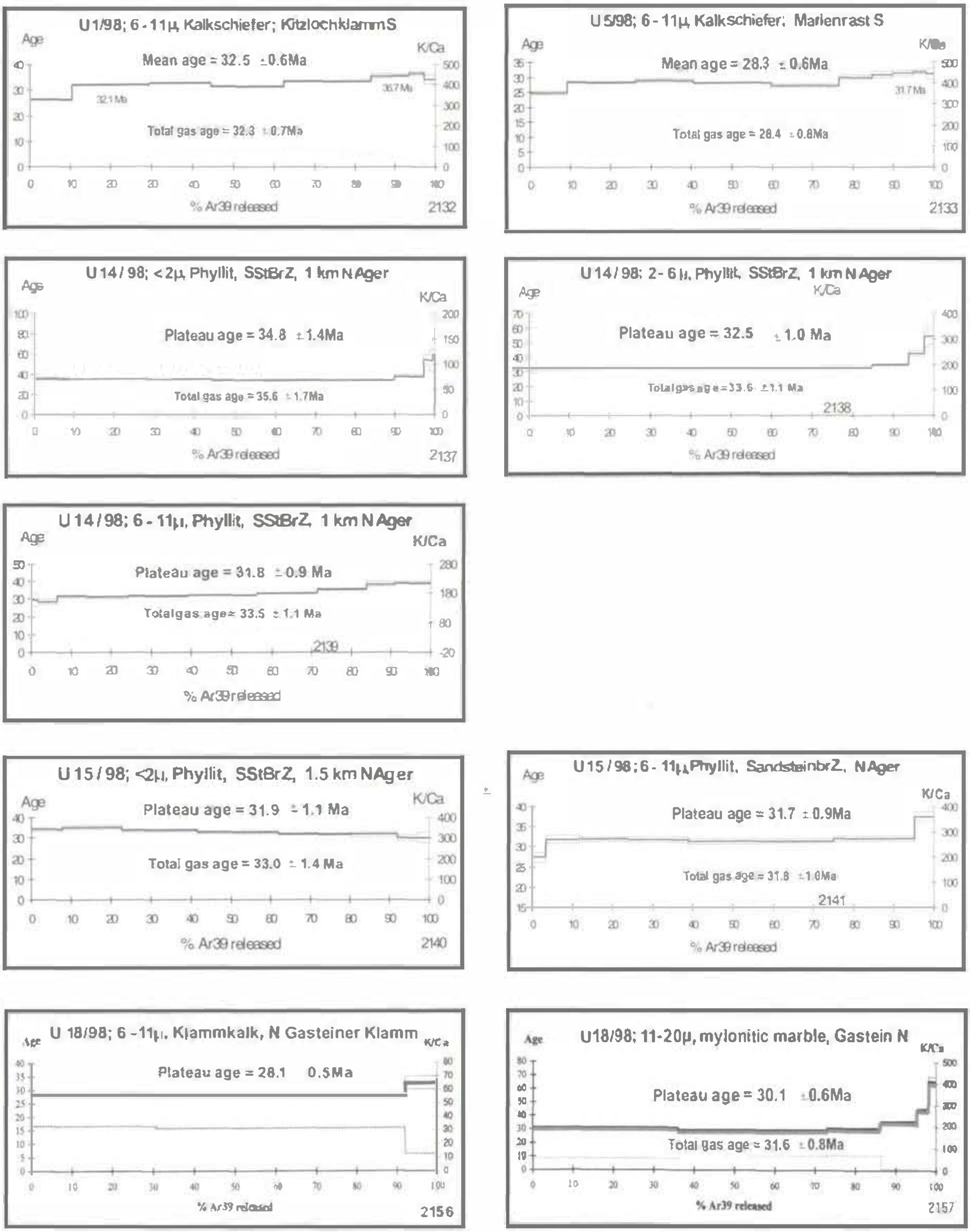

Fig. 2

defined by 9 Ar/Ar data from mica of different grain size fractions (< 2 m, 6-11 m and 11–20 m; Fig. 2). Indications for cretaceous ages in the cores of the micas are given.

(B) The rocks of the Greywacke Unit are devoid of comparable transpressional structures. The unit was affected by three main Cretaceous (***eoalpine) deformation*** events: **(a)** ***ductile shear*** ***(D_n)*** related to the formation of ±E-W striking, subhorizontal stretching lineations, **(b)** ***south-vergent folding*** ***(D_{n+1})*** and **(c)** ***normal faulting*** ***(D_{n+2})*** towards N indicated by SC-fabrics. 6 Createous Ar/Ar-cooling ages ranging from 90 to 115 Ma from white mica (< 2 m, 6–11 m and 11–20 m) indicate that the deformations D_n to D_{n+2} occurred during the Cretaceous.

Structures related to ***sinistral transpression*** provide further evidence for the kinematics of the sinistral SEMP-wrench fault north of the Tauern window, which is kinematically related to the exhumation of the Penninic Units south of the fault (LINZER et al. 1997; NEUBAUER et al., 1999). This *wrench zone* previously was interpreted as a Late Oligocene and Early Miocene structure. However, Ar/Ar data record ***Late Eocene/Early Oligocene (28 Ma – 35 Ma) ages*** for transpressional deformation at the northern border of the Tauern window. The data presented in this study are in line with previously published age data constraining the onset of decompression of the Penninic Units of the Tauern Window with 35 Ma (SELVERSTONE 1993).

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DISCRIMINATING METAMORPHIC GRADE AND STRUCTURAL LEVEL IN FIRST-CYCLE MODERN SAND FROM WESTERN ALPS

Giovanni Vezzoli, Eduardo Garzanti & Michele Russo

The present work focuses on modern first-cycle sand from low- to high-grade basement nappes of the thick-skinned Alpine Orogen, with the aim of describing the diagnostic signature of orogenic detritus and of devising the more suitable petrographic parameters allowing discrimination of metamorphic grade and structural level of source rocks.

Sources of Alpine crystalline detritus are varied and include: a) basement rocks of the European continental margin (Hercynian plutonic and metamorphic rocks of the External Massifs, metamorphic nappes of the Brianzonese Domain); b) distal continental margin to oceanic metamorphic units of the Ligurian-Piemontese Domain; c) basement nappes of the Adria continental margin (Sesia-Lanzo Zone, Dent-Blanche Klippe); d) Southalpine basement of the the Southern Alps thrust belt); e) Tertiary magmatic rocks of the Alpine cycle (Peri-Adriatic arc).

Sources are commonly intermingled, and detrital signatures are not univocal. Moreover, recycling of sedimentary cover and foreland basin units makes unraveling of primary sources a complicated task. For these reasons, we collected a large petrographic data set on all major alpine tributaries of the Po River draining the crystalline nappes of the Western Alps, from Liguria to Lombardy.

In order to obtain full quantitative information particularly on rock fragments, which provide essential information in orogenic sands, data were collected by means of a very detailed scheme including over 80 categories of grain-types, and according to both the Gazzi-Dickinson QFL and Indiana traditional QFR methods. A simple but complete synthesis of framework petrography is provided by an extended spectrum of nine compositional key indices: Q = quartz; F = feldspars and feldspathoids; Li = intrusive lithics (aplite, granophyre); Lv = volcanic and subvolcanic lithics; Lc = carbonate lithics, including marble grains which could not be consistently distinguished from recrystallized sparite; Lp = pelitic terrigenous lithics; Lch = chert and cherty mudrock lithics; Lm = metamorphic lithics; Lo = serpentinite and serpentine-schist lithics.

Further informations of source rocks are provide by heavy mineral with a spectrum of ten key indexes: ZTR = ultrastable minerals (zircon, tourmaline, rutile; HUBERT, 1962); T&O = titanium minerals and others (e.g. sphene, anatase, brookite, apatite, barite); Hb = horneblende; AA = other amphiboles; CPX = clinopyroxenes; OPX = orthopyroxenes; OS = olivine and spinel; LgM = low-grade metamorphic minerals (e.g. pistacite, clinozoisite, zoisite epidotes, chloritoid, pumpellyte); Gt = garnet; HgM = high-grade metamorphic minerals (e.g. staurolite, andalusite, kyanite, sillimanite).

In order to differentiate between structural level of different composition and metamorphic grade, a detailed classification of metamorphic lithics was designed. Metapelite, metafelsite, and metabasite grains were further subdivided into subspecies according to increasing degree of phyllosilicate crystallization, progressive development of foliation, and mineralogical parageneses. Among metapelite grains in particular, slate lithics with tiny sericite and weak rough cleavage (Lmp1), were distinguished from phyllite lithics with sericite lamellae and strong cleavage

(Lmp2), from schist lithics with micaceous lamellae and schistosity (Lmp3), micaschist lithics with muscovite flakes, well-developed schistosity and occasionally medium-high grade minerals (e.g., garnet) (Lmp4). This classification represents an extension of that originally proposed by DORSEY (1988).

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STRUCTURAL AND GEOCHRONOLOGICAL EVIDENCE CONSTRAINING THE GEOMETRY, KINEMATICS, AMOUNT OF DISPLACEMENT AND TIMING OF THE GIUDICARIE FAULT SYSTEM (ITALIAN EASTERN ALPS)

Giulio Viola*, Neil Mancktelow & Diane Seward

The Giudicarie fault system (Giudicarie *sensu stricto*, Meran-Mauls, Passeier, Thurnstein and Jaufen faults) represents a sharp break in the generally E-W strike direction of the orogen-scale Periadriatic fault system. Establishment of whether this break in strike is an inherited structural feature (pre-Oligocene) or a late, collision-derived structure is crucial for estimating the maximum possible amount of accumulated dextral shearing along the Periadriatic fault. The Giudicarie fault system is therefore a key element in understanding the Late Oligocene to Neogene evolution of the Alpine chain. In this study, the kinematics, timing and magnitude of movements on the various component segments of the Giudicarie fault system are considered, based on a detailed structural investigation combined with zircon and apatite fission-track analysis from closely spaced samples. Two main tectonic phases are established (see also Prosser, 1998, 2000; Müller et al., in press): a) back-thrusting of the Austroalpine units over the Southern Alps around 32 Ma, recorded by basement and limestone mylonites along the Giudicarie and Meran-Mauls faults with transport directions towards 100-110∞, and b) later sinistral transpressive displacement, characterized by structures at the ductile-brittle transition, which overprinted the top-to-E/ESE thrust-related mylonites but also partitioned into a major system of transcurrent faults in the Southalpine domain. It was during this later event (b) that the Periadriatic fault attained its present-day geometry. However, the amount of sinistral displacement along the Giudicarie system was only ~15-20 km. The magnitude is established from the sinistral offset of the Jaufen mylonites across the Passeier brittle fault and the discontinuous distribution of Oligocene tonalitic lamellae along the Giudicarie fault. A direct structural connection is also established between the Brenner and the Jaufen faults. This constrains the timing of phase (b), since it must postdate the main exhumation phase of the Tauern Window at 20-18 Ma (Fügenschuh et al., 1998). The results of this study argue strongly against an originally straight Periadriatic fault. The Giudicarie fault formed a restraining bend in this part of the Periadriatic fault system since at least the Late Miocene and probably since the Late Oligocene.

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THE THERMAL REGIME OF THE EASTERN ALPS FROM INVERSION ANALYSES ALONG A N-S TRENDING PROFILE

Hans-Dieter Vosteen, Christoph Clauser & Bernd Lammerer

In the summer of 1999 at twenty-six locations in the Eastern Alps a collective of 118 rock samples were taken. Between 3-7 rock samples represent each of the main lithologic units which contribute at least one kilometer thickness of the Eastern Alpine crust. The rock samples represent different depth levels of the Eastern Alpine crust.

After the sampling campaign petrographic and geochemical investigations were carried out to permit an accurate rock naming. At the same time rock-physical laboratory measurements of bulk and pure density, thermal conductivity (measured on water saturated rocks at room temperature and on dry samples in the range from 0 – 800 °C), thermal heat capacity (at temperatures ranging from 20-300 °C) and heat production rate were executed.

The results of the measurements concerning temperature-dependence of thermal conductivity of different rocks were further on used to check a formula, set up by SASS et al. (1992) and originally tested for magmatic rocks in the temperature range from room temperature up to 250 °C. Additionally it was tried to determine coefficients, making it possible to predict temperature dependence of heat conductivity also for other rock types (e.g. different magmatic, metamorphic and sedimentary rocks) and for temperatures from 250 °C to at least 500 °C.

A further new objective was to create a pseudo depth profile of heat production for at least a part of the Eastern Alpine crust on the basis of measured data extracted out of rock-samples. Thereby it should be tried to resume an approach of HAWKESWORTH et al. (1974) who made an attempt to create a pseudo-depth-profile of heat production for a small area in the Tauern Window and basing also on measured data obtained from pick-samples. The authors projected rock samples, taken in the context of a geological mapping in a small area in the Tauern Window into their original depth of genesis to verify trends in the reduction of heat production with depth for the basement of this area.

In order to get reliable input parameters for stationary finite element simulation calculations on conductive heat transport all measured values were re-evaluated, using the Bootstrapping procedure. A FE-mesh was generated firstly based on the TRANSALP profile generated by LAMMERER et al. (1998) and adapted later on permanently to the newest results of the other TRANSALP working-groups. The simulation calculations were carried out with a FE-mesh with 2015 finite elements (6382 nodes). Later on the mesh had to be simplified to 936 finite elements (2989 nodes) because of fixed limitations in the inversion program. The results of the simulation calculations were calibrated by means of temperature and heat flow data from drill holes, tunnels and lakes in Germany, Austria and Italy.

Later on inversion calculations were executed with a FE program based on the Bayesian parameter estimation technique, which was originally developed by WANG (1989) and extended by LEHMANN (1998) regarding the temperature dependence of the rock-physical parameters. A substantial target of the inversion analyses was to estimate the uncertainty of the modelled conductive heat transfer processes in the basement of the Eastern Alps (one major aim is to define the variability of the heat flow from the mantle into the crust). Additionally Peclet number analyses were carried out to estimate the influence of transient effects (uplift and erosion) on the current temperature distribution.

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EMPLACEMENT TECTONICS OF THE RIESERFERNER PLUTON AND ITS COUNTRY ROCKS (EASTERN ALPS)

Ralph Wagner, Claudio L. Rosenberg & Mark R. Handy

Structural mapping of the Austroalpine basement south of the Tauern Window between the Pfunderer Valley in the W and the Lasörling group in the E revealed three major deformation phases. The first one (D1) was nearly completely overprinted by D2 and D3 under greenschist facies conditions. The occurrence of the latter two deformation phases in Mesozoic rocks of the Matreier Zone (MZ) proves their Alpine age. The main foliation S2 is oriented parallel to axial planes of F2 folds. S3 foliation occurs along Oligo-Miocene shear zones. In the western part of the area (Pfunderer Valley) the main foliation is a steeply dipping S3. Further to the E (Ahrn Valley and Lasörling Group) S2 seems to be the dominant foliation. In contrast to S3, S2 may also dip gently to subhorizontally in some areas.

The area is affected by several map-scale shear zones, all of which are approximately E-W trending and subvertically dipping. These shear zones have subhorizontal stretching lineations, but accommodated opposite senses of shear. The northern margin of the Austroalpine basement, just south of the western Tauern Window, is characterized by a dextral shear zone that was active under lower greenschist facies conditions. This shear zone is located mainly in the Cima Dura Series and is therefore named the Cima Dura Shear Zone (CDSZ). The occurrence in the CDSZ of both sinistral shear sense indicators in addition to the more common dextral ones is interpreted to result from transpressive deformation.

Further south the sinistral Speikboden mylonitic shear zone (KLEINSCHRODT, 1987) overprints the northern border of the 30 Ma old Rieserferner Pluton (BORSI et al. 1978b). Overprinting relationships indicate syn- to post-intrusive deformation, thus constraining mylonitization to have been syn- to post 30 Ma.

The southern border of the Rieserferner Pluton is bounded by another transpressive sinistral shear zone, the Defereggen-Antholz-Vals Line (DAV). The local occurrence of magmatic foliations and lineations oriented parallel to the mylonitic foliation and stretching lineation of the DAV suggests that this shear zone was also active during intrusion of the Rieserferner Pluton. The widespread solid-state overprint of the magmatic fabrics indicates that deformation continued after 30 Ma.

Our Rb-Sr dating of fine grained (< 0.2 μm - < 63 μm) white micas within dextral shear bands of the CDSZ revealed an age of 35,7±5,4 Ma (Rb-Sr on white mica). We interpret this age as the maximum age of dextral shearing. Sinistral shearing along the DAV was dated at 33-30 Ma (MÜLLER et al., 2000). It is therefore suggested that dextral and sinistral movements south of the Tauern window were coeval and effected the eastward extrusion of the Austroalpine basement.

Biotite cooling ages in the investigated area are progressively younger from E to W (BORSI et al. 1978a), reflecting a later or greater exhumation of the western part of the area. First results from Al in hornblende barometry (ALBERTZ 1999) on the tonalitic rocks of the Rieserferner Pluton seem to confirm this interpretation; the crystallization pressure increases from E to W. In addition, the progressive disappearence of F2 folds from E to W associated with the increasing occurrence of S3 foliations suggest that N-S shortening increases from E to W. Therefore, N-

S shortening appears to be accommodated by both vertical and eastward extrusion.

The varied orientation of the axial planes of F2 from subhorizontal (in the pluton roof) to subvertical (along the pluton sides) suggests that prior to intrusion the main foliation affected by these folds was heterogeneously oriented, probably due to prior folding. Therefore, folding of the Early Alpine foliation started before 30 Ma.

The geometry of the roof is characterised by two domal structures, separated by a syncline with a N-S striking axial plane. This orientation is perpendicular to the regional foliation. In other areas of the roof the foliation of the country rocks is folded, with axial planes dipping gently to the NW, parallel to the roof of the pluton. These orientations are not found away from the pluton and are therefore interpreted to result from emplacement-related deformation. Large parts of the roof of the pluton are discordant with respect to the enclosing rocks, and no significant strain increase is observed at the contact. Xenoliths of the country rocks are rare.

Large parts of the southern margin of the pluton dip steeply to the south and show fabrics oriented parallel to those of the DAV-Line. The floor of the pluton is exposed at its western end. Here, the country rocks dip with 20° to 40° to the E, beneath the tonalite. This allows one to estimate the thickness of the pluton at ca. 2 km.

Mapping in the SW part of the pluton (upper Val Fredda) reveals concentric magmatic foliation traces with steep lineations, both on the map- and the outcrop scales. We interpret these fabrics as feeders for the ascending melts.

Our observations lead us to the following emplacement history of the Rieserferner Pluton: the ascent of the tonalitic melts takes place along the mylonites of the DAV. At a depth of ca.12 km the melts intrude discordantly into the country rocks, just north of the DAV and form a subhorizontal, magmatic protrusion of ca. 2 km thickness. Gravitational instabilities of this protrusion lead to the domal stuctures of the pluton. Our interpretation of the Rieserferner Pluton as an elongate sheet-like body with an asymmetrical protrusion contrasts markedly with the interpretation of MAGER (1985) and STEENKEN et al. (2000) of the pluton as the magmatic filler of a purported releasing bend or pull-apart between the DAV and Speikboden mylonites. The lack of a field evidence for a continuous Speikboden mylonite zone precludes a pull-apart geometry, and suggests that deformation was widely distributed with conjugate domains of dextral and sinistral mylonitic shear.

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BACKSTRIPPING FAULTS: APPARENT DIP SLIP RATES ALONG MIOCENE FAULTS IN THE VIENNA BASIN (AUSTRIA)

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The dating of movements on synsedimentary faults relies mainly on relative ages of offset and sealing strata. Ten Veen & Kleinspehn (2000) used backstripped basement subsidence curves from both the hanging wall and the footwall blocks adjacent to major normal faults to evaluate timing and sense of dip-slip along these faults. The sense of fault movements can be directly determined, e.g. converging or crossing basement subsidence curves indicate reversals in the sense of faulting. Based on this method, we calculated the normal slip component of slip rates of major faults for given biostratigraphic zones and formations along a transect through the central part of the Miocene Vienna Basin.

The structural evolution of the Vienna Basin is characterized by a complex interplay of compression, strike-slip movements and extension, related to final compression and lateral extrusion. Sedimentation started during the Early Miocene (Eggenburgian-Ottnangian-Karpatian) with the development of a marine piggyback basin on top of moving Alpine thrusts. Inversion in the central Vienna Basin at the Karpatian-Badenian boundary, indicated by an erosional unconformity and fluvial conglomerate deposition (Weissenbäck, 1996), was followed by the development of a fully marine pull-apart basin in a strike-slip/transtensional setting during the Badenian (Decker, 1996).

Standard backstripping and fault backstripping methods were applied, based on borehole data provided by OMV, including lithology information from interpreted logs (spontaneous and resistivity logs). Absolute basement subsidence rates are as high as 3000–4000 m/Ma, absolute tectonic subsidence rates range up to 3000 m/Ma; the highest subsidence rates are recorded during the Karpatian (sedimentation of Gänserndorf and Aderklaa formations). Subsidence rates decrease during the Lower Badenian. During the Middle Badenian (*Spiroplectammina*-Zone), the Lower Sarmatian, and the Middle Pannonian increased subsidence rates are recognized.

Backstripping for individual fault systems of the transect indicates varying time intervals and senses of fault movements. The western marginal fault, the Bisamberg Fault, displays no or pure strike-slip activity during the Karpatian to Early Badenian, followed by dip slip rates up to 540 m/Ma during the Late Early Badenian to Middle Badenian and a second major fault activity during the Late Sarmatian to Middle Pannonian. Major dip slip with rates as high as 940 m/Ma is recorded in the central part of the Vienna Basin during the Karpatian. Reversed sense of movements along normal faults during the Early Badenian indicates a major rearrangement in the fault pattern. During the Early Sarmatian a short pulse of dip slip along the investigated faults is recorded.

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THE LITHOSPHERIC STRENGTH OF THE EASTERN ALPS: NFERENCES FROM NUMERICAL PREDICTIONS

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The present-day lithospheric strength of the Eastern Alps is calculated along the N-S running reflection seismic line "TRANSALP" and the W-E running refraction seismic line "ALP75". The results of the deep seismic surveys (e.g. SCARASCIA & CASSINIS, 1997; Transalp Working Groups) and the surface geology constrain the geometry of the modelled sections and allow setting up a lithospheric-scale rheological model. For both sections we calculated the thermal structure of the lithosphere through solving the heat transfer equation in two dimensions based on surface heat flow data (SACHSENHOFER, in press; DELLA VEDOVA et al., in press) and thermal boundary conditions. Finally, the yield strength along the TRANSALP and ALP75 sections was calculated based on failure (Byerlee's Law) and creep (power law creep) functions for which experimentally determined rock mechanics data (e.g. CARTER & TSENN, 1987) and constant strain rates are used. In agreement with the present-day stress regime strength calculations have been performed for compressional (TRANSALP) and extensional (ALP75) deformation.

Along the TRANSALP profile highest frictional strengths are predicted for the European upper and lower crust and the upper mantle underneath the Molasse Basin. Southward, lithospheric strength decreases and reaches a minimum in the area of the Tauern Window where frictional strength is restricted to the upper crust, only. South of the Periadriatic Line lithospheric strength increases again such that high frictional strengths are predicted for the Adriatic upper crust and the uppermost mantle. Unlike to the European crust hardly any strength is left within the Adriatic lower crust pointing to strong decoupling between the Adriatic upper crust and mantle. In W-E direction (ALP75 Line) frictional strength is concentrated within the top15 km of the upper crust in the Tauern Window area. Further to the east, underneath the Austroalpine Units, a distinct increase of strength within the lower crust and the upper mantle is related to a dramatic shallowing of the Moho as deduced from P-wave velocities. Towards the Styrian Basin lithospheric strength again decreases as a function of higher heat flow values in this area. Along the ALP75 section a strong crust-mantle decoupling is suggested.

The model predictions have been tested against the seismicity of the Eastern and the Southern Alps assuming that seismic activity is indicative for brittle deformation. The majority of the seismic events occurred along both lines (25 km wide zone on both sides of the lines) within the upper 15 kilometres of the crust. They correlate fairly well with the predicted depth extent of the brittle upper crust assuming a wet rheology and a constant strain rate of $10^{-14}s^{-1}$. Little seismic activity in the area of the European foreland supports the model predictions of a strong European plate. Within the Adriatic plate, movements along shear zones, within which strain rates are higher and, therefore, cause a downward shift of the brittle-ductile transition, may explain seismicity below the predicted cut-off depth for brittle deformation. Model predictions suggest that strain rates as high as $10^{-11}s^{-1}$ could account for the deeper earthquakes. Along the ALP75 Profile the upper part of the lower crust (ca. 20 km depth) retains some seismicity too, which is in better agreement with a dry rheology or higher strain rates.

The predicted lateral variations of lithospheric strength in N-S as well as W-E direction is in good agreement with the theory of extrusion models that promote the squeezing out of weak material from in-between more rigid blocks. Furthermore, lateral extrusion is supposed to be facilitated by a strong crust-mantle decoupling orthogonal to the convergence direction as also suggested by the model predictions. Seismicity and GPS data (e.g. GRENERCZY et al., 2000) suggest that this process is still active in the Eastern Alps.

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INTERRELATIONSHIP BETWEEN BRITTLE DEFORMATION STRUCTURES AND GROUND SETTLEMENTS ABOVE TUNNELS IN FRACTURED CRYSTALLINE ROCKS

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Recent measurements of surface displacements above the Gotthard highway tunnel in central Switzerland have shown up to 12 cm of subsidence over approximately 800 meters of overburden. Subsidence of this magnitude in a fractured crystalline rock mass is unexpected and appears to be related to large-scale consolidation resulting from fluid drainage and a reduction in the water table level. These displacements are of notable concern since they could adversely affect the integrity of surface structures (e.g. dams) above the underground opening.

Construction of the Gotthard highway tunnel occurred between 1970 and 1980 and was driven through the fractured polymetamorphic, crystalline rocks of the Aar and Gotthard massifs. During construction initial water inflows of up to 150 litres per second were measured in an area where several brittle fault zones with steeply dipping joint sets occurred. Analysis of the hydrological data from the tunnel revealed spatial relationships between the water inflow from these large-scale fractures and the settlements observed on surface. A study was therefore initiated to investigate the apparent relationship between the tunnel construction and the measured subsidence. This study incorporates the use of geodetic measurements, surface and underground discontinuity mapping, and numerical modelling techniques.

Brittle discontinuities, i.e. brittle fault zones and joints, play a major role in geotechnical engineering problems in crystalline rock masses. Ground water flow in low-permeability rock masses (e.g. granitic gneiss), is predominantly controlled by brittle structures which form a connected fracture network. If a tunnel then intersects this water-filled pressurized, fracture network, the rock mass will drain. Several examples from recent and previous tunnel construction sites have shown that high water inflow rates often lead to serious technical problems. Another effect related to tunnel drainage is the change in pore pressure within the rock mass. This hydro-mechanical coupled process affects the mechanical behaviour of discontinuities and also the low-porosity intact rock matrix. Thus, the knowledge of fracture-orientation, -spacing, -frequency and -length is essential to construct a 3-D fracture network, which in turn provides the basis for subsequent hydro-mechanical numerical modelling.

The first stage of this investigation involved the mapping of existing joints and brittle fault zones on a regional scale. The diverse behaviour exhibited by brittle fault zones relative to joints, especially with respect to hydro-mechanical behaviour, required that these structures be treated and evaluated independently. Geological and topographical data were collected and managed through a GIS database, which was subsequently programed to resolve the orientations and spatial relationships between dominant joint sets. Results presented in this talk show that the jointing system can be characterised by three to four main joint set orientations depending on the rock type: two steeply dipping sets sub-parallel and perpendicular to the foliation; and one to two sets with a medium to flat dip angle. The number of joint sets and orientations vary with rock type and region. One major joint set, with respect to frequency and length, is sub-parallel in orientation to the strike of the main brittle fault zones.

The full brittle fault zone pattern shows two major sets striking SW-NE and NNE-SSW, and one minor set with a W-E strike. The structural composition of the brittle fault zones can be characterised as a heavily fractured cataclastic zone with layers of mm to dm thick sand-clay bearing fault gouges. These fault zones dip steeply and form, together with the sub-parallel joint set, a 'fan-like' structure with a NE-SW striking axis. Most of the fault zones can be described as strike-slip faults with right-handed shear.

Findings from the second stage of this investigation are also presented and involve the detailed mapping of joints through the use of scanlines along surface outcrops above the Gotthard-road tunnel. A high degree of correlation, with respect to the number of joint sets and orientations, was found between both regional and local scale analyses and between surface and tunnel measurements. Whereas outcrop measurements in general produce only discontinuity orientation data, the more systematic scanline technique allows for measurements of joint-spacing, -frequency and -length. These geometrical parameters, when represented by different probability distributions (negative-Exponential-, Weibull- or Log-normal-distributions), form the input for the 2-D or 3-D network generation.

An example is provided using the 2-D distinct-element code UDEC, used to model discrete block displacements induced through the opening and closing of discontinuity apertures as a function of changing fluid pressure and normal stress due to tunnel drainage.

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EVOLUTION OF THE LARGE SCALE DRAINAGE PATTERN OF THE SWISS ALPS IN RESPONSE TO COLLISION TECTONICS

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The present day structure of the Swiss Alps is largely the result of a continent-continent collision which occurred in the past ca. 40 Ma. This collision led to the exhumation of high grade metamorphic rocks. A steeply N-dipping backthrust in the south (Insubric Line) is associated with denudation of a nappe pile 25 km thick. Further north, subsequent thrust faulting resulted in external basement uplifts, and associated denudation removed about 10–15 km of section.

The large scale 1st order geomorphic characteristics of this chain include two water divides and two belts of high elevations. On an erodibility map these areas of high elevation correlate to bedrock types with low erodibility (granitic rocks).

Numerical surface process modeling was carried out to examine the coupling between surface and deep processes. Surface processes include fluviatile and hill slope diffusive mass transfer. Deep processes are modeled with tectonic forcing as deduced from the crustal evolution of the Swiss Alps. This includes two uplift maxima: an earlier uplift along a model-Insubric Line which is followed by uplift of a model-external basement uplift. Combining a model-crust with rocks of homogeneous erodibility with this Alpine-type tectonic forcing results in a drainage pattern dominated by very stable rivers insensitive to changes in uplift rates. These rivers maintain their course perpendicular to the orogen axis almost irrespective of changes in uplift rates or erosional parameters. Only if two uplift maxima are taken to operate simultaneously do two water divides develop. If on the other hand a highly erodible unit, intended to represent a 2 km thick nappe stack of sedimentary rocks sandwiched between crystalline basement, is included in the model, the drainage pattern undergoes a profound change. Instead of incising the later forming northern model-basement uplift, axial rivers get captured by headward erosion of longitudinal rivers developing along the highly erodible units. The defeat of these axial rivers is held responsible for the ensuing development of the secondary water divide and the migration of the main water divide away from the maximum uplift of the model-Insubric Line.

Applied to the Swiss Alps the model results suggest that the primary signature of the collision, a nappe stack composed of rocks of very different erodibilities, together with the late-collisional uplift played an important role in the reorganization of the Miocene drainage pattern with axial rivers to the longitudinal rivers flowing today.

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