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Tectonic map of the Alps and overall architecture of the Alpine orogen

Stefan M. SCHMID[1], Bernhard FÜGENSCHUH[1] and Ralf SCHUSTER[2]

(with 3 figures)

The Alps record the closure of several ocean basins in the Mediterranean region during convergence between the African and European plates. In recent years it became increasingly evident that the oceanic and continental palaeogeographic realms, from which the alpine tectonic units derive, were arranged in a rather non-cylindric manner. This led to very important along-strike changes in the overall architecture of the Alps, also reflected for example in the deep structure of the Alps or in the different age of the main metamorphic events (Tertiary in the Western Alps, Cretaceous in the Austroaalpine units of the Eastern Alps). In view of these changes the correlation of tectonic units between Western and Eastern Alps is not an easy task, and is additionally hampered by a bewildering complexity in the nomenclature of regional tectonic units, that often change name across national boundaries.

This contribution presents a new tectonic map of the entire Alps. The map intends to introduce non-specialists into the major units of this orogen and, it will, at the same time, hopefully provoke discussions amongst specialists. The authors are fully aware that some colleagues will not agree with some of the correlations made, or that others might disapprove with the nomenclature used. Concerning nomenclature and correlations, we primarily used palaeogeographical affiliation for those tectonic units that preserved their Mesozoic cover, and tectono-metamorphic evolution in case of high-grade metamorphic basement (Meozoic and/or pre-Mesozoic), amongst other criteria of course. We tempted to avoid too many local names and keep the number of mapped units as small as possible.

This paper also gives a short overview of the overall architecture of the Western and Eastern Alps of Europe and their forelands by presenting a series of

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large-scale cross-sections. These are largely based on recent geophysical-geological transects.

Largely following FROITZHEIM et al. (1996), the various units mapped in the new tectonic map of the Alps may be conveniently grouped into the following major palaeogeographic and tectonic units: 1) Apulian Plate south of the Peridriatic Line: Southern Alps and Adriatic indenter; 2. Apulian Plate north of the Periadriatic Line: large parts of the Austroalpine nappe system; 3. Neotethys and its distal passive margin: Hallstatt, internal Dinarides, Eoalpine subduction channel in the Austroalpine nappe system; 4. Tisza Unit: only outside the Alps s.str.; 5. Margna-Sesia fragment: Penninic–Austroalpine transition zone; 6. Piemont–Liguria Ocean: Upper Penninic nappes; 7. Briançonnais terrane: Middle Penninic nappes, present only west of Tauern Window; 8. Valais Ocean: Lower Penninic nappes, including obere Schieferhülle of Tauern Window and Rhenodanubian flysch; 9. European margin: Subpenninic nappes of Lepontine and Tauern cores and detached sediments of the Helvetic nappes.

The new tectonic map is based on the "Structural Model of Italy" (BIGI et al. 1990) and includes alternative and/or new sources of information. The great number of different units defined by BIGI et al. (1990) was reduced and assigned to a mere 41 units chosen for compiling the new tectonic map. Only the northeastern and southwestern corners near Vienna and in former Yugoslavia were outside the "Structural Model of Italy" and taken from the official Geological maps of these two countries, respectively. The subdivisions used for the basement-dominated Austroalpine units of the Eastern Alps, situated south of the Grauhwackenzone and north of the Periadriatic Line, have been completely revised. The traditional subdivision into Lower, Middle and Upper Austroalpine nappes was abandoned in favour of new subdivions, largely following SCHUSTER et al. (2001).

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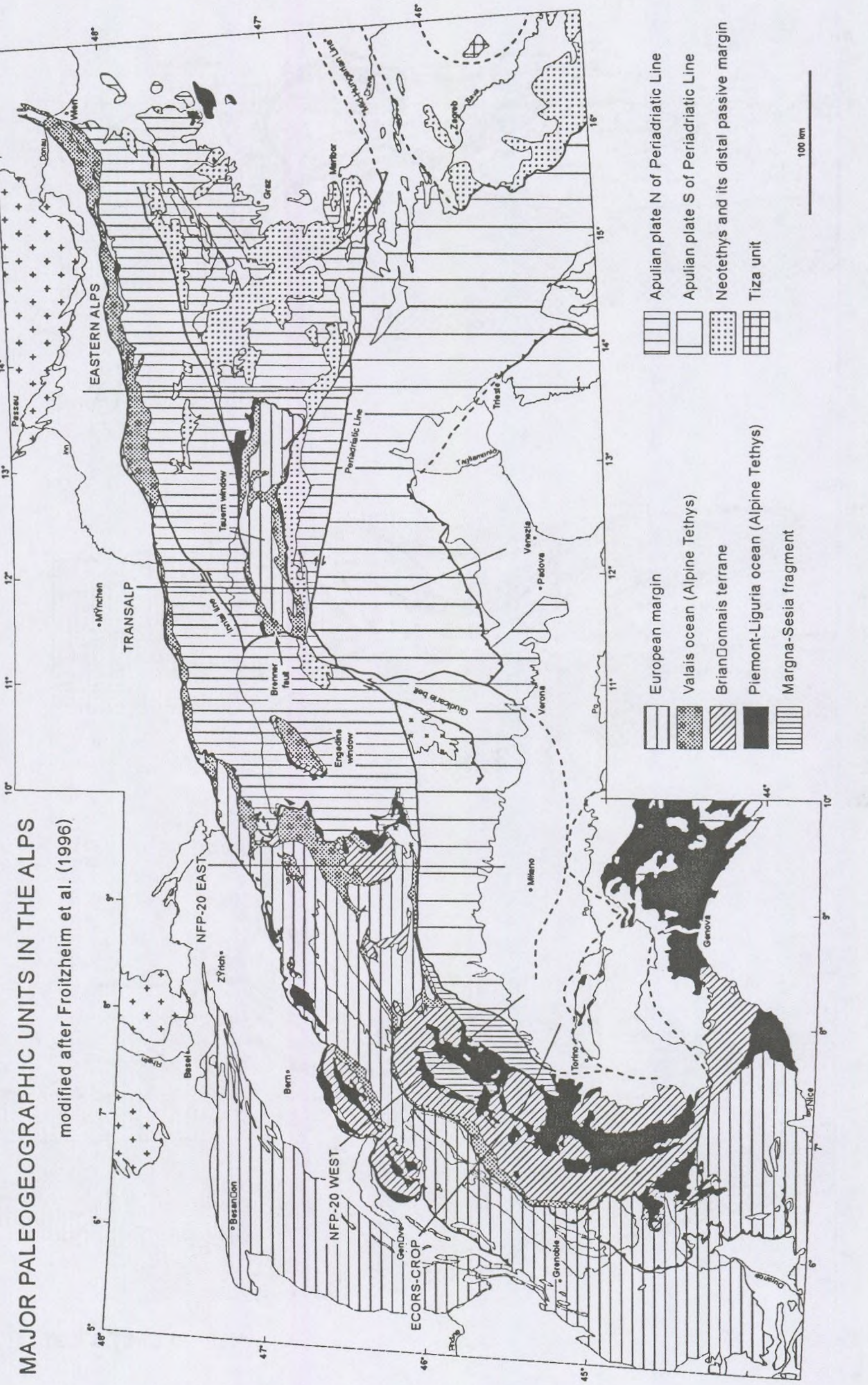
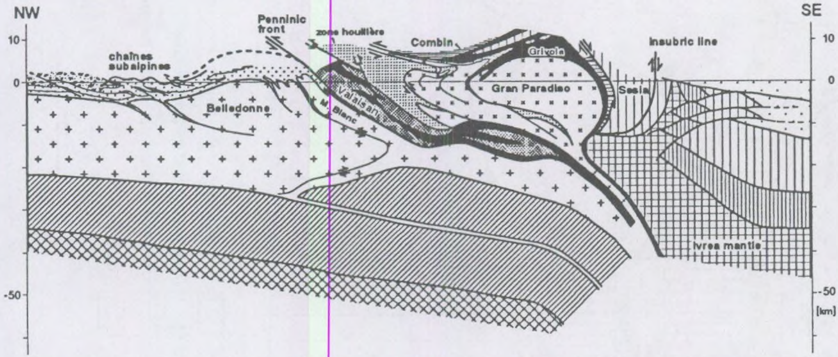
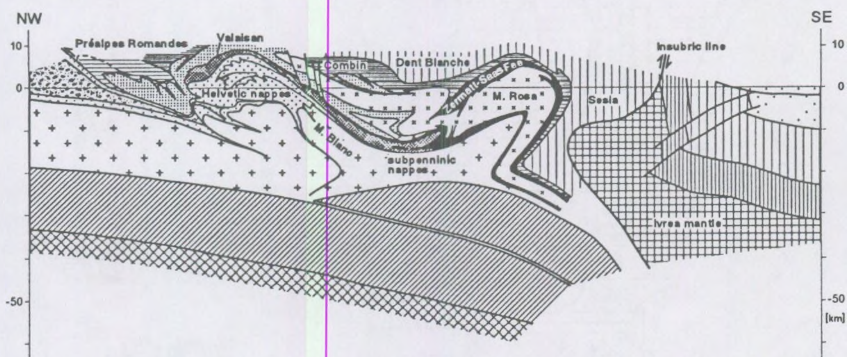
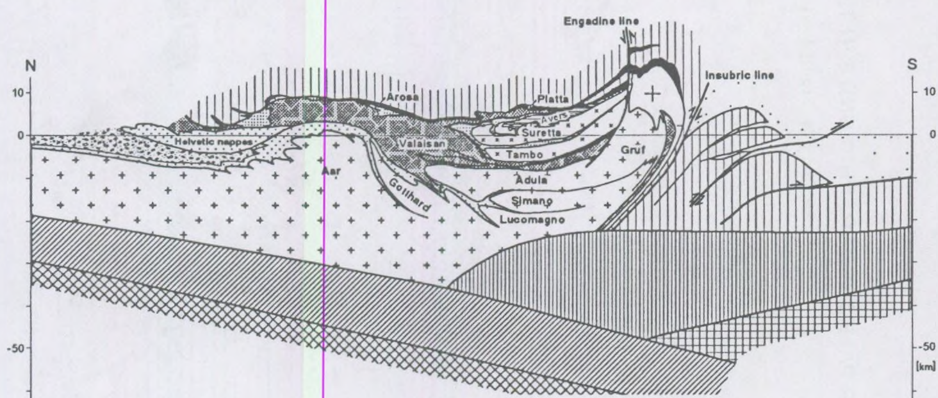

MAJOR PALEOGEOGRAPHIC UNITS IN THE ALPS
modified after Froitzheim et al. (1996)
EASTERN ALPS
TRANSALP
NFP-20 EAST
NFP-20 WEST
ECORS-CROP
Tauern window
Periadriatic Line
Brenner fault
Engadine window
Giudicarie belt
Wien
Graz
Maribor
Zagreb
Passau
Basel
Bern
Torino
Milano
Genova
Nice
Grenoble
Verona
Padova
Venezia
Trieste
European margin
Valais ocean (Alpine Tethys)
Brian□onnais terrane
Piemont-Liguria ocean (Alpine Tethys)
Margna-Sesia fragment
Apulian plate N of Periadriatic Line
Apulian plate S of Periadriatic Line
Neotethys and its distal passive margin
Tiza unit
100 km



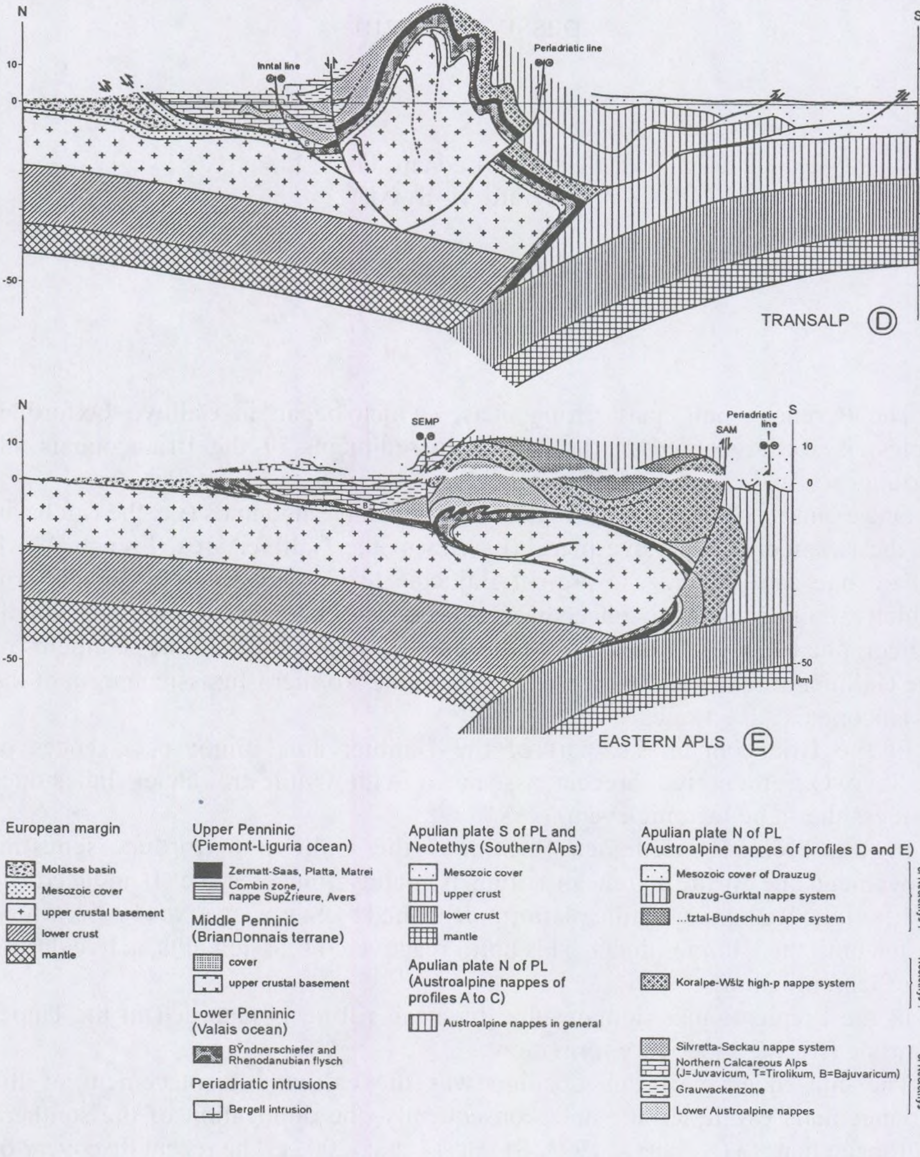
ECORS-CROP (A)



NFP-20 WEST (B)



NFP-20 EAST & EGT (C)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Inntal line
Periadriatic line
B
TRANSALP D
SEMP
SAM
Periadriatic line
EASTERN APLS E
European margin
Molasse basin
Mesozoic cover
upper crustal basement
lower crust
mantle
Upper Penninic (Piemont-Liguria ocean)
Zermatt-Saas, Platta, Matrei
Combin zone, nappe SupŽrieure, Avers
Middle Penninic (Brian□onnais terrane)
cover
upper crustal basement
Lower Penninic (Valais ocean)
BŸndnerschiefer and Rhenodanubian flysch
Periadriatic intrusions
Bergell intrusion
Apulian plate S of PL and Neotethys (Southern Alps)
Mesozoic cover
upper crust
lower crust
mantle
Apulian plate N of PL (Austroalpine nappes of profiles A to C)
Austroalpine nappes in general
Apulian plate N of PL (Austroalpine nappes of profiles D and E)
Mesozoic cover of Drauzug
Drauzug-Gurktal nappe system
...tztal-Bundschuh nappe system
southern margin of Neotethys ?
Koralpe-Wšlz high-p nappe system
suture of Neotethys ?
Silvretta-Seckau nappe system
Northern Calcareous Alps (J=Juvavicum, T=Tirolikum, B=Bajuvaricum)
Grauwackenzone
Lower Austroalpine nappes
northern margin of Neotethys

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Formation and evolution of the northern Briançonnais passive margin

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and Gerard M. STAMPFLI[1]

(with 1 figure)

The Pyrenean pull-apart rifting phase, which began in Callovo–Oxfordian times, is well recorded in the Mesozoic sediments of the Briançonnais s.l. terrane.

One example of such record is given by the Subbriançonnais (i.e. the rim basin of the Briançonnais passive margin) series of the Galibier area (French Alps), where one can recognize a pre-rift Bajocian to Callovian carbonate platform which rapidly passes into a deep basinal facies after the deposition of the syn-rift Télégraphe Breccias. This led us to the conclusion that the Jurassic sediments of the Galibier are the only known witnesses of the Northern Jurassic margin of the Briançonnais s.l. terrane.

In the Briançonnais s.s. part of the Galibier area minor occurrences of Callovo–Oxfordian red breccia associated with Guillestre facies limestones witness the same tectonic event.

In the Préalpes Médianes Plastiques the Callovo–Oxfordian senestral movement due to the Pyrenean rifting is mainly transpressive. It induced the uplift of the Bathonian oolitic platform described by SEPTFONTAINE (1995), which lasted until the Kimmeridgian. This uplift reactivated Liassic faults, active during the Piemont rifting.

In the Prepiémontais domain, the Pyrenean rifting is recorded in the Upper Jurassic Brèche Supérieure formation.

The consequence of this opening was the eastward displacement of the Briançonnais exotic terrane and, consequently, the duplication of the southern European margin (STAMPFLI 1993, STAMPFLI et al. 2002). The recent discovery of metabasites belonging to the Piemont Ocean (the metagabbros of Quarata and

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Simplon, dated around 155 Ma by LIATI et al. 2003) in a lower Penninic structural position (Valais domain) confirms this duplication.

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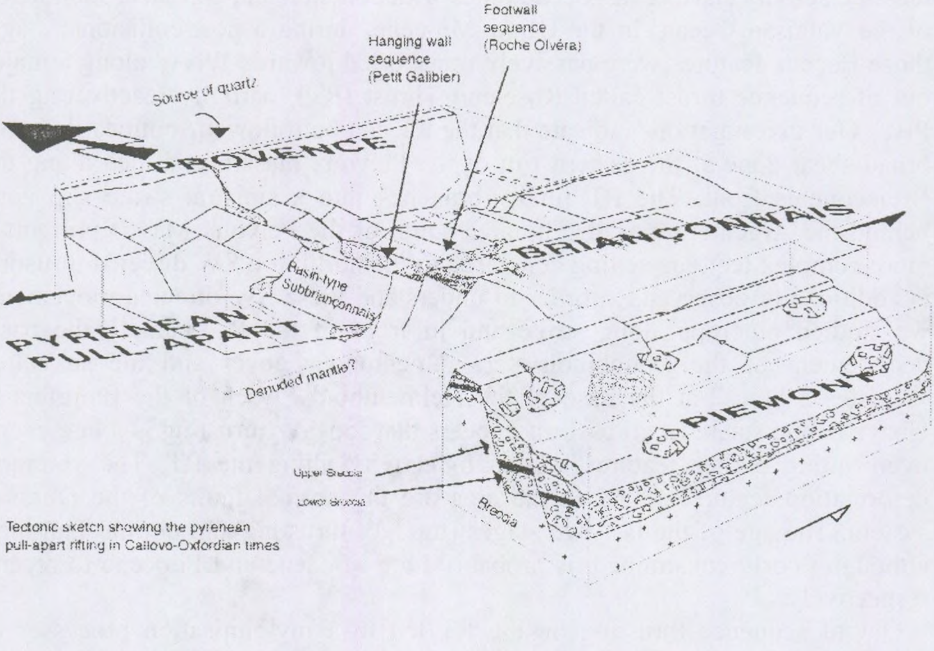

Tectonic sketch showing the pyrenean pull-apart rifting in Callovo-Oxfordian times

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Polyphase tectonic activity on the Penninic front: a combined tectonic and microstructural study

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A recent structural analysis was carried out along the Penninic Basal Contact (PBC) of the Western Alps, i.e. along the contact between Penninic and European units between Mont Blanc and Argentera massifs. North of the Pelvoux massif, CERIANI et al. (2001) have shown that the PBC is the result of a polyphase tectonic activity starting in Eocene times with collision and complete subduction of the Valaisan Ocean. In the Oligo–Miocene, during a post-collisional stage, those Eocene features were passively transported towards WNW along a major out of sequence thrust called Roselend Thrust (RT), partially reactivating the PBC. Our investigations indicate that the RT can be followed southwards into a broad shear zone at the eastern rim of the Pelvoux massif, and then along the Briançonnais front. The RT finally branches into a sinistral strike slip zone behind the Argentera massif. The area south of the Pelvoux Massif presents a more complex tectonic setting compared to the north: top SW directed thrusting is additionally observed. In order to understand these SW directed movements we studied outcrops along strike and in front of the RT, namely the basal decollement of the Dauphinois para-autochtonous cover and the so called "schistes à blocs" at the base of the Helmenthoïd Flysch of the Embrunais–Ubaye nappe stack. In all cases it appears that top-SW thrusting is a late event, overprinting earlier features related to activity along the RT. The youngest deformation features found in the area are the normal faults of the Durance system. The age of the last two stages (top SW thrusting and normal faulting), although poorly constrained, is probably Late Miocene and Pliocene to recent, respectively.

Out of sequence thrusting on the RT led to a mylonitisation processes of different lithologies. Concerning the calc-mylonites derived from the Nummulitic limestone we subdivide the observed textural and microstructural evolution during progressive deformation into three stages (St1 to St3). St1 represents the deformed but nearly texture-free samples, while St3 is the ultramylonitic stage. At intermediate stage St2, the samples are characterized by a c-axis orientation normal to foliation. Recrystallised grains present a strong

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grain shape preferred orientation, the long axis being oriented parallel to foliation. The average grain size of the recrystallized grains shows a mode of about 7 mm equivalent radius. At the final stage St3, the c-axis is rotated by 15 to 20° in respect to the foliation and with the sense of shear. This type of c-axis pattern corresponds to what is consistently found for quartz mylonites. This is unusual because so far oblique c-axis textures for calcite were oriented « against the sense of shear », as is expected if calcite twinning is responsible for texture evolution. The grain size distribution remains unchanged from that observed for stage St2. Our results suggest that the new type of oblique c-axis orientation found in calcite ultramylonites is caused by the activity of basal a slip and the absence of significant amounts of twinning.

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Progressive shear in naturally deformed calcitic rocks: microfabric evolution and a new type of oblique c-axis-orientation

Ghislain TRULLENQUE[1], Stefan M. SCHMID[1], Renée HEILBRONNER[1], Holger STUNITZ[1] and Karsten KUNZE[2]

The Penninic front of the western Alps is defined as the tectonic boundary between the European foreland and the more internal Penninic units. Out of sequence thrusting on this structure led to a mylonitisation processes in different lithologies and which can be observed east and south of the Pelvoux massif.

We subdivide the textural and microstructural evolution during progressive mylonitization of limestones into three stages (St1 to St3). St1 represents the deformed but nearly texture-free samples, while St3 is the ultramylonitic stage. Progressive evolution of the C-axis preferred orientation has been analysed by X-ray diffraction goniometry and subsequent calculation of the "Orientation Distribution Function" (ODF), combined with Computer Integrated Polarisation microscopy (CIP). All pole figures measured by X-ray goniometry have been recalculated from the ODF.

At stage St2 the samples are characterized by a c-axis orientation normal to foliation. In average, the textures exhibit maxima of about 2 times random in the c-axis pole figures. The 104 (*r*) pole figures show a single maximum, also oriented perpendicular to foliation. Recrystallised grains present a strong grain shape preferred orientation, the long axis being oriented parallel to foliation. The average grain size of the recrystallized grains, calculated using a three-dimensional distribution, shows a mode of about 7 mm equivalent radius.

In the intermediate stage St2/3 the c-axis orientation starts to become rotated with the imposed sense of shear. Simultaneously, a second maximum starts to appear in the 104 (*r*) pole figures. This maximum is positioned 45° away from the other maximum with the sense of shear which is still found oriented perpendicular to foliation.

During the final stage St3 the c-axis is rotated by 15 to 20° in respect to the foliation and with the sense of shear. This type of c-axis pattern corresponds to what is consistently found for quartz mylonites. This is unusual because so far

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oblique c-axis textures for calcite were oriented « against the sense of shear », as is expected if calcite twinning is responsible for texture evolution. The textures are strong, i.e. the maxima of the C-axis concentrations are between 2.3 and 3.7. The 104 (*r*) pole figures exhibit two clearly separate maxima. The grain shape preferred orientation shows the long axis of the recrystallised grains to be tilted by about 30° in respect to foliation. The grain size distribution remains unchanged from that observed for stage St2.

Our results suggest that the new type of oblique c-axis orientation found in calcite ultramylonites is caused by the activity of basal a-slip given the absence of significant amounts of twinning. This intracrystalline plasticity also leads to the strong grain shape preferred orientation of the recrystallised grains. Hence, there appears to be no switch to grain size sensitive flow in these mylonites.

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Metamorphism in the Lepontine Dome (Central Alps): Apparent simple pattern but complex history

Alfons BERGER[1] and Martin ENGI[1]

The apparent simple zoning of the "Lepontine Dome" in the Central Alps conceals a complex history. This fact is strikingly borne out by recent attempts to combine the metamorphic record with results of kinematic and thermal (numerical) models.

The metamorphic zoning patterns (mineral zones, isograds, isotherms, isobars) depicting the Barrovian overprint (Lepontine thermal dome) are diachronous (by as much as 17 My) and reflect three superimposed stages of tectonic evolution of the Central Alps:

Subduction phase: A record of progressive metamorphism some 35–38 Ma ago? (timing unsure!), appears to be preserved at the northern margin of the dome. The metamorphic field gradient over ~10 km N→S shows a slab-parallel increase in pressure and temperature.

Late extrusion phase: Several mélange units were extruded onto the top of the subducting nappe pile at mid-crustal level. Units such as the Adula "nappe" represent disrupted portions of the accretion channel, as do parts of the Southern Steep Belt, where leucosomes (up to 35%) were produced during late transpression. Upon decompression T_{max} attained ~700 °C, some 28–30 Ma ago, at $P(\sim T_{max}) \approx 5$–6 kbar.

Collapse phase: The central Lepontine attained temperatures of 550–650 °C, but at pressures of 6.5–7 kbar, i.e. higher than at the N- and S-margins of the belt. The thermal maximum was thus reached at greater depth, but later: Age data — interpreted to represent mineral formation — indicate 22–24 Ma. After this time, the thermal budget in the evolving dome was dominated by heat loss through the orogenic lid, which was being thinned by orogen-parallel extension and rapid erosion.

Comparison of the metamorphic histories documented from different parts of the Lepontine belt clearly shows that the conditions reflected in preserved assemblages were attained along very different P-T paths. The fact that the metamorphic zones cut across major nappe boundaries implies neither a uniform nor a simple process. For example, different reaction sequences are responsible

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for the formation of staurolite, depending on the P-T-t histories experienced by metapelites hosting Al-silicates in (now) neighbouring tectonic units.

Only by integrating numerical models to complement geophysical, tectonic, petrological and geochronological detective work can we hope to unravel collisional orogeny. Metamorphic zoning patterns are deceptively simple in the Central Alps — and possibly elsewhere.

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Synform or monocline — the structure of the Southern Steep Belt in the Central Alps of Switzerland

Michael MAXELON[1] and Neil S. MANCKTELOW[1]

Although the Lepontine Alps are the classic region for fold nappe development at mid-crustal levels, the detailed geometry of these large-scale (generally reclined) fold structures is still not unequivocally established. The debate over the regional correlation of individual nappes (and therefore their initial palaeogeographic position) continues and has been particularly intense in the last years, with several new and radically different models presented. A clear understanding is naturally difficult in metamorphic units without a consistent (tectono-) stratigraphy that have undergone at least five different deformation phases.

The first two deformation events (D_1 and D_2) are associated with Alpine nappe-stacking. They entailed the formation of tight to isoclinal folds and produced a pervasive foliation ($S_{1/2}$). Later deformations, i.e. D_3 and D_4, corrugated the nappe pile and warped the newly formed tectonic units into a succession of regional folds with variable amplitude and wavelength.

The present work focuses on the southern central part of the Lepontine Region, bordered by the Swiss–Italian frontier in the east and Bellinzona to the west and by Biasca and Locarno to the north and south. In this area the otherwise wavy and smooth D_3-folds tighten dramatically as the trend of their fold axial planes (FAP_3) swings into parallelism with the Insubric Fault. This also gives rise to increasingly steep orientations of S_2 forming the Southern Steep Belt (SSB).

Despite the remarkably strong later overprint, recent field work suggests that many structural features associated with D_3, like parasitic folds or S_2/FAP_3 relationships have been preserved and can thus be interpreted. These observations show a comparably consistent pattern, suggesting the existence of a tight D_3 synform of regional importance within the SSB: the Locarno Synform.

This hypothesis is well supported by the results of three-dimensional foliation field modelling, which also indicates a major synform north of the Insubric Fault. The model is based upon nearly 2000 measurements of S_2 and only shows the imprint of D3 and D4, regarding the already stacked (during D1/D2) nappe pile as a pre-existing tectonostratigraphy.

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The existence of a major synformal structure within the SSB has far-reaching consequences for the regional geology of the Central Alps and thus for palaeogeographic correlations. The fold axial trace of this synform runs through the Cima Lunga Unit, separating the Maggia from the Simano Unit. The Maggia and Simano units form the opposing limbs of a single fold and therefore are considered to be the same regional tectonic unit, forming part of the passive continental margin of Europe prior to Alpine collision.

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Exhumation of Alpine high- and ultra-high-pressure metamorphic rocks by slab extraction

Nikolaus FROITZHEIM[1], Jan PLEUGER[1], Sybille ROLLER[1]
and Thorsten NAGEL[2]

(with 1 figure)

Exhumation of high-pressure-(HP-) and ultra-high-pressure (UHP) metamorphic rocks in collisional orogens may be explained by upward extrusion of these rocks from a subduction channel, erosion of their overburden, or extensional thinning of the overburden. Some HP–UHP pressure terranes, like the Adula Nappe in the Central Alps, fit none of these scenarios. We propose an additional way how part of the overburden may be removed: It may sink off into the deeper mantle.

Structural and metamorphic relations in and around the Adula nappe (Central Alps) indicate that the emplacement of this Alpine HP–UHP nappe (up to 3.2 GPa) in a pile of lower-pressure nappes resulted from the interaction of two south-dipping subduction zones that accommodated the closure of two ocean basins, the Valais Basin to the North and the Piemont Basin to the South. At a time between 40 and 35 Ma, both of these basins had been closed by southward subduction, leading to the imbrication of three plates: The Adriatic Plate to the South and at the top, the Briançonnais Plate in the middle, and the European Plate to the North and at the bottom. The south-dipping Piemont oceanic slab was still attached to the Briançonnais Plate. The Adula HP–UHP rocks were situated in the lower subduction channel, between the Briançonnais and European plates. Further convergence between Europe and Adria resulted in detachment of the upper continental crust (Tambo and Suretta nappes) from the Briançonnais Plate. The relatively dense mantle lithosphere and lower crust of this plate, now devoid of the light upper crust and pulled by the Piemont oceanic slab, sank off into the deeper mantle. The virtual void that was created by the extraction of the Briançonnais Plate was filled by rapid upward movement of the Adula rocks and by unflexing of the European Plate. Finally, further convergence resulted in the underplating of less deeply subducted European margin rocks below the Adula Nappe.

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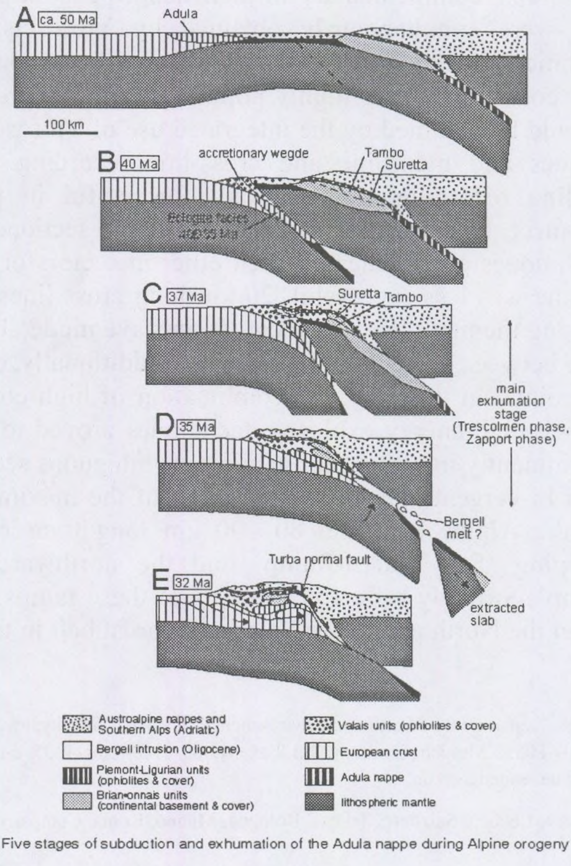
The process of slab extraction as described above depends on particular circumstances, i.e. the interaction of two closely neighbouring subduction zones dipping to the same side. This is fulfilled in the Alps, because the Iberian (=Briançonnais) microplate wedged out in the region of the Eastern Alps, so that the convergent plate boundaries on both sides of this microplate where only about 100 km apart in the eastern Central Alps. Besides Adula, the model of slab extraction probably applies to the other Alpine high-pressure units derived from the distal European margin: the Monte Rosa, Gran Paradiso and Dora Maira nappes, and the Eclogite Zone of the Tauern Window.

In terms of mechanics, the driving force of the exhumation process was not the buoyancy of the high-pressure rocks but the negative buoyancy of the extracted slab. This is identical to the slab pull force, the main driving force of plate tectonics. When the overburden is removed in this way, the underlying HP–UHP-rocks are isostatically uplifted, irrespectively of their own density. At least in the case of the Adula nappe, this mechanism may explain the exhumation of high- and ultra-high-pressure rocks from great depths.



Five stages of subduction and exhumation of the Adula nappe during Alpine orogeny

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Orogenic structure of the Eastern Alps revealed by TRANSALP Vibroseis, Dynamite and Cross-Line Surveys

Ewald LUESCHEN[1] and TRANSALP Working Group[2]

The TRANSALP Group, comprising of partner institutions from Italy, Austria and Germany, acquired seismic data on a 340 km long deep seismic reflection line crossing the Eastern Alps between Munich and Venice. Although the field campaign was split into four different parts, between fall 1998 and summer 2001, the project gathered for the first time continuous sections in the Alps using consistent field acquisition and data processing parameters. These sections include the orogen itself, at its broadest width, as well as the two adjacent basins. The seismic sections, complementary in their depth penetration and resolution characteristics, were simultaneously obtained by Vibroseis, explosion and teleseismic techniques. Although the survey suffered from noisy recording and difficult permit conditions along highly populated north-south running valleys, clear images could be obtained by the integrated use of Vibroseis and explosive source techniques and main-line and cross-line recording. Particularly the passive cross-line recording was not only successful in providing three-dimensional control, but also in providing alternative sections along the main line. These techniques complemented each other in sectors or at depths where one method alone was less successful. 20 km long cross lines were spaced by about 30 km along the main line and recorded in slave mode all seismic sources of the main line between adjacent cross lines and, additionally, off-end cross-line explosive shotpoints. In this way, the combination of high-coverage Vibroseis and low-coverage high-energy explosive techniques proved to be economic on one hand and eminently important for gaining unambiguous sections.

They show a bi-vergent asymmetric structure of the maximum 55 km thick crust beneath the Alpine axis and 80–100 km long transcrustal ramps, the southward dipping 'Sub-Tauern-Ramp' and the northward dipping 'Sub-Dolomites-Ramp'. Strongly reflective patterns of these ramps can be traced to the Inn Valley in the North and to the Valsugana thrust belt in the South, both of

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which show enhanced seismicity in the brittle upper crust. The seismic sections do not reveal any direct evidence of the Periadriatic Fault system, the presumed equivalent to the Insubric Line in the Western Alps. According to our new evolutionary model, the Sub-Tauern-Ramp is linked at depth with remnants of the subducted Penninic Ocean. The 'crocodile'-type model describes an upper/lower crustal decoupling and wedging of both the European and the Adriatic–African continents. The alternative 'lateral extrusion' model emphasises the east–west escape tectonics.

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TRANSALP deep seismic section as a key for understanding active tectonics along the Inntal fault zone

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(with 1 figure)

The Inntal shear zone is a Tertiary strike-slip fault which obliquely cuts the Northern Calcareous Alps. Seismicity along the Lower Inn Valley (Tirol, Austria) has been known for a long time past. The strongest earthquakes with intensities up to I_0= 8 occurred in medieval times. Instrumentally determined earthquake hypocenters are scattered horizontally in a several km wide zone and vertically across the crust down to a depth of 12 km. Broad scattering probably results from a combination of a) inaccurately determined hypocenters and b) the fact that present-day deformation does not occur along a single fault. When moving along the Inn Valley from SW to NE, the base of the hypocenter distribution rises along a line inclined ~10° to SW. This WSW-downplunge trend corresponds to depths of the top of the European crust, proved by wells. According to our interpretation of the TRANSALP seismic section deep hypocenter clusters are located in a ramp fold of the European crust.

In mining galleries north-up and sinistral strike-slip displacements in the range of few mm per year along several faults with fault gouge are preserved and prove an active fault system.

Recent in-situ stress measurements from a reconnaissance tunnel in the northern flank of the Inn Valley revealed that the maximum principal stress direction is oriented subhorizontally in NW–SE direction. Data are in line with the regional stress field (World Stress Map).

We conclude that deep structures in the European thrust control neotectonic activity in the alpine nappe stack:

— The offset of the strong reflection pattern of the autochthonous Mesozoic below the Inn Valley is interpreted as inverted half graben structures.

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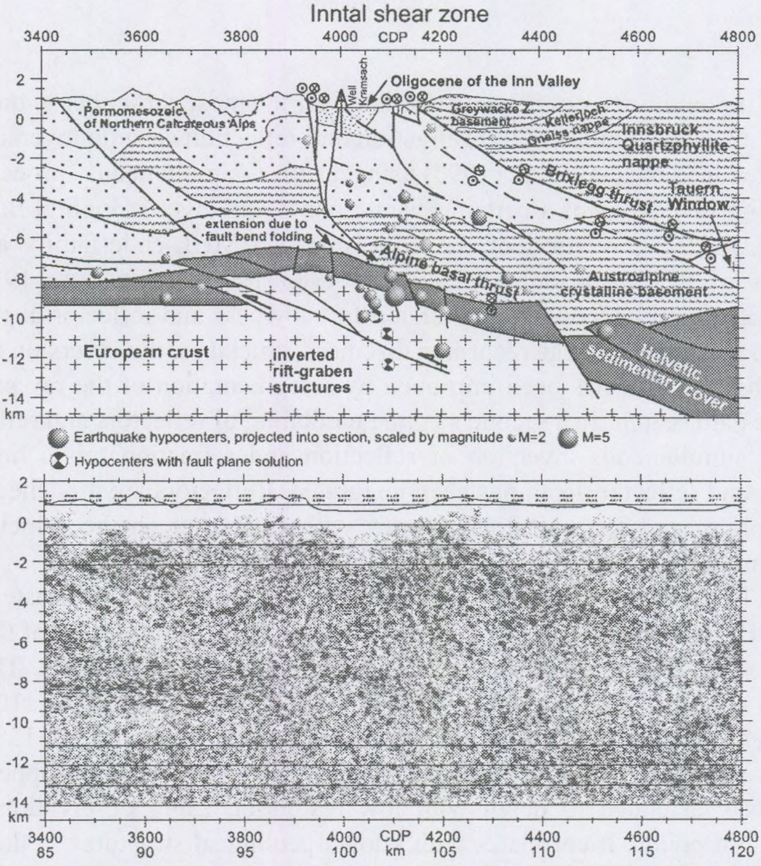
— Earthquakes extending into the European Plate indicate active reverse or oblique faulting caused by ongoing N–S shortening between the Adriatic and European plates. Present-day deformation north of the Tauern Window is concentrated along the Alpine basal thrust and extends also into the European Plate.
— Above the ramp fold structure of the European crust the deformation is transferred to the surface through the Alpine nappe stack by the broad seismotectonic zone of the Lower Inn Valley.
— Recent movements reactivate pre-existing structures of the polyphase Inntal fault zone.



Bottom: Depth-migrated TRANSALP section between km 85 and 120. Top: Geological interpretation of seismic transsect and earthquake hypocenter distribution. A broad earthquake zone between 6 and 12km depth extends into the European plate in a zone where the strong reflections of the helvetic sedimentary cover disappear. Fault plane solutions indicate thrusts or reverse faults. Due to fault bend folding, local N-S extension may also be expected.

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Simultaneous refraction and reflection seismic tomography based on SIMUL with applications to the TRANSALP wide-angle data

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(with 1 figure)

Seismic travel time tomography is restricted for the most part either to the direct wave or to 2-D. Combined 3-D refraction and reflection seismic inversion was first introduced by ZELT et al. (1996) using a "quasi-simultaneous" procedure of alternating inversions of a certain seismic phase and layer stripping. Based on the SIMULPS13Q version of the wide-spread SIMUL-code-family and the concepts of flexible gridding (THURBER, 1983–1999; RIETBROCK, 1996) we developed a simultaneous 3-D inversion for slowness and reflector depth. In a first step accuracy for large recording distances, crucial for the inversion of PMP or Pn observations, has been improved by resegmentation of the ray path and multiple path search. In a second step the modelling of reflectors and reflections and the simultaneous inversion of reflection and refraction travel times for velocity and reflector depth has been integrated. Reflectors are modelled by bi-cubic splines and can be "floating", i.e. without impact on the velocities, or discontinuous.

This method was applied to a wide angle data set from the Eastern Alps acquired within the TRANSALP project aiming at the investigation of the deep structure of the Eastern Alps (TRANSALP Working Group, 2001). The data consists of vibro- and explosion seismic signals recorded by 30 to 110 three-component stations distributed along a 220 km long N–S-profile at 12°. From the Vibroseis recordings we obtained a high resolved model of the upper crust, which was extended to depth with low resolution using observations from distant shot points. It correlates with known geological structures in the upper crust. The middle and lower crust shows distinct velocity functions for the

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European and the Adriatic part. The European Moho is resolved from the Northern Calcareous Alps in 40 km depth to the Alpine root in ca. 55 km depth. Only few reflections from the Adriatic Moho were recorded indicating a position in ca. 40 km depth. These structures can be interpreted within the scope of southward subduction of the Penninic Ocean.

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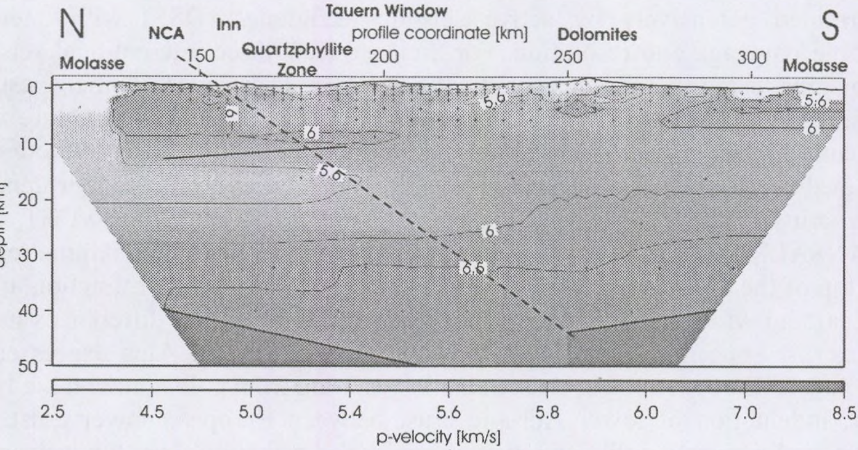

Figure: P-wave velocity model for the TRANSALP profile. The dashed line indicates the position of a major crustal ramp inferred from the reflection seismic image. Adriatic basement is characterized by higher velocities than European basement

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Lithosphere structure and tectonic evolution of the Alpine arc: new evidence from high-resolution teleseismic tomography

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Several different continental and oceanic plates amalgamated during the formation of the tectonically complex Alpine arc. To understand the evolution of this orogen, the ongoing interaction of the lithospheric blocks, and to assess the amount and orientation of subducted lithosphere requires reliable knowledge of the present structure of the lithosphere-asthenosphere system throughout the Alpine arc from the Western through the Central to the Eastern Alps. We have compiled results from earlier studies and reinterpretations of existing seismic and geological data for the Alpine crust and Moho. High-resolution teleseismic tomography was used to determine a detailed 3-D seismic model of the lower lithosphere and asthenosphere. The combination of both provides new images for the entire lithosphere-asthenosphere system which show significant lateral variations to depths of 400 km. Over the years the crustal structure has been determined extensively by active seismic techniques (DSS) with laterally variable coverage and resolution. For a closer view three international seismic campaigns using mainly near-vertical reflection techniques in the Western, Central and Eastern Alps were carried out to assess the crustal structure with presently highest possible resolution. The synoptic reinterpretation of these data and evaluation of existing interpretations has allowed to construct four detailed deep crustal transects across the Alps ECORS-CROP, NFP-20/EGT, and TRANSALP. In addition contour maps of the Moho for the wider Alpine region and top of the lower crust were compiled from existing seismic refraction, near-vertical and wide-angle reflection data. Substantial structural differences in the deep crust appear between Western, Central, and Eastern Alps expressed in doubling of European lower crust in the W resulting from collision with the Ivrea body, indentation of lower Adriatic crust between European lower crust and Moho, and a narrow collision structure under the transition from the western to

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the eastern subduction regime under the Tauern Window with steep formations resembling large-scale flower structures.

Most recently high-resolution teleseismic tomography based on the a priori known 3-D crustal structure and compilation of a high-quality teleseismic data set was successfully developed and applied to derive reliable detailed images of the lower lithosphere. Along strike of the Alps a fast slab-like body is revealed which in the western part is subducted beneath the Adriatic microplate. In the Western Alps parts of the lower continental slab were detached possibly induced by the Ivrea body which acted as a buttress in the collision process of the European and Adriatic plates. The generally SE directed subduction of the European continental lithosphere changes gradually from W to E to almost vertical under the westernmost part of the Eastern Alps (western Tauern Window and Giudicaria lineament). Quite unexpectedly some 50 km further east the subducted continental lower lithosphere is now part of the Adriatic lithosphere and dips NE beneath the European Plate. Our tomographic image documents clear bipolar slab geometries beneath the Alpine orogen. The depth extent of the subducted continental lithospheric slab agrees rather well with estimates of post-collisional crustal shortening for the Western and Central Alps. This kinematic control on amounts of lateral motion of the collision zone in the W allows also estimates of the subduction and collision process in the Eastern Alps.

The new 3-D lithospheric picture for the wider Alpine region to 400 km depth demonstrates the clear connection and interaction between the deep structure of the lithosphere-asthenosphere system and near-surface tectonic features as seen today. It provides new and unexpected evidence for the evolution and understanding of the entire Alpine tectonic system, a process which obviously changes significantly from W to E.

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The ALP 2002 seismic experiment — data acquisition and first results

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(with 2 figures)

ALP 2002 was organized as an international seismic experiment whose scientific objective is to further scientific understanding of the structure and evolution of the lithosphere in the eastern Alps and surrounding areas of the Bohemian Massive, the Pannonian Basin and the Dinarides. A major consideration in the design of the ALP 2002 project was to build on the CELEBRATION 2000 seismic experiment and provide comprehensive seismic coverage in the eastern Alps region.

The ALP 2002 experiment included passive seismic monitoring during portions of June and July 2002, and an active source seismic refraction experiment was conducted from 1–6 July 2002. Furthermore, local high-density deployments were carried out in Austria and Hungary to investigate local geologic problems. During the active source experiment about 1000 portable seismograph recorders were deployed to record 32 specially designed explosions. The standard shooting configuration in Austria was divide 300 kg of explosives between 5–8 boreholes 30–50 m in depth. In Hungary, Slovenia and Croatia, a similar approach was used. In the Czech Republic, quarries were used as sources. The main type of instrument used were the 'Texan' single channel recorders. We employed the same methodology of deploying instruments along a series of interlocking profiles (Figure 1) as was used during CELEBRATION 2000. We had 13 lines (ALP01–ALP13) with a total length of about 4300 km.

A maximum of 70 3-component recorders for recording the seismic shots as well as earthquakes were deployed along two lines from 07 June to 12 July 2002. One line, ALP04, overlaps and extends CELEBRATION 2000 line CEL10. The other passive monitoring line, ALP12, follows the TRANSALP line providing

Working Group and addresses on www.alp2002.info

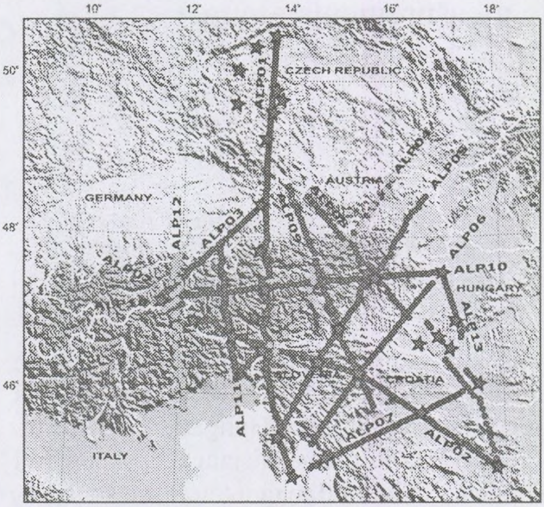

Figure 1: Shot locations (stars) and receiver lines (dark grey circles are Texans, light grey circles are 3C-stations for passive monitoring)

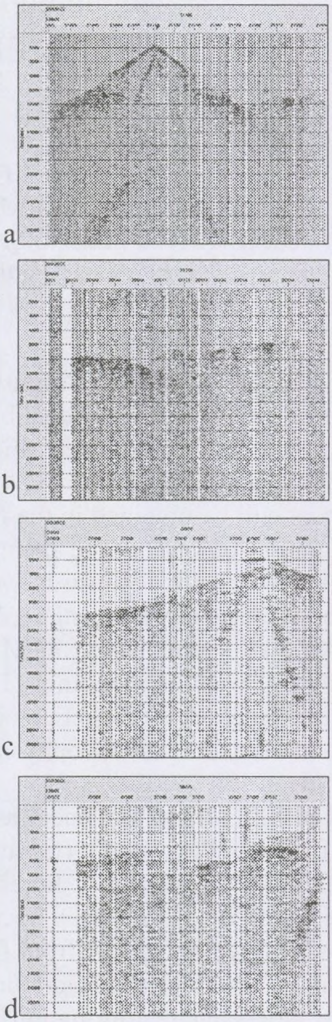

Figure 2: Samples of record sections a) Shot 101 on ALP01 b) Shot 101 on ALP 02 c) Shot 207 on ALP07 d) Shot 08 on ALP 07

the tie to this important reflection seismic experiment.

Samples of recordings, demonstrating the quality of the data are shown on Figures 2a–d. In order to guarantee a good coverage of the area of investigation and to take advantage of the existing data from CELEBRATION 2000 the data sets from ALP 2002 and the 3rd deployment of CELEBRATION 2000 were merged. We are using these merged data to construct 2-D and 3-D models of the lithosphere containing structural and compositional information derived from P- and S-wave travel times and amplitudes. Result from first arrival 3-D tomography and 2-D modelling by interactive ray tracing using refracted and reflected waves will be presented. Additional to these results achieved by the application of standard techniques in refraction studies we have applied signal detection and stacking techniques to the data and have inverted these processed data by 1-D and 3-D tomographic methods. A 3-D model of the whole area is under construction by using these techniques and the status of evaluation will be presented.

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Magnetotelluric measurements along the CELEBRATION–07 line

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From 28 July to 31 August 2003 magnetotelluric (MT) measurements are carried out in SW Transdanubia, along the 140 km long Hungarian part of the CELEBRATION–07 deep seismic refraction line. The distance between MT stations along the line is 1–2 km. Altogether about 80 magnetotelluric sounding curves will be obtained in the frequency/period range 1000 Hz–1000 s, enabling indication of crustal and mantle resistivity changes. About a dozen soundings will be extended towards very long periods, allowing a magnetotelluric interpretation down to asthenospheric depths.

All instruments (five SPAM MkIII instruments with sensor boxes, 10 Castle systems with 6 channel Earthdata loggers+sensor boxes, 5 fluxgate magnetometers, 30 induction coil magnetometers and 90 AgAgCl electrodes) are borrowed from the Geophysical Instrument Pool of GeoForschungsZentrum Potsdam.

The MT measuring line was selected on basis of experiences of the project CELEBRATION 2000 (Central Europe Lithospheric Experiment Based on Refraction carried out in June 2000, followed by the ALP 2002 experiment), as one of the most important section between the Alps and the Pannonian Basin. The MT measuring line from Barcs to Szentgotthárd crosses the Rába Line, the Balaton Line and the Mid-Hungarian Line. The magnetotelluric results should give independent information to several open questions of the deep refraction measurements: (a) if the Rába Line represents a microplate border, (b) what is the reason for the observed upper-crustal velocity increase in the SW elongation of the Transdanubian Range, (c) what is the MT response of the seismically undetected Mid-Hungarian lineament.

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The profile measurements are completed by triangular GDS measurements, where possible geometric scenarios for magnetic variational soundings to be carried out on planet Mars in frames of the NetLander project are tested.

Since the Alpshop meeting is held just two weeks after the end of the field campaign, in the presentation the geological-geophysical background, the technical details, and the very first preliminary results will be shown.

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On the influence of lateral strength variations on the evolution of collision zones: inferences from lithospheric-scale physical modelling

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and Jean-Pierre BURG[2]

The rheological stratification of the lithosphere and its lateral variations exert a first-order control on both the distribution and mode of deformation, on the resulting geometry of the deformed area and on its topographic expression. We studied these issues through a series of crustal- to lithospheric-scale analogue experiments incorporating lateral as well as vertical variations in the strength of the crust and the upper mantle. Such laterally and vertically irregular configurations of rheologically layered lithospheres have applications in continent-continent collision settings such as the Eastern Alps. For example, the European and Adriatic plates were relatively stronger than the Penninic and Austroalpine Units, in between, prior to the continental shortening that began ca. 30 Ma ago. Arguments in favour of a weak zone between two stronger plates comprise: (1) the intense deformation to the north of the Periadriatic Line, in the region of the Tauern Window; (2) the young tectonothermal age of this area and (3) the intrusion of Periadriatic plutons, which induced thermal softening of the adjacent rock units.

Accordingly, the starting experimental set-ups included a weak linear zone bordered on both sides by stronger plates. The models were bordered by the glass wall (on one side) and a weak silicone layer (on the other side) in order to contain but not oppose to lateral extrusion. These two sides and the shortening direction were perpendicular to the strike of the weak zone. The model lithospheres consisted of three (brittle crust/viscous crust/strong viscous upper mantle) or four (brittle crust/viscous crust/brittle upper mantle/strong viscous upper mantle) layers. The analogue materials were quartz and feldspar sands for the brittle layers and silicone mixtures for the viscous layers. Lateral variations of lithospheric strength are implemented by varying the thickness of both the brittle and the ductile layers. The models floated on a dense fluid representing the lower lithosphere and ensuring continuous isostatic adjustment. The models were

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shortened at rates that respect geological conditions. During deformation the surface of the models was regularly scanned by a 3-D video laser to enable a quantitative analysis of the evolving relief.

Three-layer models deformed by thickening and upwelling of the central weak zone. Forward (in the direction of the push) and backward (against the direction of the push) thrusting accompanied this broad upwelling and evolved into thrusting of the thickened weak zone over the forelands. Minor lateral escape of the central weak zone occurred. The major structures revealed in cross-sections comprise (a) a thick crustal zone, which is the thickened and anticlinally folded viscous layer of the weak zone, (b) the main thrusts are along the boundaries between the weak and strong plates, placing the thickened middle zone onto the strong plates (c) upright and overturned folds in the footwall of these thrusts, and (d) almost undisturbed thickness of the ductile layers within the strong parts of the models.

Four-layer models deformed in the same bulk manner as three-layer models. Bivergent thrusts border the high topography zone formed on the initially weak layer, which also suffered minor lateral extrusion. However, cross sections reveal major structural differences. a) the weak zone was thickened, but the viscous layer developed a downward bulge forming the root of the folded high topography zone, b) the main thrusts are still along the boundaries between the weak and strong plates, but several subsidiary thrusts formed within the initially weak zone, c) no significant deformation affected the footwalls of the main thrusts, and d) the stronger plates were only bent downward to maintain continuity with the root zone of the thickened zone.

In addition, the topography formed with three-layer models is noticeably higher than that of four-layer models.

We conclude that the relative strength between converging plates and intervening weak zones controls the location and the deformation style. If the contrast is small, the bulk system is dominated by antiformal buckling that nucleates in the weak zone, and the deformed zone does include both the initially weak zone and the bordering domains on the stronger plates. If the contrast is large, the viscous parts of the weak zone are thickened and forced down to produce a root zone below a narrow deformation belt, which includes the initially weak zone and does not transgress into the bordering strong plates.

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Erodability vs. uplift rate: what controls the properties of the geomorphic domains in the Eastern Alps? — considerations based on Surface Processes Modelling

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and István DUNKL[1,3]

There is a long-lasting debate on the post-Oligocene geomorphic evolution of the Eastern Alps. Some authors suggested numerous planation surfaces, while some others consider the observable palaeosurface relicts as stages of only a few denudation/sedimentation phases. Furthermore, the role of the increased uplift rate in the Quaternary and the effect of the glaciation is not well understood.

Commonly, the different geomorphic characteristics of an area are attributed mainly to the diverse erodability properties of the underlying rocks. Our earlier results based on statistical analysis of DEM of the recent topography showed that the Eastern Alps can be divided into different characteristic domains. These domains correspond to tectonic units with similar uplift history, but the units themselves consist of different lithologies suggesting that the lithology plays a secondary role, if the uplift rate is high.

To have some insights concerning the role of the erodability contrast and the uplift rate, numerical simulation of the erosion and uplift was carried out with the help of a Surface Processes Modelling code CASCADE (generously provided by the author, J. Braun, Canberra).

According to our model results the lithological difference (here: erodability contrast) may determine the evolution of the drainage system if the uplift rate is relatively low (in the order of 0.1–0.3 mm/a). If, on the contrary, the uplift rate is high (>0.5 mm/a) in a part of the model space, it seems that the lithological contrast plays only a secondary role, because the surface adapts to the high uplift rate. In the erodable area a somewhat smaller relief builds up, but valleys cut through the erodable region and lower the base level for the erodable zone, too. If the erodability contrast is not so high (less than a factor of 2) the different zones show similar surface properties.

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A fault system (modelled by a linear zone of weak lithology) running obliquely to the thrust front governs the evolution of the drainage pattern if the uplift rate is low. In our tests the Inntal Fault Zone (IFZ) was envisioned as an obliquely running fault dewatering a large area, which plays a major (now declining) role since the Late Oligocene. Results show that a stable situation can be maintained if the uplift rate is smaller than 0.5 mm/a (with an erodability contrast factor of 5). Otherwise the zone plays a role in the dewatering and deflects the path of the evacuated sediments, but it is not always the main trunk channel. This result implicitly supports the idea based on other observations, that the uplift rate could not be so high for long time as it is presently measurable or deductible from the glaciation induced sediment evacuation during the Pleistocene. Thus, results suggest the glaciation induced relief enhancement in the Eastern Alps, too.

Concerning the sediment production, the high uplift rate implies slow onset of sediment output, because surface uplift in the initial phase buffers the incoming material flux and postpones the increase of the sediment production. The consequently high relief provides capacity of temporary sediment storage. Time by time, this capacity is used by the sediments en-route to the sedimentary basin, i.e., the sediment output flux becomes volatile. Accordingly, the outflux curve reaches more slowly the dynamic equilibrium level and fluctuates more strongly around it, than in the case of low uplift rates.

If the model contains differential uplift, sometimes a slowly uplifting part temporarily will be covered by the sediments being transported to the main depocenter, if the evacuation routes are partly or completely blocked by the products of the high uplift rate. Thus, some temporal intermontane basin-like areas may develop, despite their uplifting trend. Later, when the sediment evacuation paths reopen or the sedimentary cover overfills the bordering scarps, the previously existing paths may be reestablished, or in the case of overfilling, new paths may come into existence. This scenario seems to be plausible for the relict intermontane basins in the Eastern Alps.

Assuming differential uplift of several tectonic units, it is possible to get results resembling to the present topography of the Eastern Alps. However, the presently available modelling techniques do not model correctly the effect of the glaciation, therefore further studies are required to include the glaciation-induced relief enhancement as well.

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Palaeozoic to Triassic palaeogeographic and tectonic relationships of the Gurktal nappe complex, Eastern Alps: constraints from $^{40}Ar/^{39}Ar$ ages of detrital white mica

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The $^{40}Ar/^{39}Ar$ ages of detrital white mica from pre-Variscan Late Ordovician/Silurian and post-Variscan Upper Carboniferous to Middle Triassic sandstone successions of the Gurktal nappe complex of the Eastern Alps have been studied in order to reveal palaeogeographic origin and relationships of these units and late to post-Variscan tectonic processes of the Austroalpine mega-unit in the Eastern Alps. Single grains of a sample from a Late Ordovician/Early Silurian sandstone of the Golzeck Fm. show ages ranging from 497 to 614 Ma (Late Neoproterozoic to Cambrian), possibly with two age clusters (ca. 600 and 540–520 Ma). These ages are interpreted to record two stages of cooling or two sectors with different ages of a Cadomian orogen exposed in the hinterland. The ages are consistent with previously reported multi-grain ages from the Carnic Alps and Greywacke Zone of the Eastern Alps indicating a similar palaeogeographic origin of all these units.

Both multi-grain concentrates and single white mica grains of nine samples of post-Variscan Upper Carboniferous (Paal and Turrach Conglomerate Formations) and Permian molasse sandstones (Werchzirm and Bock Breccia Fms), and Permoscythian to Middle Triassic sandstones of a rift environment ("Permoscythian" Quartzite, Pfannock Formation) include uniform Late Variscan ages, mainly ranging from 300 to 320 Ma. No significant variation of age patterns was detected within these Late Carboniferous to Middle Triassic sandstones. As these 320–300 Ma ages also occur in the Westfalian C/D to Stefanian Turrach Conglomerate, these suggest very rapid cooling from mid-crustal levels, typical for temperatures of ca. 400 °C, and associated exhumation to the surface and denudation within a few million years. As no older ages occur in the Late Carboniferous to Middle Triassic sandstones, we assume that the Cadomian terranes lost any major importance at the surface exposure level which was predominated by Variscan metamorphic crust. This also suggests that erosion of upper brittle sectors of the Variscan orogenic wedge with old ages was

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nearly completed. Furthermore, sparse previously reported Rb-Sr ages of ca. 390 Ma from the Bundschuh basement of the Middle Austroalpine nappe complex seemingly exclude a primary source-deposition relationship between the Bundschuh basement and Upper Carboniferous Turrach/Paal Conglomerates. It appears that the Ackerl basement of the Gurktal nappe complex with its 315–300 Ma could represent the source for these molasse formations.

The exclusively Late Variscan white mica ages are similar to those reported from the same stratigraphic levels, mainly molasses-type successions, of Western and Eastern Alps, Bohemian Massif, Carpathians and Balkan Mountains. Consequently, the Variscan orogeny appears to have resulted in throughout rejuvenation of older crust, and denudation of all upper brittle crust above the ca. 400 ºC-level prior to deposition of molasse-type sediments.

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Upper Jurassic strike slip versus subduction in the Eastern Alps and the Meliatic palaeogeographic problem

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Late Jurassic stratigraphy of the Northern Calcareous Alps (NCA) contains ample evidence of synsedimentary tectonics in the form of elongate basins filled with turbidites, debris flows and slumps. Clasts are derived from the Mesozoic of the NCA; they commonly measure tens of metres in diameter and occasionally form kilometre-size bodies. These sedimentologic observations and the presumed evidence of Late Jurassic high pressure metamorphism recently led to the hypothesis of a south-dipping Jurassic subduction zone with accretionary wedge in the southern parts of the NCA.

New $^{40}Ar/^{39}Ar$ data from the location of the postulated high pressure metamorphism bracket the age of this crystallization as not earlier than 114–120 Ma. The event is therefore part of the well-documented mid-Cretaceous metamorphism of the Austroalpine domain. Thus, there is currently no evidence of Late Jurassic high-pressure metamorphism to support the subduction hypothesis. The sediment record of the Late Jurassic deformation in the NCA, including the formation of local thrust sheets, is no conclusive evidence for subduction. All these phenomena are perfectly compatible with synsedimentary strike-slip tectonics. Large strike-slip fault zones with restraining and releasing bends and associated flower structures and pull-apart basins are a perfectly viable alternative to the subduction model for the Late Jurassic history of the Northern Calcareous Alps.

However, contrary to the Eastern Alps transect, where arguments for a Jurassic subduction are missing, a glaucophane-bearing Jurassic high pressure metamorphism in the Meliatic realm is well documented in the W-Carpathians. Here the HP/LT-slices (Borka Nappe) occur between the Gemeric Unit and the Silica nappe system (including the Aggtelek–Rudabánya units), which corresponds in facies with the Juvavic units at the southern part of the NCA. To solve the contrasting palaeogeographic reconstructions we propose the hypothesis that the Upper Jurassic sinistral strike slip system proposed for the Eastern Alps continued eastwards and caused the eastward displacement of the

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Silica units into the Meliatic accretionary wedge. The Jurassic Meliata sediments contain characteristic detrital micas which are obviously derived from the Klatov tectonic elements within the Gemeric Unit. Therefore the hypothesis of a north-dipping Meliatic subduction zone is proposed, which was later overturned during the north-vergent Cretaceous nappe stack. The two contrasting geotectonic regimes in the Middle – Upper Jurassic: strike-slip dominated in the western termination of the Tethyan gulf and subduction-dominated in the eastern transect have been probably decoupled along a transform system.

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Low-grade metamorphism within the Greywacke Zone of the Eastern Alps: Adjustment of carbonaceous material to advective heat transport

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(with 1 figure)

The structural ordering of graphite formed in a low-grade metamorphic terrain (Greywacke Zone of the Eastern Alps) reflects a complex tectono-thermal history. High-resolution transmission electron microscopy has revealed two types of microtextures representing different degrees of graphitization. The first type is characterized by elongated ring-shaped microtextures, whereas the second type is characterized by graphite lamellae and polygonal flakes with perfectly stacked aromatic layers. In spite of the heterogeneity of the carbonaceous materials, the transitional nature of the graphitization process, and the different spatial resolutions, a correlation between the microtextures and quantitative metamorphic parameter (Raman spectra parameter, x-ray diffraction pattern, microscopic reflectance) constrains two phases of the metamorphic history. The data of this study demonstrate that graphitization is promoted by advective heat transport during post-collisional processes, whereas shear stress has no influence. During Early/Middle Cretaceous thrusting, ordering within the graphite basal planes and perpendicular to them increases continuously at different rates. Late Cretaceous uplift of an adjacent metamorphic core complex results in an increase of ordering to perfectly stacked aromatic layers. The structural ordering of carbonaceous material is very sensitive to temperature variations. Therefore, the use of the Raman spectrum as a geothermometer is confirmed by the data of this study.

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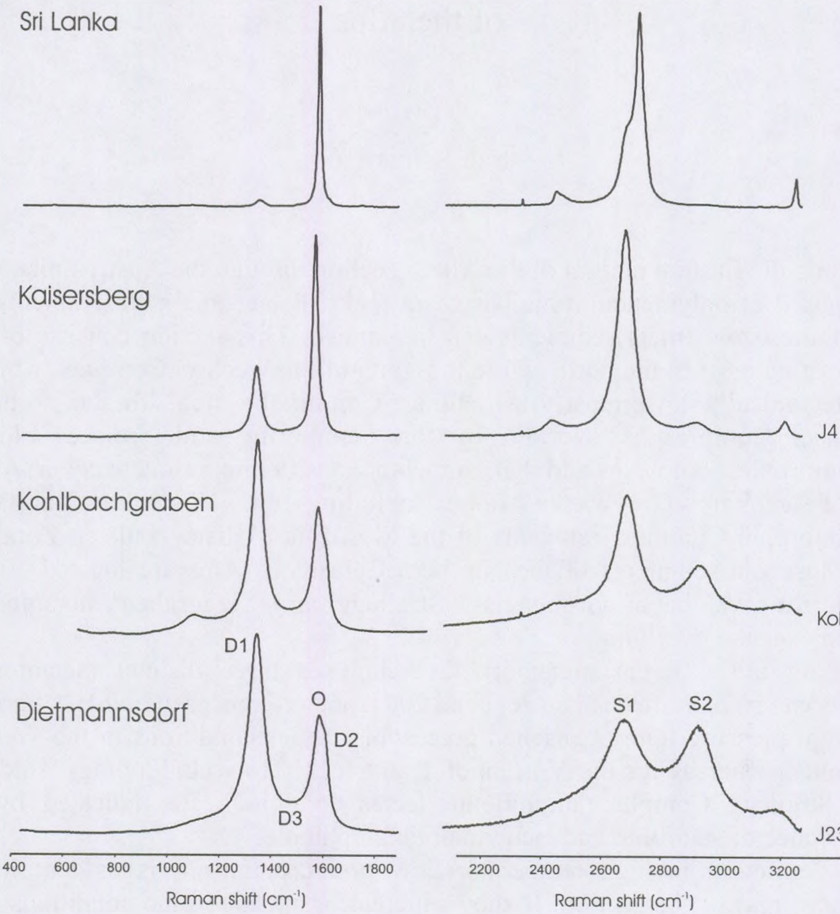

Figure 1. Representative first- and corresponding second-order Raman spectra of graphite of the eastern Greywacke Zone in comparison to a full-ordered graphite sample from Sri Lanka

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Metamorphic evolution along the Eastern margin of the Alps

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Along the Eastern margin of the Alps a section through the Austroalpine Unit, composed of polymetamorphic basement rocks, Palaeozoic metasediments and Permomesozoic (meta)sediments can be studied. This section consists of two contrasting parts to the north and to the south of the Wechsel Complex, which is the tectonically lowermost Austroalpine Unit in the area. To the north the Wechsel Complex is overlain by the Semmering and Troiseck-Floning metamorphic Complexes and their autochthonous Permomesozoic cover. Above the Palaeozoic Greywacke Zone including the Vöstenhof–Kaintaleck metamorphic Complex, remnants of the Mesozoic Meliata–Hallstatt Zone and the Mesozoic sediments of the Northern Çalcareous Alps are located. To the south the Waldbach, Grobgneiss, Strallegg and Sieggraben metamorphic Complexes are overlying.

Within the different metamorphic complexes three distinct metamorphic events can be identified (Schuster et al. 2001, and references therein): A Variscan medium pressure imprint reached greenschist facies conditions in the Wechsel Complex, whereas for the Vöstenhof–Kaintaleck, Troiseck–Floning, Waldbach and Strallegg Complex amphibolite facies conditions are indicated by the occurrence of staurolite and tschermakitic amphibole.

A Permotriassic high temperature/low pressure imprint is evident in the southern part of the section. It shows increasing metamorphic conditions from lowermost greenschist facies in the Wechsel Complex to upper amphibolite facies and local anatexis in the uppermost Strallegg and Sieggraben Complexes. Typical medium-grade assemblages contain andalusite and/or sillimanite. Based on geochronological age data peak metamorphic conditions accompanied by a widespread magmatic activity were reached at about 270 Ma.

The eo-Alpine imprint shows different trends to the north and south. To the north the metamorphic conditions are decreasing from lower greenschist facies in the Semmering Complex to anchizonal conditions in the Greywacke Zone and diagenesis in the Northern Calcareous Alps. Corresponding geochronological age data are increasing from about 80 Ma in the Semmering Complex to 115 Ma in the Greywacke Zone. Above scattering age data up to 150 Ma have been

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found. In the southern part the metamorphic conditions are increasing from lowermost greenschist facies in the Wechsel Complex to eclogite and subsequent high amphibolite facies in the Sieggraben Complex, whereas Ar-Ar white mica ages are decreasing from 85 Ma in the Wechsel Complex to 70 Ma in the southern part of the Strallegg Complex. The high-pressure overprint caused the transformation of Permotriassic andalusite and sillimanite into fine-grained batches of kyanite.

The observed metamorphic zoning indicates two different eo-Alpine nappe stacking events: The older is visible in the northern part and occurred by W–NW directed thrusting prior to the metamorphic peak at about 100 Ma. The second event occurred after the eo-Alpine metamorphic peak. It caused exhumation of the high-pressure rocks by N-directed thrusting.

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Tectonic structure of the Malé Karpaty Mts. in the light of the magnetic and structural research

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The Malé Karpaty Mts. (MKM), located at the Alpine-Carpathian junction is composed predominantly of pre-Tertiary units. From top to bottom, the MKM involves scarcely preserved Palaeogene and possibly Senonian post-nappe sediments, two large-scale cover nappe systems (Hronic and Fatric) and several thrust units ranged to the Tatric (Lower Austroalpine) superunit. The latter is generally composed of pre-Alpine basement complexes and Mesozoic sedimentary cover successions. It consists of the Bratislava thrust sheet overriding the subautochthonous (Infratatric) Borinka and Orešany units. Two major allochtonous Variscan granitoid bodies dominate within the Tatric Unit — the southern Bratislava and the northern Modra Massif .

The basement locally records Variscan events: nappe thrusting, deformation and medium- to low-grade metamorphism, emplacement of granitoid plutons (Bratislava M. at ca 350 Ma, Modra M. at ca 320 Ma) and late Variscan transpression. During Jurassic, the area experienced extensive rifting and shelf to pelagic sedimentation at the edge of the Tatric continental area facing the Vahic (South Penninic) ocean. Late Cretaceous inversion and nappe thrusting was followed by early Tertiary dextral transpression and Late Tertiary sinistral transtension and extension.

The aim of this study is to find out how this complicated evolution is reflected by the anisotropy of rock magnetic susceptibility (AMS) of various basement and cover rock complexes in the MKM and how AMS correlates with strain and kinematic analysis data. To meet this aim, more than 1,000 samples from basement granitoids, metasediments and metavolcanics, as well as from Mesozoic cover rocks were collected.

Even though Bratislava granites are classified as S-type and Modra tonalites as I-type, the difference in their bulk magnetic susceptibilities is smaller then expected - the mean value for granites is 1.3×10^{-4} [SI], and 7.9×10^{-4} [SI] for granodiorites. The thermomagnetic curves confirm that biotite is the main magnetic carrier in granites and magnetite in granodiorites and tonalites. The anisotropy degree in investigated rocks is rather low. In granites the maximum of the magnetic lineation degree only seldom exceeds 1.03. Even though the magnetic foliation is more conspicuous, its degree in most

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samples does not exceed 1.1. These values are slightly higher in granodiorites of Modra type, where the most frequent values of magnetic lineation degree vary around 1.05. Magnetic foliation degree is quite similar to that of the Bratislava granites. Planar magnetic fabric predominates over linear one in all types of rocks.

The basement of the subautochtonous Orešany Unit shows a comparatively homogenous SW-NE oriented magnetic fabric, probably related to perpendicular Alpine contraction. Jurassic rocks of the Borinka Unit suffered ductile noncoaxial shearing in the footwall of the overriding Bratislava nappe. This is recorded by subhorizontal foliation and NW-SE trending stretching lineation; shear sense criteria point to top-NW thrusting. The magnetic fabric parallels this orientation.

The magnetic foliation in granitoids of the Modra Massif mostly dips moderately SE and the magnetic lineation is virtually subhorizontal, trending WNW-ESE. This fabric coincides with the mesoscopic deformation pattern characterised by subhorizontal Alpine mylonite zones with NW–SE trending stretching lineation. However, the deformational magnetic fabric of the Scythian quartzites rising up from Modra granodiorites in map-scale SW–NE trending fold structures, as well as the magnetic fabrics of granodiorites in their close vicinity exhibits a SW–NE orientation. This magnetic fabric is entirely of Alpine origin, parallel to the coaxial deformation with SW–NE elongation (fold cores) and perpendicular to the NW–SE oriented noncoaxial shearing (thrust-related shear zones).

In the Bratislava massif, neither the magnetic lineation, nor the magnetic foliation has a homogenous orientation. Two main directions of magnetic lineation prevail: NW–SE and W–E. Magnetic foliation poles concentrate into an irregular S–N oriented girdle with one maximum, characteristic for sub-horizontal foliation. Based on comparison with deformation structures it is inferred that this pattern resulted from both Variscan emplacement-related fabric relics and Alpine overprint concentrated into a ductile-brittle shear zone accompanying the basal overthrust plane of the Bratislava nappe. The magnetic fabric of metamorphic complexes in the middle part of the Bratislava nappe coincides with the metamorphic schistosity and lineation, therefore it is most probably Variscan.

Our preliminary interpretation of the regionally complex pattern of magnetic fabric in various Tatric superunit rock complexes in the MKM shows that:

— the Variscan metamorphic-deformation (in volcanosedimentary complexes) and emplacement (in granitoids) processes within the basement domains were weakly affected by Alpine overprint;

— the inhomogeneously distributed Alpine fabric in the basement complexes results from low-grade metamorphic-deformation overprint mostly confined to ductile-brittle shear zones associated with overthrust planes;

— spatial and probably also temporal changes took place between coaxial and noncoaxial deformation regimes within both the basement and cover complexes during the Alpine orogeny.

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Synmetamorphic deformation mechanisms in the fine-grained Triassic limestones of the Eastern Bükk Mts., Hungary

Ferenc MÁDAI[1] and Norbert NÉMETH[2]

According to former investigations (e.g. CSONTOS 1999), the ductile deformation of the Late Palaeozoic – Triassic sequence in the Eastern Bükk is a generally recognised feature. The macroscopic ductile deformation elements are best observed in beds where limestone alternates with seams or lenses of materials of different competence, e.g. in cherty limestone. The early, ductile deformation took place during an Alpine low-grade dynamothermal metamorphism (ÁRKAI 1973, 1983). According to these publications, the conditions of the peak metamorphism can be characterised by 300–350 °C temperature and 200–300 MPa fluid pressure. Later deformation phases took place under lower temperature in most localities (DUNKL et al., 1994), and their style in the limestones was partly or entirely brittle.

In the present investigation the style of folding and the different microstructural elements of limestones were studied which should have developed during the ductile deformation phase. The position of the samples in an early lower order fold was also considered: samples both from the hinge and limb zones of folds were investigated. The following microstructural elements were examined:

- grain shape preferred orientation (SPO) of the fine-grained (10–20 mm) matrix;
- shape of the intercrystalline boundaries in the matrix;
- lattice preferred orientation (LPO) by constructing inverse pole figures;
- formation and further deformation of calcite twins in large (150–200 mm) pre-kinematic crystals.

The folds show a certain style variety according to the stratigraphic and geographical position but most frequent folds are class 2 (RAMSAY 1967) multilayer folds with a divergent fan cleavage. The samples from a hinge zone had weak SPO and no LPO. Conversely, a weak but definite LPO was detected on samples from the limb zones with SPO strongest along the bedding-cleavage intersection lineation. They showed a "c-axis fibre type" LPO (LEISS &

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ULLEMEYER 1999) having a simple c-axis maximum normal to the main schistosity. The slight LPO and the predominance of straight boundaries in the matrix indicate that the limestones in limbs of the early phase folds could deform by grain boundary sliding accomodated by dislocation creep (EVANS et al. 2003).

The large, pre-kinematic calcite crystals from the intensively sheared limbs usually show a typical "mortar structure": the large crystals are surrounded by small, dynamically recrystallized grains. The large crystals show undulatory extinction, subgrains or curved and recrystallized deformation twins. Conversely, the large calcite crystals from the hinge zones showed only serrated grain boundaries and straight, undeformed twins.

These features indicate that the folds could have formed with flexural shear or flexural slip. The differential stress was relatively weak (about 20 MPa) in the hinge zones, where the strain was nearly homogeneous, and the limestones deformed by diffusion mass transfer (pressure solution). The additional shear stress on the limbs rose the differential stress (up to 35–60 MPa) thus dynamic recrystallization and superplastic creep could take place. The parameters for the activation of these mechanisms corroborrate the parameters of the metamorphism derived from other methods (ÁRKAI 1973, 1983) and there is no sign of a later static or dynamic recrystallization so the deformation should be synmetamorphic.

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Deformation patterns and strain analysis on anchimetamorphic rocks of the Bükk Mts. (NE Hungary)

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The Bükk area (NE Hungary) is a characteristic and relatively exotic segment in respect of its neighbouring Innermost Western Carpathian units in the Alpine–Carpathian frame. Its Palaeozoic–Mesozoic tectonometamorphic and stratigraphic development is rather comparable to the evolution of certain Dinaric elements (e.g. Jadar Block, PROTIÆ et al. 2000). With the lack of any Variscan metamorphism and/or deformation, later regional dynamothermal metamorphism (160–120 Ma, followed in the NE Bükk by a Late Cretaceous 80–95 Ma metamorphic event; ÁRKAI et al. 1995) resulted in axial plane foliation and ductile deformation of variable degree in most of the Palaeozoic and Mesozoic formations. The ductile deformation of rocks in the Bükk Mts. is combined with the emplacement of small-scale nappe slices, imbricates and olistoliths, which often have an uncertain timing.

The large-scale folding and thinning of anchimetamorphic series can also be mapped, but to characterize deformation patterns, strain analysis on oriented samples was carried out. Limestones, marly limestones containing deformed, but originally nearly spheroidal elements (ooids, oncoids, corals) are ideal for this purpose. The orientation and the length ratio of the principal axes of the strain ellipsoids are measured in 3 perpendicular sections using digital image-statistic method. Significant layer-parallel flattening can be traced only in small zones (with a thickness of some cm-s or dm-s) along these sampled series outcropping even with a thickness of 200–300 metres. The maximum elongation of such clasts is generally not horizontal, and it is parallel to the cleavage and to the strike of the formation. In case of a second visible cleavage (in siltstones), intersection lineations are rather horizontal. In rocks with higher viscosity contrast the elongation in the same direction often leads to boudin formation. Shear indicators are not common, but if present (mostly around the higher imbricates), they indicate a transport direction perpendicular to the originally E–W striking, but now arched (and therefore SW–NE, then W–E, then NW–SE tending) anticline–syncline structures.

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Alpine structural and metamorphic evolution in the Uppony and Szendrő Palaeozoic (NE Hungary): consequences from two new chloritoid schist occurrences

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and Tibor NÉMETH[2]

Low-grade Palaeozoic and Mesozoic sequences in the so-called Gemer–Bükk region (NE Hungary, S Slovakia) forming the innermost segment of the Western Carpathians, generally lack characteristic metamorphic index minerals. Two new chloritoid schist occurrences from the Uppony resp. Szendrő Palaeozoic represent exceptions that allow us to put petrological and structural constraints on the Alpine tectonometamorphic evolution in these units.

From the Uppony Palaeozoic, chloritoid was first described from the Rágyincsvölgy Sandstone Fm. by NOSKE-FAZEKAS (1973) arguing for its detrital origin, while ÁRKAI et al. (1981) and IVANCSICS & KISHÁZI (1983) regarded it as newly formed, metamorphic mineral. During recent field work a new chloritoid schist occurrence was found in this chloritoid-bearing metasandstone (KOROKNAI et al. 2001).

From the Szendrő Palaeozoic, chloritoid was first reported from a dark phyllite with light, thin (mm-scaled) metasandstone intercalations (Szendrő Phyllite Fm.?) by KOROKNAI et al. (2000) in the water prospecting borehole named “Kazincbarcika–1”.

In both occurrences two foliations were observed in the chloritoid schists and the surrounding host rocks: the first, gently dipping foliation is ca. parallel to bedding (S_{0-1}), the second foliation (S_2) cuts S_{0-1} at high angle. The closely-spaced (mm-scale), steeply SE-dipping S_2 foliation is clearly formed as axial plane foliation of gently NE (resp. SW) plunging, NW-vergent F_1 folds in the Uppony Mts. Constructed fold axis orientation agrees well with the observed and calculated intersection lineations and the structural data of many other outcrops from the Uppony Mts. The dip directions of these foliation generations unfortunately could not be determined in the investigated drill core from the Szendrő Unit, but their presence is also very pronounced, suggesting basically very similar deformation history.

In microscopic scale, chloritoid forms either randomly orientated, idiomorphic, lath-shaped, frequently polysynthetically twinned crystals (0.2–2 mm) or rosettes in the fine-grained matrix. The chloritoid porhyroblasts definitely overgrow the S_2 foliation recording its generally posttectonic (rarely late syntectonic) character in both occurrences. Zoning profiles with increasing $Mg/(Mg+Fe^{2+})$ ratio from core to rims

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suggest prograde metamorphic conditions during chloritoid growth. Chloritoid reaches surprisingly high modal content (approx. 20–30%) in comparison to the surrounding host rocks also demonstrating the crucial importance of bulk chemistry on metamorphic mineral growth.

For thermobarometric purposes the chlorite-chloritoid thermometry (VIDAL et al. 1999) was applied in the chloritoid schist of the Szendrõ Unit. Temperature estimations are in the range between 430–450 °C which is in good accordance with previous petrological data (obtained mainly by the IC method) of ÁRKAI (1983).

Since posttectonic growth (with respect to S_2 foliation) of chloritoid is regarded as roughly synchronous event with the thermal climax of the Eoalpine metamorphism (ÁRKAI et al. 1995), therefore the major folding (F_1) of the Szendrõ and Uppony units must have occurred before peak metamorphic conditions were reached. Consequently, the Alpine tectonometamorphic evolution of these units is characterized by a "classical", clockwise orogenic P-T-d loop where deep tectonic burial and major ductile deformation (N(W) vergent F_1 folding) is followed by thermal relaxation in greenschist facies conditions during the Cretaceous metamorphic event. Later folding (F_2) producing locally non-penetrative S_3 crenulation cleavage did not influence basically F_1 structures in the Uppony Unit but it had important role in the Szendrõ Unit resulting in the formation of outcrop and map-scale F_2 syn- and antiforms. Top-to-the-N ductile shearing — postdating F_1 folds — probably also belongs to this deformation phase. In the late phase of exhumation, both units were affected by F_3 kink folds (generally with almost vertical axes) that are connected to mostly ca. N–S trending, semi-ductile shear zones.

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Geological setting of Triassic "Hallstatt" (s.l.) facies in NE Hungary

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(with 1 figure)

The Aggtelek and Rudabánya Mts. Occur in the NE-most part of the Pelso Megaunit (composite terrane). Non-metamorphosed Middle–Upper Anisian to Upper Norian pelagic basinal and slope facies, corresponding in part

to the "Euhallstatt" facies of the Eastern Alps, characterize the Bódva Unit and Szőlősardó Subunit of the Rudabánya Mts. and the Derenk Subunit of the Aggtelek Mts. The Aggtelek Unit and Alsóhegy Subunit were in outer shelf setting untill early Late Carnian, with southward facing reefs (Upper Anisian at Aggtelek, Carnian on Alsóhegy). Then their shelf margin broke down and pelagic Hallstatt and Pötschen Limestones were deposited untill the Late Norian. The Szőlősardó Subunit, interfingering with the Bódva Unit, and the Derenk subunit (representing the northernmost "Euhallstatt" facies in the North Pannonian – Inner West Carpathian orogenic collage; HAAS & KOVÁCS, 2001) in the southern front of Alsóhegy were in slope setting also untill early Late Carnian, then normal sequences of Hallstatt and Pötschen Limestones were deposited untill Late Norian, almost without resedimentations.

We studied the structure of these units along three sections: A–A', B–B' and C–C'.

Section A–A' cuts through the Hungarian part of Alsóhegy, with Carnian Wetterstein ("Waxeneck") lagoonal facies in the N and reef facies in the S, the latter being overthrust (although the present contact is along a young subvertical fault) onto Norian Hallstatt limestones of the Derenk Subunit.

Section B–B' cuts through the Bódva Unit of the Rudabánya Mts., enclosed within the Darnó Fault Zone. Its northern part is formed by the southward recumbent Szúnyog-tető anticline. Jurassic formations were explored by the borehole Szalonna–5 on its southern limb. After another S-ward recumbent fold (see also on section C–C'), the borehole Szalonna–4 explored a repetition of

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Gutenstein and Steinalm formations on the southern part of the section and proved the presence of Telekesoldal-type Jurassic rocks below Triassic.

Section C–C' is complementary to the former, starting from borehole Szalonna–5 SW-ward to the Bódva Valley. In its SW-part the borehole Perkupa–74 drilled a completely overturned, subhorizontally lying Triassic sequence, overthrust also on Jurassic rocks.

From these stratigraphic, facial and structural facts the following conclusions can be drawn:

1. Southward facing mesoscale thrusts and folds characterize the investigated section of the Aggtelek–Rudabánya Mts., although N-vergent ones can also be recognized (LESS, 2000). Reconstruction of the deformational history and timing of events need further detailed studies.

2. As opposed to the Lower and Upper Juvavicum of the Northern Calcareous Alps, the original southward deepening tendency has been preserved in the units of the Aggtelek and Rudabánya Mts.

3. This southward deepening tendency points to a southerly existing (according to present coordinates) Triassic pelagic/oceanic domain. This is in apparent contradiction with recently published structural and geophysical results from the northern margin of the adjacent Slovak Karst area (cf. NEUBAUER et al., 1996; PLAŠIENKA et al., 1997). However, a recently proposed pre-Late Cretaceous strike-slip faulting (FRANK, 2002 and this volume) may give an explanation for this apparent contradiction.

4. Ductile deformations observed in HP-metamorphosed rocks of the Borka Unit at the northern margin of the Slovak Karst (FARYAD, 1997) indicate a northward transport. However, these blocks metamorphosed at several 10 km-s depth can be interpreted as being rotated into the direction of Late Cretaceous nappe stacking. Reconciliation between this N-ward transport, and S-vergent folds, reverse faults and southward facies polarity needs further detailed structural studies.

5. The Bódva Unit with its specific Triassic deep-water development (Bódvalenke Limestone, Szárhegy Radiolarite) has no equivalent in the Northern Calcareous Alps (HAAS & KOVÁCS, 2001). However, this internal Tethyan facies can be followed through the Internal Hellenides up to Oman (KRYSTYN and BERNOULLI, pers. comm.)

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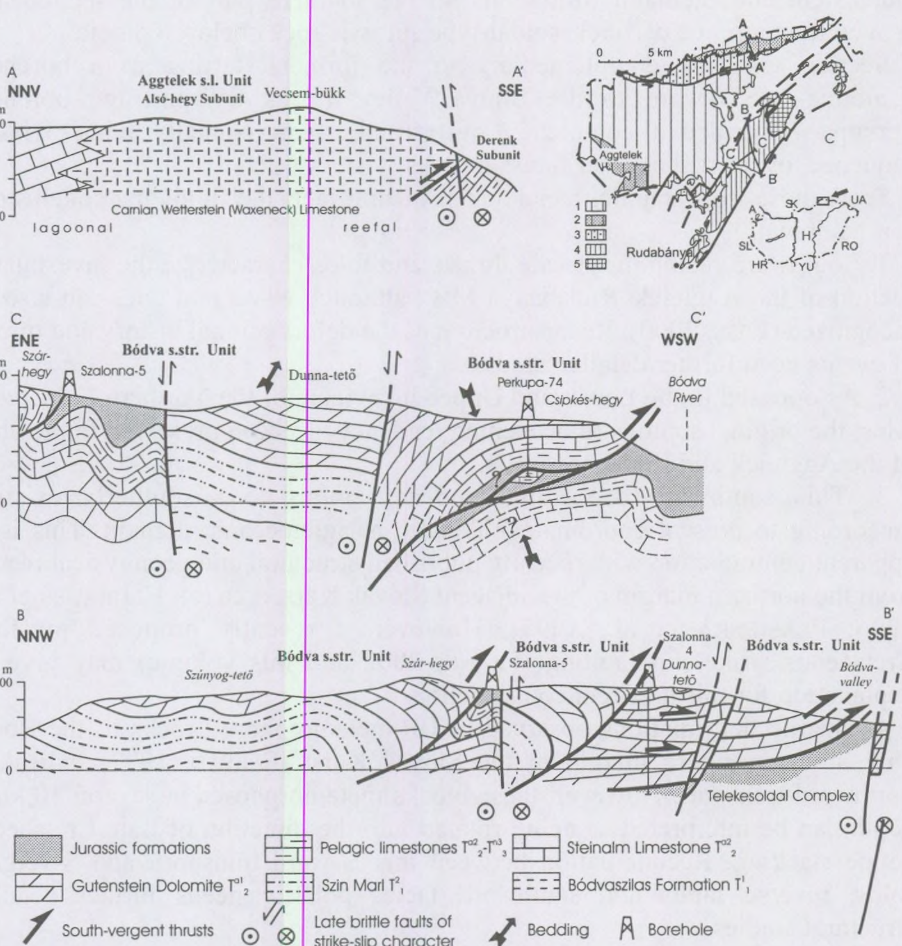

Figure: Three simplified geological sections across the Aggtelek–Rudabánya Mts, NE Hungary. For location of sections see insert at upper right

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The new geological map of the Gemer–Bükk area (1:100 000)

György LESS[1] and Ján MELLO[2]

The geological map of the Bükk Mts. and its vicinity in 1:100 000 scale issued in 1964 and edited by Kálmán Balogh served as an essential tool both for regional geological and tectonical correlation and for industrial purposes, too, because it embraces a huge territory from Plešivec to Mezőkövesd and from Recsk to Žarnov.

However, in the last almost fourty years intensive geological research and mapping both in Slovakia and Hungary resulted in several new stratigraphic and tectonic discoveries, from which the most important ones are the detection of deep marine Jurassic rocks in large territories and the discovery of nappes and strike-slips throughout the region. Simultaneously, new geological maps, demonstrating already these new achievements have been published both in Slovakia (Slovak Karst, Rimava Basin and its vicinity) and in Hungary (Aggtelek–Rudabánya Mts., Bükk and Szendrő Mts.) in different scales (1:25 000 to 1:50 000).

These new results made it possible to construct a synthetic geological map of the Gemer–Bükk region in the scale of 1:100 000 in order to substitute the K. Balogh map. The new map will be published at the end of 2003 by the Geological Institute of Hungary while its explanatory booklet will be issued by the Dionýz Štúr State Geological Institute of the Slovak Republic at the end of 2004. Both publications are being prepared in co-operation of the Slovak and Hungarian sides.

The territorial extent of the geological map is about 5500 km^2, containing the whole Mesozoic of the Southern Gemerides (including the Aggtelek–Rudabánya Mts.), the Szendrő and Uppony Mts., the Bükk and the Darnó Hill and also the Cenozoic basins surrounding these Palaeozoic–Mesozoic outcrops.

The concept of the geological map is to show the basic geology on the main sheet, i.e. mapable geological units, their metamorphism, character of the boundaries, bedding, schistosity and the most important boreholes. It will be published in one single A/0 sheet, therefore the legend has to be largely

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condensed. Quaternary deposits are subdivided only into the main genetical categories, while older rocks bearing similar lithology and age are grouped into one single unit each, such as „Upper Triassic grey cherty limestones (Pötschen, Aflenz and Felsőtárkány Limestone) or „Ladinian–Carnian platform carbonates (Wetterstein, Fehérkő, Bükkfennsík, Berva and Kisfennsík Limestone)". Metamorphic overprint is shown by overprinted dotting.

The tectonical interpretation will be shown separately from the basic geological map but in the same sheet. A tectonical sketch in the scale of 1:600 000 and five geological sections will help to orientate the readers in understanding the complex structure of the region.

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Late Jurassic – Early Cretaceous tectonics-induced deposits in N Hungary

Mónika BÁRÁNY[1] and László CSONTOS[1]

(with 1 figure)

Late Jurassic and earliest Cretaceous sequences in the Gerecse Mts (Transdanubian Range, N Hungary) frequently contain sedimentary "breccias". There is a widespread horizon of Oxfordian age within or above radiolarite. There seems to be a negative correlation between the thickness of radiolarite and the thickness of the breccia: in some localities, where breccia is thick, radiolarite is very thin or it may be even missing. There are bigger Upper Triassic – Liassic olistholites (0.5–30 m) in Oxfordian limestone in the NW part of the mountains (Hosszú-Vontató). The size of olistholites fines eastwards (Szél Mt.) where the size of the fragments ranges between 1cm and 1m. The breccia grades towards SE into nodular (redeposited) limestones or crionidal calcareous turbidites. All this indicates that the source area was W–NW from these localities.

In the W part of the mountains (Tűzkő hill) sediments of Tithonian debris flow occur, which contain fragments of Malm algal carbonates, too. In another occurence a large olistolite of Liassic age sits on Kimmeridgian limestone. This suggests that there was a Tithonian redeposition event, too. No transport directions could be deduced.

At the base of the Cretaceous section a marine conglomerate occurs. This graded "breccia" consists mostly of Dachstein Limestone, but also contains fragments of ophiolites and red cherts, Jurassic limestones. Sedimentary features and grain size distribution suggest an easterly transport in channels. The "breccia" grades upwards into a rhytmic marl or a sandy turbidite, the equivalent of the Alpine Rossfeld beds.

We speculate that the redeposition events can all be related to a single tectonic phase, which affected the former passive margin of the Austroalpine–Dinaric continent. At the end of Jurassic this margin suffered obduction of ophiolites from the Meliata (Dinaridic) Ocean. This event probably created shortening and thrusting in the overridden margin. It might have created the Late Jurassic nappes

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in Salzkammergut, Austria (GAWLIK et al. 1999) and also some local thrust sheets in the Transdanubian Range. The three redeposition events suggest a repeated activation of thrusts or thrust propagation. Still soft Jurassic sediments were swept away from the tilted back of a thrust sheet. Then more consolidated Late Triassic and Liassic deposits were mobilised from the even steeper thrust body Finally, at the advent of Cretaceous, Late Triassic was eroded off the back of the thrust body and resedimented as a deeper marine conglomerate. The obducted ophiolite nappe was then close enough to provide detritus into the same sedimentary basin. Based on the sediment pattern, the tilt was roughly east-directed and thus the supposed ramp was dipping eastwards (present coordinates). The local Gorba-ridge might be such a thrust nappe and source area of redeposited sediments.

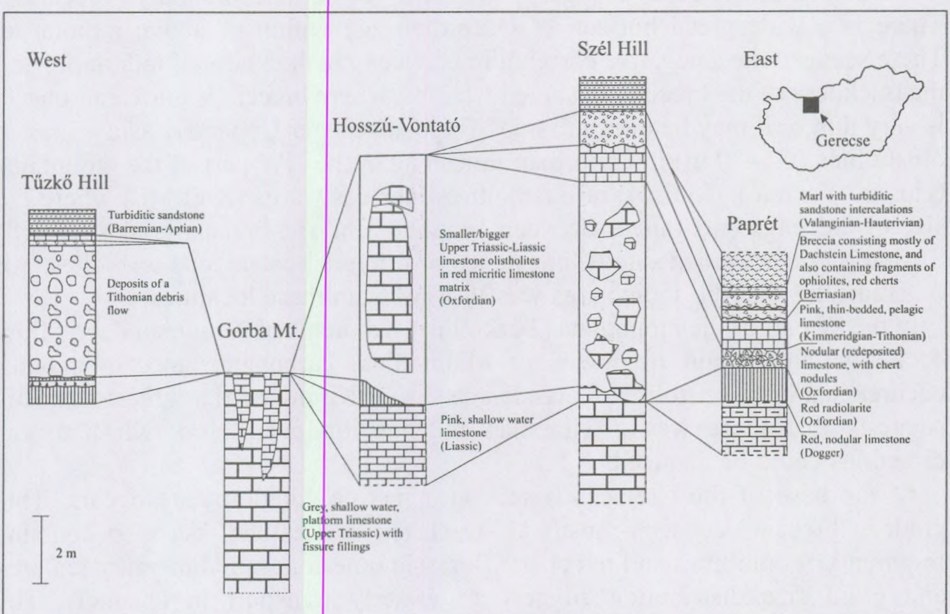

Figure 1. Schematic Late Jurassic-Early Crecateous stratigraphic columns in an E–W section across the Gerecse Mts, N Hungary.

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Tectonostratigraphic terrane and palaeoenvironment maps of the Circum-Pannonian Region

Sándor KOVÁCS[1], Károly BREZSNYÁNSZKY[1], János HAAS[1], Tibor SZEDERKÉNYI[1], Fritz EBNER[2], Jacob PAMIĆ[3], Mauritio GAETANI, Gian-Battista VAI[4], Hans G. KRÄUTNER[5], Jozef VOZÁR, Anna VOZÁROVÁ[6], †Pero MIOČ[7], Stefan KARAMATA, B. KRSTIĆ[8]

In continuation of the Terrane Map Project of the former IGCP Project No. 276: "Paleozoic Geodynamic Domains and Their Alpidic Evolution in the Tethys" (Coord.: D. Papanikolaou, F. Ebner, F. Neubauer, G. Rantitsch), the terrane and palaeoenvironment map series of the basement of the Pannonian Basin and its Alpine–Carpathian–Dinaridic surrounding has been compiled for four time slices, in scale 1:2 5 000 000:

1. Variscan preflysch (Devonian – Early Carboniferous) environments;
2. Late Variscan molasse (Late Carboniferous – Early Permian) environments;
3. Initial Neotethyan rifting (Middle – Late Triassic) environments;
4. Maximal Neotethyan spreading (Middle Jurassic) environments

The main goal of the map series to present information about the relationships of exotic blocks/terranes building up the postorogenic collage in the Pannonian basement, which amalgamated and accreted finally by the Middle Miocene.

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Early Alpine evolution of the Western Carpathians: Geological constraints on geodynamic models

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Alpine tectonic evolution of the Western Carpathians (WC) covers about 250 Ma time span, starting from the breakup of the Meliata Ocean. Orogenic shortening began in Early Jurassic and terminated in Late Tertiary. The orogenic front initiated as a limited Meliata accretionary wedge and propagated episodically from the Meliatic suture to both sides of the asymmetric, double-vergent Carpathian orogen. However, the narrower retrowedge (Internal WC – Pelso) was inactivated during the Early Cretaceous, soon after closure of the Meliata ocean, whereas the prowedge widened considerably during the Cretaceous (Central WC) and Tertiary (External WC – Flysch Belt).

Mesozoic continental to oceanic rifting was preceded by significant distensional tectonic and thermal events during Permian Early Triassic, indicated by rift- post- or anorogenic magmatism in several Central WC zones (e.g. VOZÁROVÁ & VOZÁR, 1988). Recent geochronological data shows that granitic magmatism persisted from the Permian as late as Middle Triassic (KOTOV et al., 1996; PUTIŠ et al., 2000; POLLER et al., 2002, 2003). The site of the future Meliata rift was marked by intense Late Permian – Scythian subsidence and shallow marine sedimentation. So the terminal Variscan event could have been genetically related to the pre-Alpine rifting in the southern WC zones, which ultimately led to the Anisian opening of Meliata. On the other hand, plate tectonic reconstructions (e.g. STAMPFLI, 1996) suggest that rifting occurred inboard the active northern margin of Tethys, hence the Meliata ocean should have originated as a back-arc basin evolving into a broad oceanic domain. This view is supported by the geochemistry of the basalts, which developed from BABB to MORB-types (IVAN, 2002).

In the Lias, uniform stretching of the epi-Variscan continental lithosphere formed several broad, rapidly subsiding intracontinental basins separated by narrower highs (e.g. WIECZOREK, 2000; PLAŠIENKA, 2003a, b). Synchronously, subduction of the Meliatic oceanic lithosphere started (KOZUR, 1991). Both processes were probably related to a change in large plate movements- SE drift of Africa and Adria relative to Europe during opening of the Central Atlantic (e.g. DEWEY et al., 1989). The embryonic Western Carpathian orogenic wedge was created by accretion of material derived from the subducted Meliatic lithosphere to the upper plate. The Meliatic accretionary wedge and its hinterland were affected by fore- and/or back-arc rifting during the Middle - Late Jurassic, creating a basin floored by immature oceanic crust (Bükkian Szarvasko Nappe; e.g. DOWNES et al., 1990). In the European lower plate,

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the Dogger rifting phase initiated localised asymmetric extension, which ultimately caused breakup of the Vahic (South Penninic) Ocean. The Neocomian distension phase marks further foreland-ward migration of rifting and records final opening of the Magura Ocean (PLAŠIENKA, 2003a).

The oldest Alpine structural association related to the Middle - Late Jurassic compressional event in the WC is a blueschist mineral assemblage in the Meliatic Bôrka Nappe. This Late Palaeozoic - Triassic unit represents a distal lower plate passive margin involved into subduction. Later this and very low-grade Jurassic accretionary melange were emplaced W-ward over the most internal Central WC Gemeric Unit (FARYAD et al., 2003) after closure of the Meliata Ocean. Subsequently, a collisional retrowedge originated by shortening and obduction of the Meliata-related Szarvaskő back-arc basin crust, which was thrust over the distal Bükkian foreland (CSONTOS, 2000). The retrowedge activity is attributed to the income of the buoyant Central WC crust into the subduction zone that halted the prowedge growth for some time. In the Early Cretaceous, orogenic shortening returned to the prowedge. The wedge advanced northward by episodic frontal and basal accretion of lower plate units attenuated by preceding rifting events (PLAŠIENKA, 2003b). Only upper crustal slivers were amalgamated in the form of thick-skinned and thin-skinned thrust sheets, while the lower crust and the lithospheric mantle were consumed by subcrustal subduction. Collapse events within the wedge are marked by the early Late Cretaceous emplacement of extensive Fatric and Hronic cover nappe systems over the Tatric substratum.

200–90 Ma orogenic processes in the WC were probably driven by subduction slab pull of Meliata oceanic lithosphere. Middle to Late Jurassic rifting and breakup of the lower, European plate resulting in the opening of Penninic oceanic basins, is attributed to the transmission of negative buoyancy forces from the sinking Meliata slab. This mechanism could explain collisional pro- and retrowedge propagation and simultaneous oceanic spreading in its foreland, too.

From the Senonian (ca. 90–80 Ma) onward, the Western Carpathian orogen prograded by an indentation-subduction mode, related to the kinematics of large plates in the western Tethys, particularly the start of convergence between Africa-Adria and Europe. Advance of the Adria indenter (represented by Pelso in the WC) shortened the central, thermally soft parts of the original collisional wedge and triggered exhumation of the Veporic metamorphics (JANÁK et al., 2001). At the same time, shortening was relocated to the northern Tatric edge, beneath which the South Penninic oceanic crust was consumed (PLAŠIENKA, 1995). In the uppermost Cretaceous – earliest Palaeogene, the Oravic ribbon continent in Middle Penninic position (substantial part of the Pieniny Klippen Belt) was accreted to the wedge. Then the orogenic front reached the Magura Ocean, which was consumed during Palaeogene – Early Miocene. During this indentation period, the collisional deformation zone widened considerably and initiated forced subduction of Penninic oceanic basins and widespread inversion of former extensional basins in distant European foreland areas (e.g. ZIEGLER et al., 1996).

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Metamorphic evolution and geochronology of the Algyő high at the southern Tisza basement and its analogies with Koralm type crystallin from Eastern Alps

Wolfgang FRANK[1], Györgyi LELKES-FELVÁRI[2] and Ralf SCHUSTER[1]

The Algyő structural high is located within the framework of the Békés–Codru Unit of the southern Tisza basement in the vicinity of Szeged. Cretaceous to Tertiary mineral ages have been reported from drill cores of this area in contrast to variscan ages ranging mainly within 310–320 Ma from the neigbouring basement units. The structural evolution of the Algyő high was interpreted as a metamorphic dome, however also an alpine nappe system has been postulated.

The lithology of the Algyő high shows some characteristics not found in the surrounding basement units. Biotite bearing paragneisses — micaschists form the characteristic rock type, associated with some deformed pegmatite layers. Some amphibolites and intercalations of pure to impure calcite and dolomite marbles are typical members. The mineral assemblages and their structural evolution show typical features of a polymetamorphic history. Two amphibolite grade events with two generations of garnet, feldspars and micas can be distinguished. The younger generation correlates with a pronounced deformation, often of mylonitic character with variable intensity. Typical features are aggregates of small kyanites formed at the expense of former andalusite, partly also by progressive breakdown of staurolite. A third metamorphic event with greenschist facies conditions is recognized locally, characterized by a fluid rich environment with variable retrogression and sericitisation of the older amphibolite grade assemblage, associated with deformation.

New systematic Ar-Ar data from the metamorphic basement demonstrate that kyanite aggregates only occur in rocks which yielded early Alpine muscovite ages (82–95 Ma), whereas lithologies with preserved sillimanite, andalusite and large kyanite porpyroblasts correlate with Variscan ages. Therefore, among other arguments, the transformation of andalusite into kyanite aggregates and the distribution of Alpine muscovite ages can be used to delineate the contrasting metamorphic environments of the Tisza basement rocks and the overriding nappe system with transported alpine metamorphism.

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A strong argument for this interpretation of the evolutionary history of the Algyő high is the existance of a Permian (low pressure) metamorphism. The older garnet generation from biotite-paragneisses of a Dorozsma drill core yielded a Sm/Nd age of 273 ±7 Ma, interpreted as a formation age. This indicates that the pre-Alpine mineral assemblage of the Algyő high was at least severely influenced by a Permian prograde amphibolite facies event.

The Sau-Koralm crystalline in the Eastern Alps shows a well developed amphibolite grade Permian low-pressure metamorphism and a severe structural and metamorphic overprint during mid-Cretaceous nappe stack. This crystalline is now understood as the severely transformed former attenuated European continental margin of the Neo-Tethys.

Based on the many similarities of the two locations in lithology, metamorphic and structural evolution we assume that the sequence in the Algyő high also represents an element derived from the northern European outer continental margin. It was thoroughly deformed into a nappe system during Cretaceous, possibly mixed with slivers of Variscan basement and lithologies having only Cretaceous prograde metamorphism. It reached its present position on the Tisza basement with variscan history during Early Tertiary emplacement. The Baia de Aries Unit in the Apuseni Mountains may be a possible continuation.

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Ductile tectonic evolution of the Mórágy Granite Complex (SW Hungary): a puzzle of the Variscan orogeny in Central Europe

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In the frame of the Hungarian National Research Project on the final disposal of low and intermediate level radioactive waste, numerous deep and shallow boreholes exposed the pre-Tertiary basement in the Mórágy Hills, SE of the Mecsek Mts. More than 5000 m of crystalline rock has been drilled in the Mórágy Granite Complex during this project untill now. The study of this enormous quantity of fresh core material (free of any surface alteration) allows us a detailed reconstruction of the magmatic and metamorphic evolution in this Variscan (~370–360 Ma) pluton (BALOGH et al. 1983, BUDA et al. 1999, KLÖTZLI et al. 1999).

In this contribution we will deal with the ductile deformation of this complex built up mainly by metaluminous to slightly peraluminous, K-Mg-rich, microcline megacryst-bearing, medium-grained, biotite-monzogranites and quartz monzonites (BUDA 1985) that contain generally oval-shaped, variably elongated mafic enclaves (predominantly amphibole-biotite diorites, monzonites and sienites) of various size (from a few cm to several hundred metres). Feldspar-quartz rich leucocratic dykes (at least three generations) belonging to the late-stage magmatic evolution crosscut all of the previosly described rock types.

The tectonic investigation and evaluation of drillcores was essentially based on the ImaGeo corescanning system and the adjoining CoreDump and CoreTime evaluating softwares developed in the Geological Institute of Hungary (MAROS & PALOTÁS 2000, MAROS & PÁSZTOR 2001), which make the spatial reconstruction of the observed, approximately planar phenomena as dykes, foliations, hydrothermal veins, fractures, etc. possible.

Focusing on the ductile structures in outcrop and map scale, the complex is characterized by a ca. (E)NE–(W)SW striking, steeply dipping (generally >80°) foliation (S_1), that is overprinted in many places by a less steep (dip angle between 40–75°) foliation (S_2) transposing S_1 foliation in various degrees. Both foliations dip in the same direction, mostly to the NW, in certain zones to the SE, which might reflect a late folding event.

In hand specimens, heavily elongated quartz lenses (axial ratios up to 1:7–8, generally between 1:2–6) can be observed both on the XZ and YZ fabric planes. In

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contrast, sections parallel to the foliation (XY fabric plane) do not exhibit any prominent stretching lineation (occassionally a weakly-developed lineation is present), which altogether reflects basically flattening-type strain.

On microscale, solid state deformation is best evidenced by the strong dynamic recrystallization of quartz. Fine-grained recrystallized rims around microcline, plagioclase and biotite (core-mantle structure) appear in a much less extent. Feldspars show predominantly brittle behaviour during deformation. Rarely, muscovite is observed as newly formed, syntectonic metamorphic mineral. Quartz c-axis textures from these rocks show a — more or less — symmetric pattern also pointing to coaxial strain. However, a limited amount of simple shear deformation is also proven by weakly-developed, asymmetric structures (mostly mica fish and feldspar s-clasts) in the XZ sections. The observed mineral paragenesis and fabric relationships suggest (upper) greenshist facies conditions during deformation.

Well-developed stretching lineation can be only observed on the foliation planes of the relatively rarely occurring, cm to dm scaled mylonitic shear zones that are mostly associated with the less steep S_2 foliation. The plunge of the stretching lineation in these zones slightly differs (max. 30° measured as pitch) from the dip of foliation in the most cases. Well-developed kinematic indicators show top-to-the-(S)SE (or top-to-the-N in the case of SE dipping foliation, respectively) thrusting in the XZ sections. Occasionally oblique to pure strike slip movement (both sininstral and dextral motions) were observed, which may indicate the transpressional character of the deformation. However, the age relationship between strike-slip and thrust movements is unclear yet, it requires further investigations. The mylonitic shear zones occur preferentially in fine-grained aplites/microgranites suggesting strong strain-partioning between these rheologically weaker leucocratic dykes and the surrounding host rocks at (upper-) middle crustal levels.

The results of our microtectonic investigations provide the first evidence of ductile compressional tectonics in the Hungarian part of the Tisza Megaunit. The observed structures can be related to a pure compressional or transpressional tectonic regime with supposed S(E)-vergent nappe tectonics during the Variscan orogeny.

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Miocene tectonics at the northern border of the Transylvanian Basin

Matthias TISCHLER[1], Heike R. GROEGER[1],
Stefan M. SCHMID[1] and Bern FUEGENSCHUH[1]

Translation and rotation of the geophysically defined Tisza–Dacia and Alcapa blocks plays a key role in the Tertiary tectonics of the Pannonian–Carpathian junction. While palaeomagnetic studies established opposed rotations of these blocks, separated by the Mid-Hungarian lineament (MHL), field observations are scarce due to the sedimentary cover of the Pannonian Basin.

Yet at the northern border of the Transylvanian Basin outcrops allow for field-based studies of structures related to the Tertiary tectonics and the Bogdan – Dragos Voda fault system, which is considered a first order candidate for the prolongation of the MHL to the northeast.

Focussing on this area in northern Romania (Maramures area) our study provides new kinematic data of the Burdigalian nappe emplacement of the Pienides and the subsequent strike slip dominated deformation along the Bogdan – Dragos Voda fault system.

In the Burdigalian, the Pienides (unmetamorphic flysch nappes) were emplaced onto the autochthonous Palaeogene flysch units, forming an arcuate thrust belt. Kinematic data consistently indicate top to the SE-directed thrusting of the Pienides and related imbrications in the autochtonous units. Development of the arcuate shape is dominated by differences in thrust plane geometry, at least in the northern part of the nappe stack. While the SW–NE striking part is dominated by frontal ramps, oblique ramps characterize the SE–NW trending nappe contact. At a later stage SW–NE compression led to an accentuation of the curved thrust front. Between Langhian and Tortonian the E–W trending Bogdan – Dragos Voda fault system, offset these thrust contacts. In Middle to Upper Miocene times the Bogdan Voda fault and Dragos Voda fault acted as a single, strike slip dominated fault allowing for an estimated left lateral offset of ca. 30 km. It can be shown that during this phase kinematics changed from transpressional to transtensional. Towards the east the offset is reduced by coevally active SW–NE striking faults (e.g. Greben fault) featuring a dominant normal component. In the basement units of the East Carpathians (Bucovinian nappes) the system terminates in an extensional horsetail splay geometry. Based

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on stratigraphic arguments major activity of this fault system is constrained to the time interval between 15.5–10 Ma. Recent fission track dating on apatite supports this timing (Groeger et al, this volume). Since Burdigalian thrusting is consistently SE-directed on either side of the Bogdan – Dragos Voda fault, major post-Burdigalian differential rotations can be excluded for the northern and southern block respectively. Therefore it seems more likely that the Bogdan – Dragos Voda fault is a minor branch instead of representing the single principal continuation of the MHL.

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Tertiary structural evolution and exhumation history of the Rodna Mountains in Northern Romania: preliminary fission track data

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and Matthias TISCHLER[1]

Combining fission track analysis with field data this study aims at a reconstruction of the exhumation history of the Rodna horst in comparison to the surrounding basement units. The Rodna Mountains, located in Northern Romania, form part of the basement units of the East Carpathians (Bucovinian nappes), but are situated internally of the slightly curved NNE–SSW striking East Carpathian Mountain chain.

The East Carpathian basement comprises Precambrian to Early Palaeozoic sedimentary series, which suffered a polyphase metamorphic history until Permian times. During the Mid-Cretaceous Alpine orogeny NE directed thrusting under greenshist facies conditions led to the formation of the Bucovinian nappe stack and the formation of open folds with NW–SE striking axes. The Rodna horst itself builds a big antiform, which exhumes the lowermost Bucovinian nappe in its core. Tertiary brittle tectonics led to the final exhumation of the Rodna horst in two stages. Exhumation is goverened by the E–W trending Dragoş Voda fault, bounding the horst to the north, as well as several important internal faults. Combined fission track analysis on apatite and zircon allows to shed light on the Cretaceous to Tertiary thermal history of the area.

For estimates on the exhumation rate four vertical profiles were sampled in the Rodna horst. The profiles are located within different fault bounded blocks of different tectonostratigraphic level. Additionally a horizontal profile has been sampled crossing the Dragoş Voda fault. For comparison the main basement unit located to the north of the Rodna Mountains has been sampled. Small-scale faults have been analysed to constrain Tertiary brittle tectonics, a topic more specifically dealt with by Tischler et al. (this volume).

First results show, that apatite fission track ages differ according to their structural position. The core of the Rodna horst, representing the lowermost Bucovinian, is characterized by Miocene cooling ages of around 10–13 Ma, while the rim, comprising tectonically higher units, cooled in Early Miocene

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(17–23 Ma). Exhumation and updoming of the Rodna horst led to intense fragmentation under brittle condition, with individual faults taking up substantial vertical offset up to km-scale.

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Mesozoic evolution of the Tisza Megaunit: a review

János HAAS[1] and Csaba PÉRÓ[1]

The south-eastern part of the basement of the Pannonian Basin is made up of Variscan crystalline complexes and granitoids, early Mesozoic formations showing striking affinity with the corresponding formations in the southern margin of the European plate. This large composite structural unit that is actually an exotic terrane of European plate origin was named Tisza Megaunit.

Based on relevant data on the pre-Tertiary basement of southern Hungary, reconstruction of the position of the Tisza terrane in the early Alpine evolutionary stages, process of its separation and break off from the European plate and results of its Eo-Alpine deformations are summarised. Palinspastic reconstructions indicating the setting of the Tisza Megaunit are presented on sketch maps (Fig. 1). Along with the main tectonic features, these maps also depict the major facies units.

Based on correlation of Variscan granitoids and crystalline complexes, during the Variscan orogeny the later Tisza Megaunit was located in the zone of the European plate where the Variscan terrane accretion took place. The Moldanubian Zone of the Variscan Mountain Range continued in the external zones of Tisza (BUDA, 1996). In post-Variscan stages in the same zones, transpressional tectonics led to development of molasse basins.

The Neo-Tethys opening (Middle Triassic) did not change position of the Tisza Megaunit. Long lasting process of its separation began with incipient continental rifting along the axis of the later Ligurian – Penninic – Vahic ocean branch as early as in Late Triassic. It was reflected in the development of Gresten-type basins. Cessation of terrigenous material in the most external zones (Mecsek and Szolnok units) and coeval change in the fossil assemblage (GÉCZY, 1973, VÖRÖS, 1993) indicate the separation of Tisza from the European Plate in the early Bathonian. Onset of significant rotation — coeval with the paroxism of alkaline rift-type basalt volcanism — of Tisza could be dated as Early Cretaceous (MÁRTON, 2000) suggesting an independently moving Tisza microplate.

In the mid-Cretaceous due to northward motion of the Adria block and related west to east closure of the Neo-Tethys basin and westward motion of Moesia, the extensional regime changed to compressional. This change led to the onset of nappe stacking and low-grade regional metamorphism (ÁRKAI, et al., 2000) within Tisza. In the foreland of the nappes flexural basins came into existence that are characterised by flysch-type sedimentation. In the early Tertiary north-eastward interactive motion of Alcapa and Tisza + Dacia led to formation of the heterogeneous basement of the Pannonian Basin (CSONTOS et al 1992).

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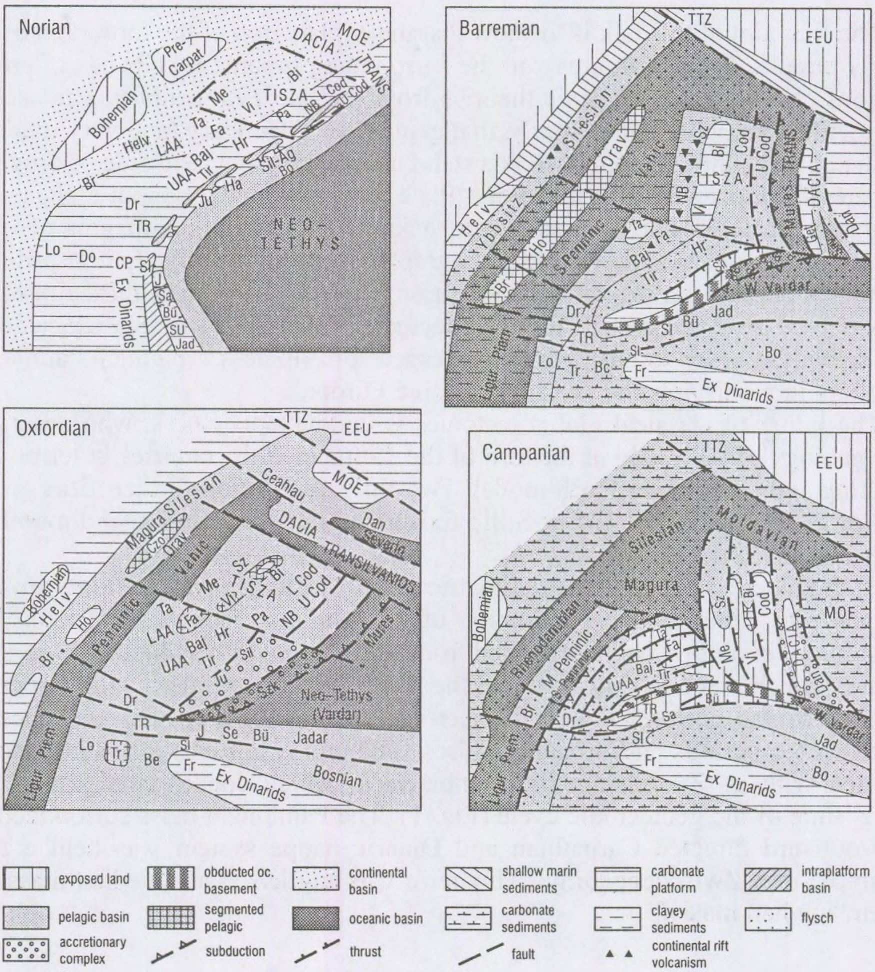

Figure 1. Palinspastic reconstructions showing changes in the setting of the Tisza Megaunit

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The Pannonian "Zwischengebirge": a test-case for classical and modern theories of orogeny

Frank Horváth[1]

(with 2 figures)

The first aim of this talk is to show that the explanation of the formation of the fairly circular Pannonian area and the surrounding mountain belts has offered a serious challenge for orogenic theories from the late 19th century. The second aim will be to argue, quite bitterly, that geologists in Hungary (and very much so in the other countries around) took a stand usually on the wrong side of orogenic debates for more than half a century. Plate tectonics brought about a change of this ugly situation, because results on backarc basin evolution, magma genesis, extrusion tectonics and seismic tomography were among the first significant results of application of a global concept on a regional scale. The third aim of the talk will be an overview of a few vital tectonic problems of the area which are to be solved in order to strengthen the respect of Alpine–Carpathian–Pannonian geology in a unifying and very competitive Europe.

The father of classical global tectonics is undoubtedly Suess, who described the geology of the world at the turn of the 19th and 20th centuries in terms of a cooling and contracting Earth model. Two fully contrasting further ideas grown out of his synthesis: the Kober-Stille fixism and the Wegener-Argand mobilism (SENGÖR, 1982).

Both Kober and Stille believed that terrestrial tectonics was working towards a final aim which was consolidation of the whole surface of the Earth. This continuous evolution was interrupted from time to time by revolution of orogenic phases which went on shortly and at the same time all over the world. Orogenic evolution was performed in a geotectonic cycle with a regular sequence of epeirogenic periods and orogenic pulses. The end result was a bi-symmetrical orogen with a "Zwischengebirge" inbetween, which consolidated during the early time of the geotectonic cycle (Fig. 1). The Pannonian mass surrounded by the outward directed Carpathian and Dinaric nappe system was held a type example of a Zwischengebirge. This term was anglicised as "median mass" or even "median massif".

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Hungarian geologists, strongly influenced by a most talented and fanatic researcher Lóczy, generally supported this fixist view. They believed that the substratum of the Pannonian basin was made up of rigid Variscan crystalline basement, very much like the Bohemian Massif. By the 1950's the median mass concept led to a "medival mess" situation, which was a complete chaos of terminology and violation most of the laws of their regular Nature. A desperate escape from all this mess was the undation theory of Haarmann and van Bemmelen (in the 1930's). This held that upwelling mantle material created "geotumors" and gravity gliding outward this central dome resulted in the orogens around. Szádeczky-Kardoss favoured this geotumor concept for the Pannonian area, before he became a wild plate tectonician.

In contrast to the fixist view, from 1905 to 1932 Wegener developed the theory of drifting continents, which was applied by ARGAND (1924) to describe most succesfully the tectonic evolution of the Alpine belt in Eurasia. Argand suggested that all along this belt, including the Pannonian area, a mega-nappe of African origin overrode the European continental margin and fragments of the intervening Tethyan sea-floor. The Pannonian Basin is the result of post-Oligocene distension of this belt of Africa–Europe collision (Fig. 2). We all know that this masterpiece of early global tectonics was hardly understood by the contemporaneous geological community.

This was probably one of the main reasons that plate tectonics was not invented in the Alps. The other reason was the modest tonnage of the Swiss and Austrian navies, because the theory, like Venus is very beautiful and born out of the sea (TRÜMPY, 2001). It is a pleasure to state that the first remarkable plate tectonic results were presented by a few non-conventional thinkers at Budapest, followed soon by valuable contributions from Slovakian, Romanian and Serbian authors. Conceptually, the most interesting idea was suggested by GÉCZY (1972, 1973), arguing that in addition to an African Unit, (Alcapa Terrane) a European Unit (Tisza Terrane) constituted the intra-Carpathian substrata. It has become widely accepted that the Alcapa terrane has been extruded from the internal Eastern Alps towards the East (RATSBACHER et al., 1991) to occupy a free-space created by roll-back of subducted slab along the Eastern Carpathians (ROYDEN et al., 1982).

The origin of the Tisza Terrane remained, however strongly debated, and an unpleasant space problem was realized, when the kinematic history of the two terranes has been attempted to reconstruct. Another deadly serious question has always been swept below the carpet: the vertical dimension of the two terranes. What are these terranes: lithospheric blocks, crustal flakes, detached nappe piles or their variants as function of space and time.

The concluding message is to remember all of us that answering these questions is very difficult, but beneficial to understand lithospheric dynamics in every orogenic belt.

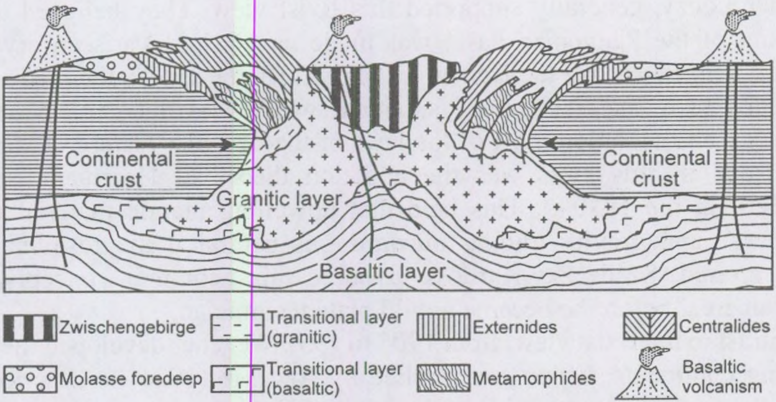

Figure 1a: Cross-section of a bi-symmetrical orogen with Zwischengebirge according to the fixist view (KOBER, 1933)

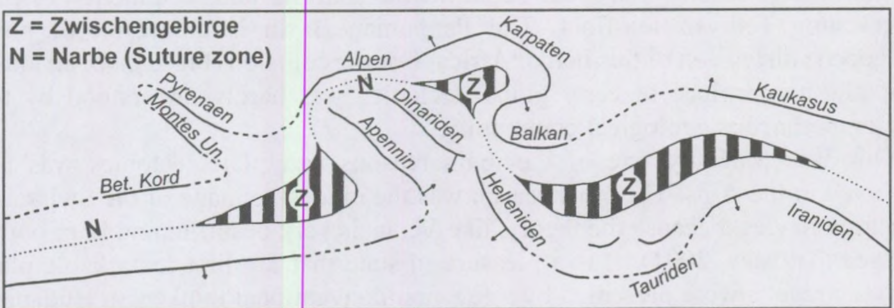

Figure 1b: Schematic map view of the Europen Alpine belt showing the bi-symmetrical polarityof the orogens (KOBER, 1921)

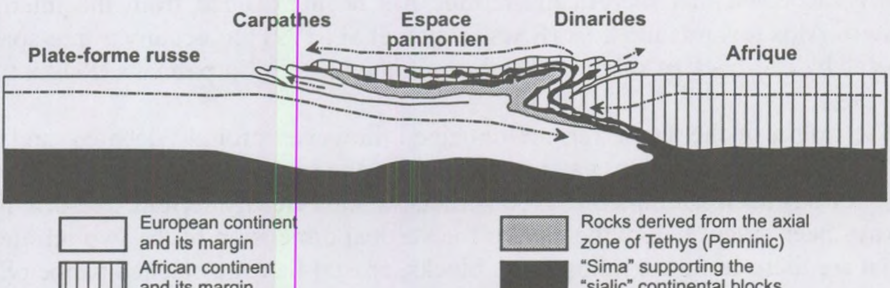

Figure 2: Section across the Central European Alpine belt according to the mobilistic view (ARGAND, 1924). Note that the Dinarids, the substrata of the Pannonian Basin and the Inner Carpathians form a mega-nappe above the Tethyan oceanic suture, and the deformed European continental margin.

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Magnetic fabric and ductile deformation of sandstones of the thrust sheets of the western sector of the Flysch and Klippen Belts of the West Carpathians

Frantisek HROUDA[1,2], Oldrich KREJČÍ[3],
Michal' POTFAJ[4], and Z. STRÁNÍK[3]

The magnetic fabric in sandstones of the thrust sheets of the Western Sector of the Flysch and Klippen Belts of the West Carpathians ranges from essentially sedimentary to mostly deformational in origin. The former magnetic fabrics are characterized by virtual parallelism of the magnetic foliations to the bedding and by close relationship of magnetic lineations to the current directions, if observable. The latter fabrics show significant deflections of the magnetic lineations from the current directions and important deflections of magnetic foliations from the bedding evolving in places into girdle pattern in magnetic foliation poles.

In the thrust sheets at the margins of the Flysch Belt (Outer Krosno-Menilite Flysch in the West and Bílé Karpaty Unit and Oravská Magura Unit in the East), the magnetic fabric is mostly sedimentary in origin, the ductile deformation being very weak, hardly detectable by magnetic anisotropy. During closing the respective basins, these thrust sheets were probably detached from the wedge relatively early and underwent deformations as rigid bodies (translation and perhaps rotation) without being affected by detectable ductile deformation.

In the central thrust sheets of the Inner Magura Flysch, the magnetic fabric is relatively strongly affected by ductile deformation represented by a combination of simple shear (responsible for overthrust movements) and lateral shortening (mostly bedding-parallel), probably associated with creation and motion of the thrust sheets driven by a push from the rear side. The ductile deformation is generally stronger in the frontal areas of the individual thrust sheets than in their central areas.

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In the Klippen Belt, which is characteristic by macroscopic signs of strong deformation, the ductile deformation indicated by magnetic anisotropy is surprisingly weaker than in the central units of the Flysch Belt.

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Accretion of the West Carpathians to Stable Europe as seen from Tertiary palaeomagnetic results

Emő MÁRTON[1], Antoni K. TOKARSKI[2], Igor TÚNYI[3], Péter MÁRTON[4] and Oldřich KREJČÍ[5]

(with 1 figure)

Palaeomagnetic directions available from NE Hungary (E of Danube, N of the Mid-Hungarian Zone) and from the W Carpathians clearly show that their Tertiary large-scale movements must have been linked. During the Palaeogene, the area shifted to the north. Significant counterclockwise rotations started in the Miocene. In NE Hungary, we recognise two palaeomagnetic sub-units, divided by the Hernád Line. The western one rotated twice (18.5–17.5 Ma and 16.0–15.0 Ma, respectively) probably together with the Central Carpathians and the Magura Flysch; during the final stage of rotation the molasse of the foredeep was also involved. East of the Hernád Line we know of a single rotation taking place at about 12.5 Ma which was probably connected to the post-Sarmatian counterclockwise rotations observed in the easternmost part of the Polish segment of the Carpathian Foredeep.

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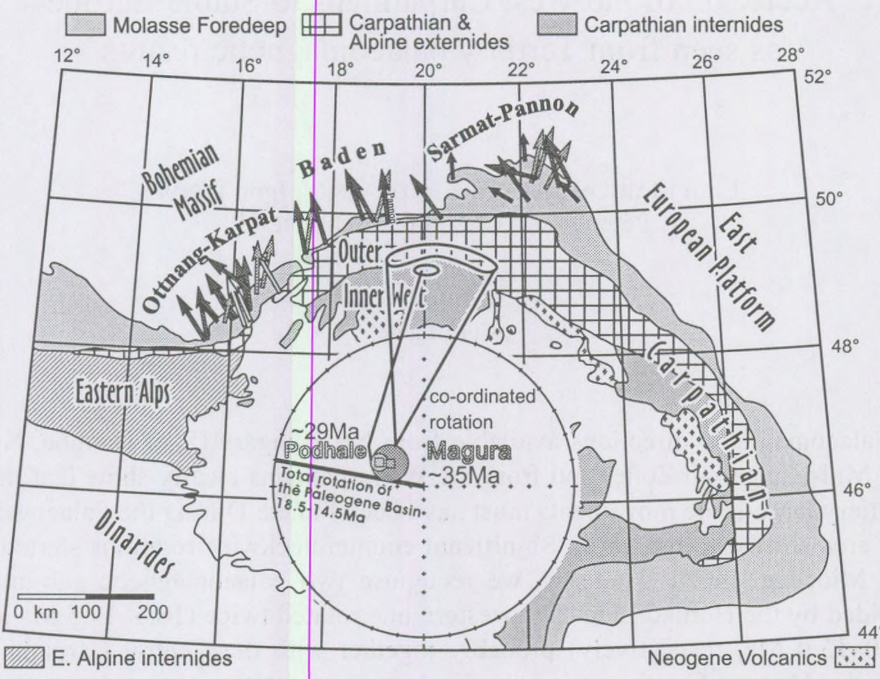

Figure 1. Counterclockwise rotations in the West Carpathians and in more southern units. Legend: arrows show the palaeomagnetic declinations; long arrows: good quality results; short arrows: results of inferior quality; dark grey arrows: CCW rotated declinations with respect to Stable Europe; light grey arrows: declinations indicating no rotation relative to Stable Europe; hollow arrows: results obtained from molasse S. of the proper foredeep

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Palaeomagnetic investigation of the Carpathian – North European platform collision zone

Igor TÚNYI[1] and Emő MÁRTON[2]

(with 1 figure)

According to current models of the Carpatho–Pannonian region the area of the present Inner West Carpathians was a flysch basin (perhaps partly with oceanic lithosphere) in the Palaeogene. The emplacement of the tectonic units is thought to have taken place in the process of an escape from SW to NE. The palaeomagnetic rotations observed in the Inner West Carpathians are dominantly in the CCW sense. Most of the data existing for this area are of Cenozoic age.

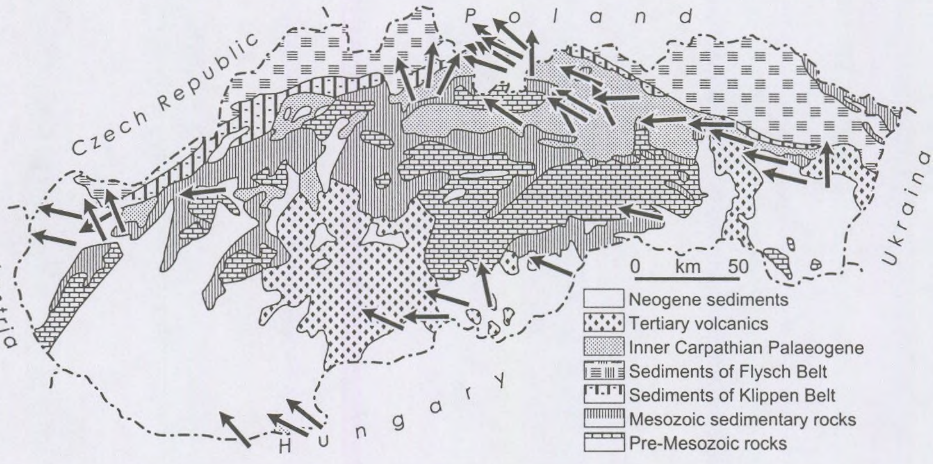

Figure 1 Cenozoic palaeomagnetic rotations in the Inner West Carpathians. (Geological map of the West Carpathians of Slovakia after J. Nemčok).

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The angles of the CCW rotations are variable. There is trend from larger to smaller angle rotation as we proceed from Eocene to Late Miocene age. There is also trend for youngening rotations as we proceed from W to E. The above observations may be explained by a simple model, in which an important role is attributed to the Bohemian Massif. As the Inner Carpathian Mega Block was escaping towards the NE, it met the Bohemian Massif as an obstacle on the left side. The obstacle broke the free movement on the left side while the right side continued to move. The consequence of such mechanism is CCW rotations as they are observed in the Inner West Carpathians.

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Structural evolution of an extrusional wedge: the Oligocene–Neogene central Eastern Alps

Franz NEUBAUER[1], Harry FRITZ[2], Johann GENSER[1], W. KURZ[3], Franz NEMES[1], E. PAUL[2] and Ernst WILLINGSHOFER[3]

Oligocene/Neogene and a few present-day fault systems have been studied within and along margins of the eastwards extruding wedge exposed along the central axis of the Eastern Alps in order to constrain the evolution of such a wedge through time. Extrusion is triggered and influenced by a number of processes including: (1) initial strongly oblique, NE–SW-directed shortening due to indentation along the future Tauern Window cross section; (2) rheological stratification as brittle deformation along steep normal and strike-slip fault deformation is confined to the brittle upper crust separated from middle/lower levels of crust by ductile low-angle normal faults. This led to floating of rigid brittle crust on top of rheologically weak crust, lead to (3) geometrical control of deformation as the extruding wedge is stretching both parallel and perpendicular to the motion direction of the extruding wedge. The resulting fault and palaeostress patterns are complicated, and show large differences between different locations within the extruding wedge. Relative and absolute timing is constrained by the relative chronology at investigated sites, the superposition on ductile fabrics within the Oligocene/Neogene Tauern and Rechnitz metamorphic core complexes and by stratigraphy of intramontane Neogene basins. Reversal of displacement is common along many faults, e. g. along the Salzach–Ennstal fault which changed from sinistral transtensional shear to late-stage dextral displacement.

Together, the fault data and palaeostress data display two major stages of evolution of the extruding wedge: (i) initiation and full development of the extrusional wedge within a overstep jog of a sinstral E-trending wrench corridor D_1 and D_2: see below); and (ii) inversion and late-stage shortening (both N–S and E–W; D_3 and D_4, see below). In western and eastern sectors of the extruding wedge, we observed several sets of palaeostress tensor groups deduced from

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outcrop-scale fault patterns. The orientations of palaeostress tensor groups vary significantly over the area. (1) The dominant pattern records N–S to NNE–SSW contraction in the west (D_1) and ca. N–S to NNW–SSE extension in the east respectively along sinistral transtensional strike-slip faults at the northern margin of the extruding wedge. In the eastern sectors of the extruding wedge, the pattern includes predominant gently S- to SE-dipping oblique normal faults with dip-slip and sinistral oblique slip sense of displacement. (2) These N–S normal faults are often overprinted by E–W (to subordinate ENE–WSW) extension patterns that include ca. N-trending normal faults which seemingly correlate with ductile ESE-shear along the Katschberg normal fault at the eastern margin of the Tauern Window, and top-W shear along upper western margins, respectively E–W stretching within the Rechnitz Window group (D_2). The Styrian Unconformity is considered to have formed within that time interval. (3) Extensional patterns are overprinted by Late to post-Sarmatian N–S to NNE–SSW compression (D_3). The pattern is obviously related to compressional structures, folds and reverse faults, found in Neogene sediments. They include both conjugate sets of steep strike-slip and reverse faults along S- to SSE-dipping faults. (4) These are overprinted by E–W to ENE–WSW strike-slip compression (D_4) which reactivated earlier fault sets, led to surface uplift of blocks like the Koralm and Saualm blocks and formed N–S trending gentle folds within Neogene basins.

The palaeostress tensor groups and succession of deformation events are essentially similar to those found to the north of the Mur–Mürz wrench corridor although some differences exist. Palaeomagnetic data (MÁRTON et al., 2000, Tectonophysics, 323: 163–182) give evidence for both major clockwise and anticlockwise rotations of Neogene basins in these sectors close to the northern margin of the extruding wedge. These in part structurally unresolved rotations may be responsible for differences in details of the structural evolution. Quaternary fault patterns indicate both E–W extension (as, e.g., seemingly evidenced by the N-trending Zollfeld and Krappfeld graben structures and E–W shortening constrained by GPS data.

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New palaeomagnetic results from the Eastern Alpine Neogene basins indicate rotations of micro-plates during the Miocene

Robert SCHOLGER[1], Karl STINGL[1]
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A new, comprehensive palaeomagnetic database from the Eastern Alpine Neogene basins was developed in order to construct a palaeogeographic model of the geodynamic development of the Eastern Alps. Earlier studies gave evidence for palaeomagnetically detectable tectonic movements during the Miocene. For instance, MAURITSCH (1972, 1975) and POHL & SOFFEL (1982) observed large rotations of the Neogene volcanics in the Styrian Basin. Sediments of Ottnangian to Sarmatian age from several intramontane basins of the Eastern Alps yielded a tendency of larger rotations in the older rocks indicating essentially Middle Miocene rotation (MÁRTON et al., 1997). In Slovenia, MÁRTON & JELEN (1997) found moderate rotations that matched those of the Lavant Valley Basin and the Styrian Basin of Austria as well as the Transdanubian Range of Hungary.

The new results from basins located North, East and South of the Eastern Alps show a general trend for counterclockwise rotations of 20 degrees with respect to the present North direction (according to 30° rotation with respect to the stable European continent). The observed rotation values and palaeo-inclinations are in agreement with previous palaeomagnetic results from Karpatian deposits in Teiritzberg (Dec= 340°, Inc= 49°) and Obergänserndorf (Dec= 336°; Inc= 56°) in the Korneuburg Basin (SCHOLGER, 1998). The uppermost Miocene results are in accordance with the Eurasian geodynamic reconstructions. At the same time, rotations in clockwise sense are observed in the Eastern and South-Eastern parts of the study area.

This pattern of rotations cannot be explained only by means of contemporary individual movements of the subbasins. The new results extend the observation of a common behaviour of southern Tethyan elements, which lead to the postulation of a palaeomagnetic superunit characterized by counterclockwise rotations (MÁRTON & MAURITSCH 1990; SCHOLGER & STINGL 2002). Further work is needed to define the exact extend of the young counterclockwise rotations and the dating of the rotational movements with respect to stable Europe.

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Palaeomagnetic data from the Northern Calcareous Alps, Central Alps and Southern Alps: joined post-Oligocene counterclockwise rotation

Wolfgang THÖNY[1,2], Hugo ORTNER[1] and Robert SCHOLGER[2]

In order to reconstruct the rotational history of the Eastern and Southern Alps, a combined palaeomagnetic and structural geological study has been carried out in the frame of an Austrian Research Fund project (FWF P13566–TEC). Part of the new palaeomagnetic results from numerous sites in the Northern Calcareous Alps, Central Alps and Southern Alps that are concerning the post-Oligocene rotational history (28 sites) are presented.

Predominantly magnetite and hematite could be identified as magnetic carrier minerals by using standard mineral-magnetic characterization methods. Tectonic corrections and structural interpretations were based on fold-, contact- and conglomerate-tests. In the Northern Calcareous Alps, the characteristic remanent magnetisation (ChRM) directions of Oligocene Molasse sediments is characterized by a post-folding magnetic overprint with NW directed declinations and steep inclinations of 60°. The ChRM of Upper Cretaceous sediments in the area of Brandenberg at Eiberg and Muttekopf is similar to the direction found in the Oligocene sediments. The ChRM directions of Oligocene basaltic dykes from the Ortler-Campo basement nappe in the Central Alps is typically NW directed with steep inclinations of 55°. We interpret this as a result of tilting of the Ötztal–Stubai basement nappe. Localities in the Dolomites (Eocene dykes near Corvara) and in the Permian Kreuzberg granite body (Ulten Valley south of Merano) again yielded ChRM directions with characteristically NW directed declinations and steep inclinations of approximately 60°.

We suggest, that the Northern Calcareous Alps, Central Alps and Southern Alps were rotated counterclockwise 30°– 40° in post-Oligocene times. This is in line with resultsfrom the Western Alps (HELLER, 1980; THOMAS et al., 1999; COLLOMBET et al., 1999) and the Eastern Alps (MÁRTON et al., 2000; SCHOLGER & STINGL, 2002). The reason for this major counterclockwise block rotation might be the opening of the Tyrrhenian basin west of the Appenine chain (MUTTONI et al., 2000).

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Microstructural investigation of the Telegdi Roth Line (Bakony Mts, W Hungary)

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The Telegdi Roth Line, a major WNW–ESE fault in the Transdanubian Range, West Hungary is analysed. Fault data suggest that the line and its neighbourhood experienced polyphase brittle deformation during Tertiary. The first phase is a major lateral slip along the line. First sinistral, then dextral, or first dextral then sinistral shear was measured. These deformations affected Palaeogene – Early Miocene rocks. The deformation may have started in Late Eocene and ended in Middle Miocene, but the main right lateral shear is suggested to be Late Oligocene – Early Miocene. After that event, first a NW–SE ($\sigma 1$) directed, then a N–S directed stress field was creating strike slip and normal faults. These cut across the main line. The suggested age for these deformations is Middle and Late Miocene.

The main right lateral shear along the Telegdi Roth Line is supposed to be linked with the right lateral motion along the Periadriatic line and its continuation, the Balaton Line. The Telegdi Roth Line and some other major parallel faults are suggested to be Riedel shears to the main Periadriatic–Balaton Line. Later deformation is in good agreement with the results of former studies and was born from the rifting of the Pannonian Basin. Good topographic expression of the main line suggests a Quaternary reactivation as well.

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Brittle structures of the Bakony Hills, western Hungary: constrains from palaeostresss analysis and local structural mapping

Adrienn KISS[1] and László FODOR[2,3]

(with 1 figure)

This study presents palaeostress and kinematic data from the Bakoy Mts in order to better constraint the structural development. The Bakony Mts is part of the Transdanubian Range (TR), interpreted as an uppermost situated Cretaceous thrust (TARI, 1995). Corresponding to this phase, the gently to moderately dipping thrusts, folds and few strike-slip faults were formed by NW–SE to WNW–ESE compression both in the northern and southern Bakony Hills. Faults are pre- or syn-folding structures. They are discordantly covered by Albian sediments in the southern Bakony, so the age of this deformation could be latest Aptian – Early Albian. The small-scale structures can correspond to the main phase of Cretaceous structural evolution of the TR, where the Permo–Mesozoic succession was folded, and detached from its pre-Alpine basement (TARI, 1995).

W(SW)–E(NE) compression can be documented in a number of places in the Bakony Hills and further to the NE (BADA et al., 1996; BIRÓ, 2003). The related faults are mostly WNW trending left-lateral microfaults (parallel strike with the TRL). They affected Triassic, few Liassic, Albian sites and one Senonian occurrence (Ugod, KNAUER et al., 1993) while no faults from Eocene was reported yet in the TR. The age of this phase seems to be post-Albian but post-Senonian (Palaeocene) timing cannot be ruled out (FODOR, 1998).

Some indications for strike-slip type stress field with WNW–ESE compression affected Egerian as youngest formation. The age of the deformation can be Early Miocene also constrained by general model of the rotation and deformation of the Bakony Hills and the Pannonian Basin (MÁRTON & FODOR, 2003). The putatively earlier existing large WNW–ESE trending faults might have operated with normal (normal-dextral) character. A change in the stress field occurred in the Badenian, the new deformation was characterized by NE-SW tension. This phase controlled the formation of Herend and Várpalota Basin (KÓKAY, 1996) border by normal and normal-dextral faults. This (trans)tension can be connected to the initial rift phase of the Pannonian Basin.

An important phase happened in the Middle Miocene. Strike-slip stress field developed with NNW–SSE compression and perpendicular tension. The main structures are WNW–ESE trending dextral faults, which are widespread in the whole TR

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(MÉSZÁROS, 1983). The transpressional reactivation of the main dextral faults was connected to overturned en echelon folds and thrusts in the Csesznek area (N Bakony). Underthrusted Badenian strata indicate main Sarmatian activity (MÉSZÁROS, 1983).

The last detected tectonic phase is marked by E–W to ESE tension measured on Pannonian strata. Major structures are normal faults oriented perpedicular to the tension controlling deposition of the Pannonian sediments at some places. This Late Miocene period is traditionally regarded as a postrift-phase but our data indicate that it is connected with noticeable crustal extension.

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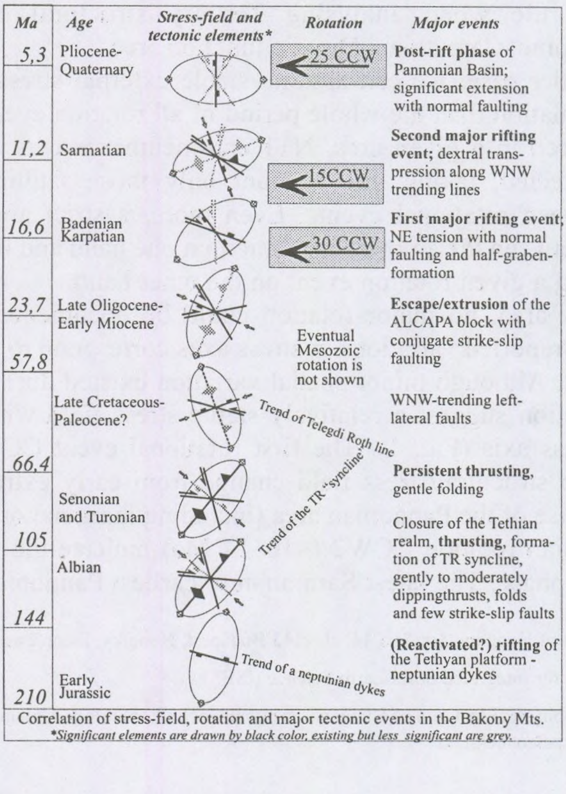

Correlation of stress-field, rotation and major tectonic events in the Bakony Mts.
*Significant elements are drawn by black color, existing but less significant are grey.

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The role of rotation in the Tertiary structural and stress field evolution of the Pannonian–Carpathian–East Alpine–North Dinaridic domain

László FODOR[1,2] and Emő MÁRTON[3]

(with 1 figure)

The northern and western Pannonian area, the Western Carpathians, the easternmost Eastern Alps and the northernmost Dinarides are dominantly marked by counterclokcwise rotation from the Miocene to Quaternary times (Fig. 1.). The amount and timing of rotation events vary within this area. These variations have to be reflected in the coeval evolution of the stress field, because rotation and faulting are connected by a simple but strict rule. In our presentation, we explore this rule when analysing Tertiary structural evolution of the Pannonian–Alpine–Carpathian–Dinaric junction area.

In the simplier case, we can assume stable external stress field and longer faulting deformation than the whole period of all rotation events. If *N* events of rotation occurred in a given area, N+1 end-member events of the stress field should be detected, taking into account only those faulting phases, which occurred between rotational events. Even more, a strict angular equivalence should exist between the amount of rotation on one hand and the stress axes pre- and post-dating a given rotation event on the other hand.

In the study area, no major rotation could be documened before ~18 Ma. Therefore, the reported variations in stress axes correspond to spatial changes of the stress field. Although minor spatial variation existed during later evolution, our reconstruction suggest a relatively stable stress field with ~N–S maximal horizontal stress axis (Fig. 1). The first rotational event CCW1 (~18–17 Ma) corresponds to structural/stress field change from early extrusion tectonics to first rifting phase of the Pannonian area (including marginal orogenic belts). The second, Badenian rotation CCW2 (~16–14 Ma) indicate the shift from first to second rifting phase. The latest Sarmatian to earliest Pannonian rotation CCW3

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(~12–10 Ma) was localised to the northeastern Pannonian–Carpathian domain and could be connected to local stress field changes. All these events can be connected to spatial and temporal variations in subduction geometry along the Carpathian front.

Latest Miocene to Quaternary rotation CCW4 mainly affected the southern part of the study area, including Croatia, Slovenia, the easternmost Alps and western Hungary. The relatively homogenous counterclockwise rotation did not always counter-balance the opposite rotation CW1 of small blocks within shear zones, which occurred earlier or during this event. The regional counterclockwise rotation is connected to strong shortening around the tip of the Adriatic Plate and inversion of the Pannonian Basin. The areal distribution of this young rotation could reflect the intensity and/or the propagation of inversion tectonics into the Pannonian Basin.

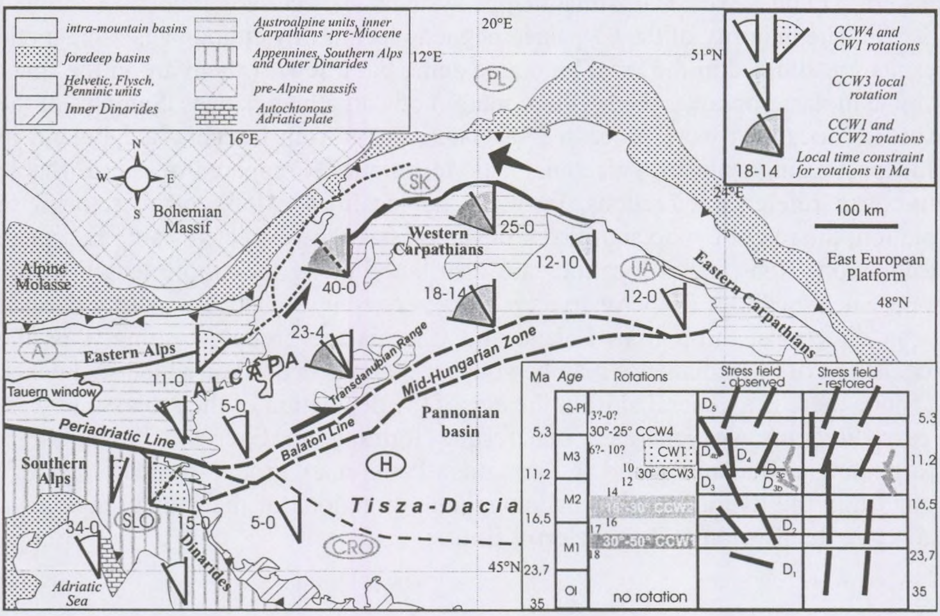

Figure 1. Simplified map of rotation in the NW part of the area. Inset shows timing of rotation (bands with different colours), local event (short band), opposite rotation (dotted band). Maximal horizontal stress axes are shown to see effect of rotation

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Counterclockwise rotated Miocene molasse at the southern margin of Stable Europe indicated by palaeomagnetic data

Emő MÁRTON[1], Robert SCHOLGER[2], Hermann J. MAURITSCH[2], Antoni K. TOKARSKI[3], Wolfgang THÖNY[4] and Oldřich KREJČÍ[5]

(with 1 figure)

We studied Miocene strata from the molasse zone running at the front of the Eastern Alpine – West Carpathian nappe systems, between longitudes 12.1°E and 23.2°E. The majority of the 41 palaeomagnetic localities yielding palaeo-magnetic results are situated in the "real" molasse zone, but a few of them are in the Inner Alpine molasse or cover the northern margin of Carpathian nappes. Samples of the Austrian localities were processed in Gams, those from Czechia and Poland in Budapest, using standard palaeomagnetic techniques. Compared to coeval Stable European reference directions, most of the localities exhibit counterclockwise rotation; the rest show no significant deviation from the expected stable European declination. Non-rotated localities are distributed along the whole length of the zone. Such localities from Austria are characterized by statistically poorly defined mean directions; those from Poland and Czechia are greigite bearing, thus the acquisition of the remanence may be younger than the deposition of the sediments.

Since there is a general shift in the age of the deposition of the molasse in west –east direction we separated our results forming an Egerian–Ottnangian, a Karpatian, a Badenian, and a Sarmatian–Pannonian group, respectively. We found that the overall mean palaeomagnetic directions of the four groups have the same declination within the error limit.

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The “real” molasse zone is subdivided into a folded and an unfolded sub-zone, both underlain by Stable European basement. The sub-zones are not recognised in the palaeomagnetic data and the dominance of the counterclockwise rotations on Stable European basement deserves attention.

There are two theoretical possibilities: either the rotations involved the basement or just the cover was involved in the movement.

For lack of reliable palaeomagnetic data supporting the first model we consider the second as accounting for our observations. We suggest that rotations in the foredeep molasse of the West Carpathians were triggered by rotating West Carpathian units around a pivot point in the Bohemian Massif, while similar rotations in the western molasse zone north of the Eastern Alps were induced by the indenting and rotating Adriatic Plate.

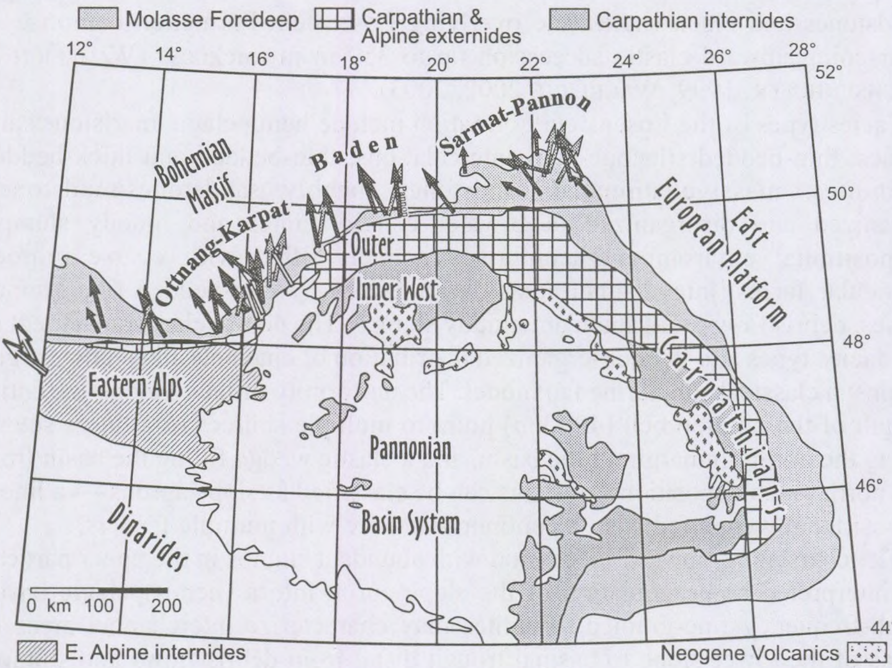

Figure 1. Palaeomagnetic declinations from E. Alpine and W. Carpathian molasse sediments of Miocene age. Legend: arrows show the palaeomagnetic declinations; long arrows: good quality results; short arrows: results of inferior quality; dark grey arrows: CCW rotated declinations with respect to Stable Europe; light grey arrows: declinations indicating no rotation relative to Stable Europe; hollow arrows: results obtained from molasse S. of the proper foredeep

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A mid-Cretaceous piggyback basin filled by a slope apron succession: the Tannheim and Losenstein Formations of the Northern Calcareous Alps (Austria)

Michael WAGREICH[1]

The mid-Cretaceous Tannheim and Losenstein Formations of the northernmost tectonic units of the Northern Calcareous Alps (Allgäu–Ternberg–Frankenfels Nappe System) were deposited within an elongated basin which formed on the early orogenic wedge of the Eastern Alps during Eo-Alpine northwestward thrusting of sedimentary cover nappes. The formations were deposited above a pelagic limestone succession. The Tannheim Formation includes hemipelagic mudstones and black shales; the overlying Losenstein Formation comprises a coarsening upward clastic succession up to 350 m in thickness (WAGREICH & SACHSENHOFER, 1999; WAGREICH, 2002, 2003).

Facies types of the Losenstein Formation include hemipelagic marlstones and shales, thin-bedded siltstone-marl intercalations, thin-bedded and thick-bedded turbidites, massive/laminated sandstones, pebbly sandstones/mudstones, organized and disorganized deep-water conglomerates and muddy slumps. Depositional environments comprise channels filled with coarse grained lenticular facies, interchannel areas characterized by thin-bedded fine grained facies, debris flows, and abundant muddy slumps. The non-cyclic arrangement of the facies types and the non-organized distribution of channels and slumps argue against a classical submarine fan model. The uniformity of facies along the entire length of the outcrop belt (400 km) point to multiple sources or a linear source along the northern margin of the basin, and a clastic wedge filling the basin from the north. Such depositional systems can be classified as slope aprons — a linear depositional wedge fed from a continuous source with multiple feeders.

The coarsening-upward succession with abundant slumps in the upper part can be interpreted as progradation of the slope apron into a (hemi-)pelagic basin. High-frequency fine-grained turbidites may characterize interchannel areas or areas of the lower slope to basinal trough distal from debris flows and slumps. Massive deep-water sands within the coarse succession are regarded also typical for coarse-grained slope-apron systems. These sands occur in small-sized chutes, channels, debris flow tongues and lobe sheets, which may have been fed by fan

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deltas. The elongated geometry of the clastic wedge of the Losenstein Formation and the small lateral extent of conglomerates transversal into the basin are also typical for such a depositional system.

The main controlling factor on deposition and geometry of this slope apron was active margin transpressional tectonism, whereas eustatic sea-level changes had only a minor effect. The basin is interpreted as an early, deep-marine piggyback basin filled by deep sea clastics in front of advancing thrust sheets. The narrow basin extended over a considerable horizontal distance as suggested by similarities in timing of deposition and tectonism and clast composition from the western part of the Northern Calcareous Alps to the Western Carpathians. Piggyback basin formation in the Late Aptian/Albian marks the transition from the passive stage of the Penninic—Austroalpine continental margin to an active, transpressional margin and the beginning of the oblique southward subduction of the Penninic Ocean.

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Metamorphic detritus in the Cretaceous Gosau Group (Eastern Alps)

Ralf SCHUSTER[1], Peter FAUPL[2] and Wolfgang FRANK[2]

The Gosau Group in the Eastern Alps comprises synorogenic Upper Cretaceous to Eocene sediments. They consist of clastic material from surrounding units and a minor amount of exotic input. This study was performed to get information on the metamorphic hinterland and on the first arrival of Eo-Alpine metamorphic detritus within the sedimentary successions. According to WAGREICH & FAUPL (1994) the Gosau Group of the Northern Calcareous Alps is composed of two subunits: The Lower Gosau Subgroup is characterised by alluvial fan deposits passing into a shallow-marine succession with a broad variety of facies. It is ranging from Turonian to Santonian/Campanian, and only in a few places up to the Maastrichtian. The Upper Gosau Subgroup comprises deep-water deposits of Campanian to Eocene age. Within the Gosau Group of the Northern Calcareous Alps coarse-grained clastic sediments, suitable for pebble analyses occur within the conglomerate facies of the alluvial fan deposits and the shallow marine facies of the lower subgroup as well as within mass flow layers of the slope facies from the upper subgroup.

From the Lower Gosau Subgroup polycrystalline quartz pebbles and Permian quartzporphyric volcanic rocks are known as exotic material. They are present in all investigated occurrences (e.g. Gosau, Wörschach, Windischgarsten, Gams, Lilienfeld, Mariazell, Gieshübel, Miesenbach, Pfenningbach and Neue Welt). Associated sandstones are poor in detrital mica. Garnet-bearing amphibolites from the localities Miesenbach and Pfenningbach are the only medium-grade metamorphic rocks, yielding Ar-Ar hornblende ages of 174 ± 5 Ma (RS14/01) and 198 ± 6 Ma (RS16/01). Also in the Upper Gosau Subgroup medium-grade crystalline pebbles are scarce. However, in the Maastrichtian–Danian Brunnbach Formation of the Weyerer Bögen, they occur in several localities. According to Ar-Ar muscovite ages, the pebbles exhibit a Variscan and/or Permotriassic metamorphic imprint (FRANK et al. 1998). Additional measurements prove this data: Ar-Ar muscovite ages yield 260 ± 4 Ma (Fu1), 280 ± 3 Ma (Fu2) and 334 ± 3 Ma (Fu3), the corresponding Rb-Sr biotite ages are 210 ± 2 Ma (Fu1) and

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314 ± 3 Ma (Fu3). In the Maastrichtian and Palaeogene successions sandstones, rich in detrital white mica, occur. Ar-Ar muscovite ages of 122 ± 5 Ma (RS22/01, Neue Welt) and 99 ± 2 Ma (RS5/01, Gams) were determined.

Summarising the data, the southern hinterland of the Gosau Group in the Northern Calcareous Alps was built up by a succession of minor Variscan and/or Permotriassic metamorphic crystalline rocks and mostly by low-grade metamorphic (Palaeozoic) rocks and Permian quartzporphyric volcanic rocks. Eo-Alpine metamorphic rocks were present at the surface since uppermost Cretaceous times.

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Eocene plagioclase-arenites from the Southern Alps: record of a "meso-Alpine" volcanic arc

Alberto GAVAZZI[1], Stefania MILETTA[1], Dario SCIUNNACH[2] and Fabrizio TREMOLADA[1]

In the scenario of the Alpine Orogeny, evidence for arc volcanism is widely held as critical to demonstrate subduction-related continental collision.

Eocene volcanism is documented in the Southern Alps by basaltic flows of Middle Eocene age in Veneto, and by andesitic crystal tuffs, resedimented in Middle to Upper Eocene hemipelagic successions from the Giudicarie area; a roughly coeval magmatic activity is also suggested by largely andesitic dykes and stocks from the Bergamasc Alps. In the Po Plain subsurface, a huge andesitic-dacitic volcanic edifice onlapped by Upper Eocene marls, in turn yielding tuffaceous intercalations of andesitic to dacitic composition, was cored by an ENI/Agip well field (FANTONI et al., 1999). In the Northern Apennines, a later stage of comparable volcanic activity is recorded by plagioclase-arenites intercalated in the Oligocene Ranzano Sandstone. Further to the west, the Lower Oligocene Taveyanne Sandstones were fed by erosion of andesitic volcanoes with high-K calc-alkaline affinity.

Middle Eocene volcaniclastics from central Brianza are here reported for the first time to our knowledge. Such fine-grained plagioclase-arenites were described by KLEBOTH (1982) as interbedded to hemipelagites in "Scaglia" facies (Tabiago Formation), but not genetically interpreted. They essentially consist of fresh, euhedral crystals of twinned plagioclase, with subordinate quartz and volcanic rock fragments; opaques, chlorite+oxides pseudomorphs after mafic minerals, kinked biotite flakes, zircon, apatite and rutile are also widespread. The abundant intrabasinal fraction is dominated by reworked planktonic foraminifera. Composition of detritus rules out provenance from a continental shelf or an accretionary wedge, and is consisted with resedimentation of newly-erupted, intermediate crystal tuffs into a marine environment. Age of the marls is Lutetian (P11: *Morozovella aragonensis* Zone according to KLEBOTH, 1982), as confirmed by the occurrence of the age-diagnostic nannofossils *Nannotetrina fulgens* and *Sphenolithus furcatolithoides* (NP 15 Zone). Due to definitely

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distinct facies with respect to the Cretaceous – Lower Eocene? "Scaglia", this stratal package is best ascribed to the Gallare Marls, an ENI/Agip subsurface unit. The Brianza outcrops, although very limited, represent a fundamental link between the volcanic districts of the Veneto-Giudicarie area and of the Po Plain subsurface, that might help unravelling extent and setting of Palaeogene arc volcanism in the Alpine–Apenninic system.

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Source area heterogeneity of Eocene flysch successions at the Southern Alps – Dinarides junction: new insights from chemistry of heavy minerals

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Upper Cretaceous to Miocene flysch successions extending from the Southern Alps along the outer margin of the External Dinarides occur in small, isolated basins. They become progressively younger towards SE. Flysch formation is related to the large-scale stress field that has affected the whole Adriatic realm since the Late Cretaceous, resulting in foreland evolution and deep marine sedimentation. Diverse palaeocurrent data and palaeogeographic restorations suggest that these basins were fed by siliciclastics from several sources.

The present study focuses on the heavy mineral associations of medium-grained arenites of the flysch so as to interpret their provenance. We have investigated several samples from the Lower Eocene Vipava Basin, the Lower to Middle Eocene Brkini Basin, and from the NW part of the Middle Eocene Triest–Koper Basin. The heavy mineral suites comprise zircon, tourmaline, rutile, garnet, apatite, chloritoid, staurolite, hornblende, blue amphibole, epidote, chlorite, serpentine, as well as Cr-spinel, magnetite, ilmenite. We measured the chemical compositions of garnet, tourmaline, blue amphibole and Cr-spinel by electron microprobe. End-member contents of major garnet populations were determined using single-variate statistics.

Chemical data of garnet cover a wide zone in the Alm–Sps–Gro–Prp compositional space. The grossular content ranges from 5% to 40%. Pyrope percentages vary from 0 % to 45%. The grouping of high-Ca pyralspites reflects a HP source whereas garnet grains of low Ca+Mg content are derived from a Barrow-type metasedimentary source.

Tourmaline displays schorl-dravite intermediate compositions with minor uvite and with Fe/(Fe+Mg) = 0.20–0.80 and Ca/(Ca+Na) < 0.20. Both the alkali-defect and proton-loss substitutions are important. Zoning is common; some grains are continuously zoned, others have detrital cores overgrown by metamorphic rims. Their ultimate sources are Li-poor granitoids. At least two types of Ca-poor metapelites, which differ in the phase relations of their Al-

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saturating silicates, were also eroded. Fe^{3+}-rich metapelites or calc-silicate rocks contributed moderately to the siliciclastic material.

Geochemical parameters of Cr-spinel (Mg#, Cr#, TiO_2, Al_2O_3, FeO/Fe_2O_3) point to both type I and type III peridotitic sources, reflecting lherzolitic and harzburgitic compositions, respectively. To a lesser extent, the exposed ophiolitic complex included also small amounts of basalts of unspecified MOR-BAB character.

The blue amphibole is invariably glaucophane and covers a narrow compositional range with typical values of Mg# = 0.55–0.65 and $Fe^{3+}/(Fe^{3+}+[4]Al+Ti) = 0.05–0.21$. It is geochemically comparable to the detrital grains in the Savoy Molasse, derived from the Briançonnais zone, and to the glaucophane of Upper Triassic blueschists of a Palaeo-Tethyan subduction zone in Nilüfer, NW Turkey. Most importantly, the occurrence of this mineral throughout the section reflects that during the Early–Middle Eocene, LT/HP metamorphic units were continuously exposed rather close to the basin margin. Thus it may play a key role in future geodynamic studies of the Southern Alps – Dinarides realm.

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Sequence stratigraphy from 3-D seismic and outcrops in the Southern Vienna Basin

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This paper presents a new detailed sequence stratigraphy in the southern Vienna Basin based on an integrated stratigraphic approach combining 2-D and 3-D seismic data (OMV), outcrop information along the Leitha Mountains as well as biostratigraphy from correlated well-logs and earlier sequence stratigraphic concepts developed for the central and northern Vienna Basin (WEISSENBÄCK).

Beside the high quality of the data the position of the 3-D seismic block Moosbrunn makes it special. Positioned only a few kilometres west of the Leitha Mountains (during the Miocene a detached island or peninsula) the 3-D seismic block offers a unique opportunity of correlating important seismic key-surfaces from the basin into the near shore settings of the Vienna Basin.

This integrated approach applied to a 3-D seismic block in the southern Vienna Basin results in a well-constrained sedimentation model. The deciphered succession of depositional environments is interpreted in terms of sequence stratigraphy revealing especially the Middle Miocene as complex story.

The oldest Neogene deposits found in the seismic block are interpreted as equivalents of the Upper Karpatian Aderklaa Formation, mostly deposited in half-graben structures. A fluvial depositional environment of a meandering river system was already predicted for that formation by WEISSENBÄCK (1996). These sediments are followed by the coarse clastics of the lowermost Middle Miocene Aderklaa conglomerate representing the LST of the first Badenian cycle, separated by a well-constrained unconformity corresponding roughly to the Burdigalian/Langhian boundary (= Karpatian/Badenian boundary). During the HST of this cycle a carbonate platform was formed. This first Badenian cycle is followed by a mayor regression, which is also described from the Matzen oilfield.

The second Badenian cycle displays a distinct low stand wedge and a well-developed transgressive wedge, which has a striking counterpart in the oil field Matzen in the central Vienna Basin. A HST with prograding sediments forms the top of this cycle.

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The third Badenian cycle is separated from the second cycle by a distinct but mostly concordant unconformity. The associated sea-level drop is clearly related to the Wielician salinity crisis that affected large parts of the Central Paratethys (RÖGL 1998). The re-newed flooding of the third Badenian cycle is biostratigraphically well constrained in the Male Karpaty Mountains to have occurred at with the onset of the nannoplankton zone NN6 (e.g. HUDÁCKOVA et al. 2000). The base of that biozone being defined by the last occurrence of *Sphenolithus heteromorphus* (DEFLANDRE) corresponds to the Langhian/ Serravallian boundary, which was recently calibrated by Foresi et al. (2002) to have occurred at 13.59 Ma.

Thus, for the first time three relative sea level cycles can be documented for the Badenian of the Austrian part of the Vienna Basin.

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The Lombardian Gonfolite Group in central Brianza: calcareous nannofossil biostratigraphy and sedimentary record of neo-Alpine tectonics

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(with 1 figure)

Foredeep basins generally preserve relevant information on the evolution of collisional belts. Turbidite sandstones and marls exposed to the South of the South Alpine foothills in central Brianza, at the triple junction among the provincial boundaries of Como, Lecco and Milano, belong to the Lombardian Gonfolite Group (LGG). Although the LGG has received considerable attention in the last 20 years, published biostratigraphic studies for this district date back to 50 years ago.

A refined biostratigraphic dating of the succession was obtained through the analysis of calcareous nannofossils. Based on the index species *Helicosphaera ampliaperta, Reticulofenestra pseudoumbilica* <7 µm, *R. pseudoumbilica* >7 µm, Sphenolithus belemnos and S. heteromorphus, the NN3 to NN6 nannoplankton zones (Burdigalian to Serravallian) were recognised. This evidence contrasts with less precise assignments to older ages, as reported in the literature (CONSONNI, 1953). Since in the type-areas (Varese, Como) the youngest part of the LGG is Burdigalian in age, the studied succession also documents a more recent part in the history of the South Alpine foredeep, that might have been recorded elsewhere in Lombardy only by the ill-dated Gurone Sandstone and Bizzozzero Mudstone (Varese area). Buckling of the studied succession is consistent with a single tectonic event, reliably constrained as Late Serravallian to Tortonian (late "Lombardic Phase" of SCHUMACHER et al., 1996).

Petrographic analysis on sandstones unravelled stratigraphic trends within the studied succession: a basal petrologic interval, dominated by lithic arkoses plotting not far from the Oligocene – Early Burdigalian LGG sandstones of the type-areas and documenting active uplift of the ensialic crystalline core of the Alpine range, passes through an intermediate petrologic interval, characterised by increasing sedimentary detritus, to a topmost petrologic interval, in which

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sedimentary rock fragments (mostly derived from the Mesozoic carbonate succession of the Southern Alps) take over, concurrent with appearance of detrital chrome spinel.

Such provenance signals point to roughly contemporaneous exhumation of the Penninic nappes and active stacking of thrust sheets in the uprising Southern Alps. This phase of tectonic activity took place at the Langhian/Serravallian boundary (early "Lombardic Phase" of SCHUMACHER et al., 1996).

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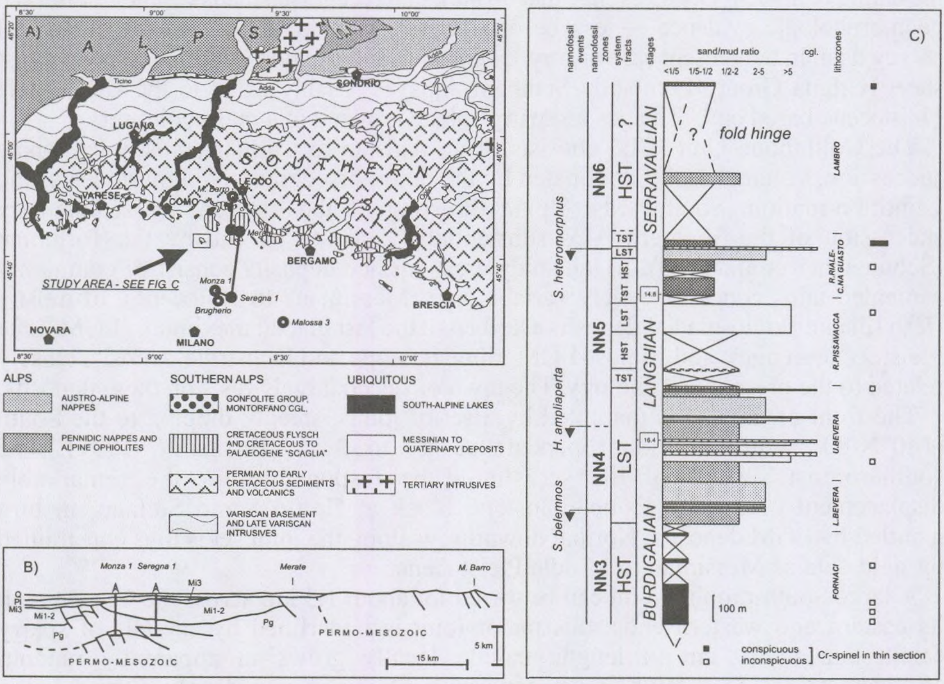

Figure A) Location map of the study area (ENI/Agip wells as circles);
Figure B) simplified seismic section along the composite North-South transect in A) (Pg = Palaeogene; Mi 1-2 = Lower to Middle Miocene; Mi3 = Upper Miocene; Pl = Pliocene; Q = Quaternary);
Figure C) composite stratigraphic log for the Lombardian Gonfolite Group in the study area

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Middle Pleistocene, deep-seated slope deformation at the front of a South Alpine thin-skinned thrust (Coltignone Unit, Lecco, Italy)

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(with 1 figure)

Deep-seated slope deformation (DSSD) of thrust fronts is a long-known process, with several reported examples and some thoughtful attempts at theoretical modelling (CHIGIRA, 1992; DRAMIS & SORRISO-VALVO, 1994). In general, major uncertainties affect the dating of ancient DSSD events, that — although recognised thanks to their preserved geomorphologic evidence — can be only loosely constrained in time by geological survey data. In the present case history, extensional deformation of the Coltignone thrust sheet (Grigna Group, Lombardy Southern Alps) is reliably dated to the late Middle Pleistocene based on U/Th ages on sparry calcite grown into a major joint set.

The Coltignone Unit (CU) consists of an Anisian to Carnian, mostly carbonate succession, volumetrically dominated by the dolomitised, massive limestones of the Esino Formation. Southwards Alpine thrusting of the outcropping sedimentary succession of the Southern Alps substantially came to an end by the Tortonian (Schumacher et al., 1996). In the study area, surface deposits consist of commonly cemented talus cones of widely variable age (Messinian? to Holocene), of mostly fresh till and fluvio-glacial deposits ascribed to the last glacial maximum (LGM, Late Pleistocene in age), and of post-LGM alluvial, slope and lacustrine deposits closely related to the present morphology. The town of Lecco largely rests on these deposits.

The front of the CU is disrupted by a set of joints, steeply dipping to the South (180°N/80), with individual persistence up to 3 m (BATEMAN, 1997). The southernmost surface of the set should be responsible for the remarkable displacement of a huge Esino dolostone block at Crotto Santo Stefano, in turn mantled by LGM deposits. Normal downthrow along the joint set is thus constrained by field data as Messinian to Middle Pleistocene.

A large South-dipping joint can be traced for about 1.5 km across the CU. At both its eastern and western ends, this major joint is underlined by crystals of sparry calcite, up to 20 cm in length; calcite locally grows in apparently random arrangement inside a fault gouge consisting of vuggy and deeply altered Esino dolostones. Seven crystals were dated following the $^{230}Th/^{234}U$ method. Bulk U

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content (ppm) and $^{234}U/^{238}U$, $^{230}Th/^{232}Th$ isotopic ratios were evaluated to test the reliability of results. The estimated ages range from about 300 Ky to 130 Ky B.P.: however, apparently older ages are biased by a low $^{230}Th/^{232}Th$ ratio, whereas the most reliable ages display a narrow 169–131 Ky B.P. age range, falling in the latest Middle Pleistocene (Fig. 1). Calcite ages are assumed to approximate the time-window when joint opening, hydrothermal circulation and local gouging of the joint walls occurred.

We suggest that the extension of the internal sectors of the CU was roughly synchronous with vertical displacement of the Crotto Santo Stefano frontal block, but we can only speculate about the triggering causes for this inferred DSSD event. As the calcite ages coincide with a glacial stage (MIS 6), stress relief under rapid valley erosion should be preferred in this case to drop of contrasting forces due to deglaciation: however, calcite ages coincide remarkably well with strike-slip motion along the Faggio Fault (7 km to the East) and are consistent with differential uplift along the Pioverna river valley (7 km to the NNE), pointing to a peak of neotectonic activity in the Southern Alps of the Lecco area at Middle Pleistocene times. The latest reactivation of the southernmost joint surface occurred in 1969, when a rock fall invaded the northernmost fringe of the town of Lecco and killed 7 people.

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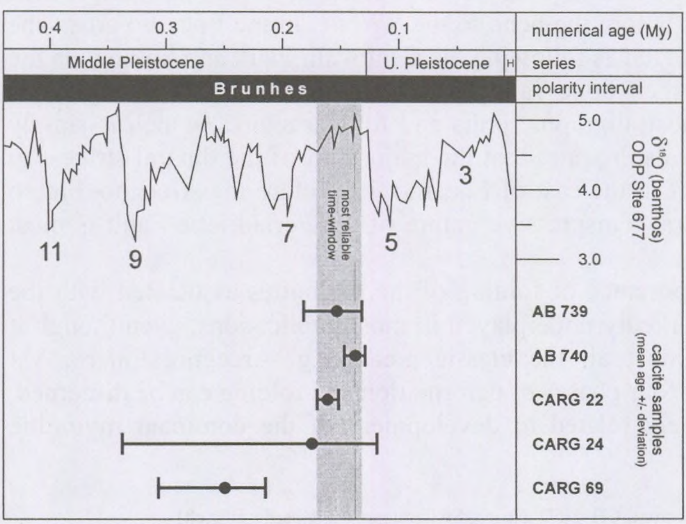

Figure 1. Selected calcite ages for the major joint set dissecting the Coltignone Unit

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The Periadriatic Fault — still a major geotectonic problem!

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In the more than 30 years since Gansser referred to the Periadriatic (or "Insubric") Fault as a "major tectonic problem", there have been many relevant publications and it might be assumed that this important late-Alpine structure is now well-characterized. In fact, this is not the case and some observations remain contradictory and unexplained. These unsolved problems will be highlighted here as an impetus to further work.

(1) *Kinematics.* It is now generally accepted that the Periadriatic Fault is a transpressive-dextral structure, with a relative N-side up component that varies from a maximum of ca. 15 km in the Central Alps to very little to the east and west of the Lepontine metamorphic dome. The amount of dextral offset remains controversial and is not well constrained. Estimates range from < 30 km to 300 km. In the central section between Val Loana/Finero in the west and Bergell in the east, this general assumption is valid, with a stretching lineation that on average plunges moderately to the W or SW. However, in the Val d'Ossola to Fobello section immediately further to the SW, the stretching lineation in the associated mylonites in general pitches moderately to steeply to the NE, with a dextral plus S-side up movement sense.

(2) *Geometry.* If, as has been proposed in some models, movement on the Periadriatic Fault is to be linked to coeval shortening in the Western Alps, then the transfer must occur before the bend to the SW, i.e. in the Locarno area. The transfer is usually envisaged as following the Centovalli Fault and linking via the Simplon Fault Zone to the Rhone Valley. Such a connection would imply major dextral offset of tectonostratigraphic units and fold structures, which is simply not observed. It would also require that the major part of the dextral strike-slip component branches-off to the east of Locarno, i.e. before the Arcegno–Finero section where the dextral-transpressive nature of the Periadriatic Fault is most clearly established.

(3) *Folding.* The importance of folding of the mylonites associated with the Periadriatic Fault is markedly underplayed in most publications, even though it is very obvious in almost all the classic areas (e.g. Arcegno, Finero, Val d'Ossola). At Arcegno, four phases of deformation and folding can be discerned, two of which are closely related to development of the dominant mylonitic

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foliation and two of which overprint this foliation as tight to open folds. The later folds with axes ca. parallel to the stretching lineation consistently give an overall vergence of antiform to the S or SE. Southwest of Arcegno, toward Finero and in the Val Strona/Fobello area, these folds clearly also fold the fabric boundary to the Ivrea Unit. The general presence of low-grade ("Canavese") Mesozoic sediments and upper-crustal granitoids in the southern "Ivrea-derived" mylonites of the Periadriatic Fault also implies a broad antiform in the adjacent Southern Alps south of the Periadriatic Fault.

(4) *Age of Mylonitization.* It is not always possible to clearly distinguish between mylonites developed during Periadriatic Fault movements and older unrelated mylonite zones that have been rotated into parallelism with the Periadriatic Fault in the Southern Steep Belt. As the youngest structure, the Periadriatic Fault truncates older zones and may show effective total offsets accumulated from several possibly distinct tectonic events.

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Active movements along the faults of the Periadriatic Line system in NE Slovenia: First results of GPS measurments

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Periadriatic fault, a major post-collisional structural feature of the Alpine orogen, accommodated many tens of kilometres of dextral displacement in its eastern part along the border between Austria and Slovenia. A previous study of the easternmost outcrop of the Periadriatic Line in NE Slovenia revealed that the line was repeatedly reactivated since Oligocene times with transfer of deformation from the core zone to adjacent dextral faults within the fault system, and inferred that it could still be active today. In its present geometry the Periadriatic fault system comprises of a) parallel to subparallel faults with several tens of kilometres of known displacement (e.g. Sava and Smrekovec faults) and b) later oblique faults with smaller displacements, either branching off the main fault zone (e.g. Šoštanj fault) or dextrally displacing it (e.g. Hochstuhl and Lavanttal faults). Faults of the Periadriatic fault system display very modest seismicity compared to similarly oriented dextral faults in the Slovenian Dinarides to the south. However, most have a striking geomorphological expression suggesting recent activity, and several of the faults are associated with small Pliocene–Quaternary strike-slip basins where severe deformation of Quaternary strata is documented.

In this study we analyse GPS-measured 6 year displacements of 9 sites in NE Slovenia, spanning across the Sava, Šoštanj, Smrekovec and Lavanttal faults of the Periadriatic fault system. The observation network was initiated by the Velenje Coal Mine Company to help assesing surface deformations caused by mining, and was subsequently expanded in cooperation of the Faculty of Civil and Geodetic Engineering, University of Ljubljana and the Surveying and Mapping Authority of the Republic of Slovenia in a programme of monitoring regional-scale geodynamics. GPS campaigns GPS measwere performed in July 1996 and September 2002, each in duration of 48 hours. Besides the 9 observed

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sites 4 permanent GPS stations (Wettzell, Zimmerwald, Graz, Medicina) with known coordinates and velocities in ITRF97 were used for connecting the region of interest to the Eurasian Plate. The coordinates computed in GPS campaigns were then used for velocity components estimation of each site. Displacements relative to fixed Eurasian Plate indicate NE-directed movements with velocities between 0.4–0.7 cm/year, which is in agreement with other known episodic and continuous GPS observations from the region. Inferred displacements across individual faults, while barely measurable and currently within error limits, indicate movements in the range of 0.1–0.2 cm/year with consistent dextral sense of shear, as expected by geological observations and in accordance with the few known focal mechanism determinations on these faults. We expect to better constrain the movements in the future by continuing GPS measurment campaigns and by expanding the observation network with additional 9 sites in Summer 2003.

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Regional and high-resolution seismic reflection investigations in the Krško Basin (SE Slovenia)

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(with 1 figure)

A reflection seismic survey was carried out in the Krško Basin (Slovenia), in the vicinity of the Krško Nuclear Power Plant (NPP), to identify seismogenic sources and capable (neotectonic) faults. The profiles were collected within the project "Geophysical Research in the surroundings of Krško NPP", supported by the European Commission (EC) under the Phare programme to assess the seismic hazard of the area. The Krško NPP is located in a Neogene sedimentary basin filled with up to 2000 m of Neogene and Quaternary sediments. The basin lies within the Sava folds, at the junction of the Pannonian Basin with the Southern Alps and Dinarides. Structurally, it exhibits heterogeneous patterns expressing both "Dinaric" and "Alpine" features. Basement rocks (Mesozoic) were mainly deformed according to typical Dinaric patterns that consist of longitudinal faults and folds in NW–SE direction as well as transversal faults in NE–SW direction. Neogene sediments exhibit Alpine structures, mainly folds and faults that stretch in general E–W direction. During the Alpine folding some pre-existing (Palaeogene) Dinaric structures were reactivated as Alpine ones. Quaternary beds are characterised by E–W oriented compressional structures. The strongest earthquake in recorded history was a magnitude 5.7 event that occurred in 1917 near Brezice. Two different scale surveys were conducted to complete the subsurface geological and geophysical information. Firstly, three near-regional scale profiles (KK–01–99, KK–02–99, KK–03–99) were acquired for imaging the structure down to the pre-Tertiary basement; secondly, four very high-resolution (HR) profiles where recorded to detect and image in detail the near-surface faults. The major depositional sequences and the geological structures were fairly well resolved in the near-regional seismic sections. The line

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KK–01–99, following the longitudinal axis of the basin, exhibits two large sub-basins separated by a saddle, interpreted as the top of a Dinaric thrust. The tomographic inversion, applied to the line KK–02–99, located west of the Krško NPP and parallel to the strike of the Alpine deformations, provided important information about the identified thrust and folds related to the north–south Alpine compression. An Alpine thrust fault displacing the Mesozoic sequences and seemingly reaching the surface, was clearly imaged in the line KK–03–99, crossing the eastern sector of the of the Krško Basin. This fault could be supposedly related to thrust systems identified east from Krsko and should be considered a potential hazard requiring seismological monitoring. In the HR lines, the Holocene filling appears undisturbed, excluding upward continuation of the previously identified deep faults with exception of the one imaged in the line KK–03–99 where near-surface sediments are also deformed.

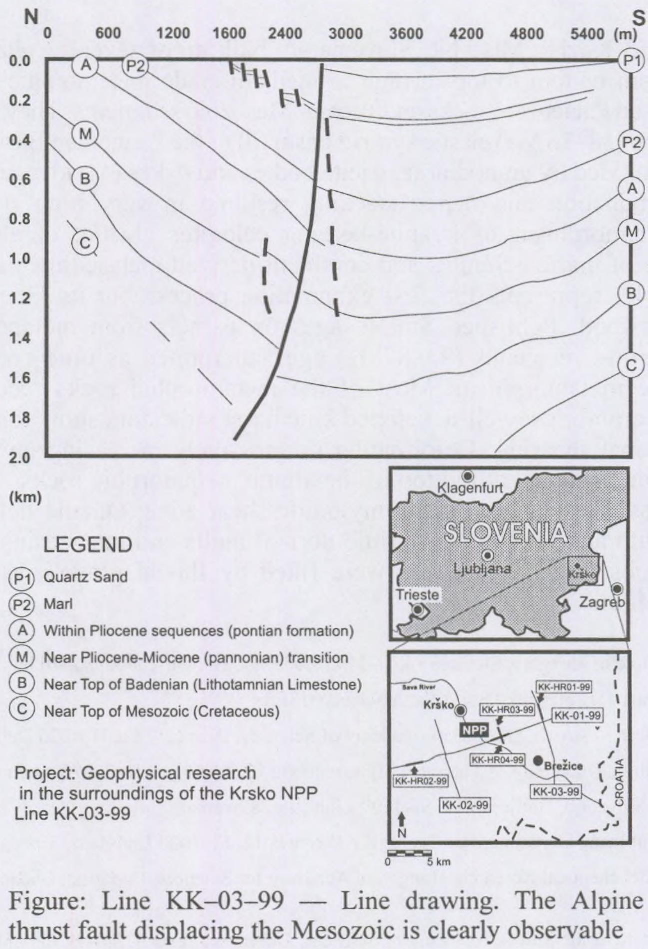

Figure: Line KK–03–99 — Line drawing. The Alpine thrust fault displacing the Mesozoic is clearly observable

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Structural evolution and exhumation of the Pohorje–Kozjak Mts., Slovenia

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(with 1 figure)

The Pohorje–Kozjak Mts., NE Slovenia are built up of several Cretaceous nappes, consisting from bottom to top of high to medium-grade metamorphic rocks, slightly metamorphosed Palaeozoic rocks and Permo–Mesozoic sediments. They are covered by Early Miocene (18–16 Ma) clastic syn-rift basin fill of the Pannonian Basin. Pre-Tertiary rocks were intruded by granodiorite, dacite bodies and dykes (MÁRTON et al., 2002).

Alpine subduction and nappe stacking resulted in very high (to ultra-high?) pressure metamorphism of kyanite-bearing eclogites (JANÁK et al., 2003). The juxtaposition of mafic eclogites and continent-derived metasediments (micaschists, gneiss, marble) represents the first exhumation process but its kinematics is still poorly understood. Published Sm/Nd ages on garnets from metapelites (THÖNY, 2002) give mid-Cretaceous (93–87Ma) ages interpreted as time constraint of the high-pressure metamorphism. Most of the metamorphic rocks record prominent mylonitic microfabrics: well-developed kinematic indicators show top-to-the-NE or -SW extensional shearing. Deformation progressively increasing upward toward a "phyllite" zone, situated at the top of the alpine metamorphic rocks. This thin zone is regarded as a low-angle ductile mylonitic shear zone. Ductile deformation was associated with and followed by brittle normal faults and intervening tilted blocks. The fastly subsiding half grabens were filled by fluvial gravels, sandstones, and marine turbidites.

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Two major cooling events can be distinguished by new thermochronological data (Fig. 1). In the northern Kozjak area muscovite K/Ar ages (102–96 Ma) and zircon fission track ages (27–22 Ma) show fast cooling immediately after mid-Cretaceous metamorphism and some thermal effect at the Oligocene/Miocene boundary. In contrast, in the southern Pohorje area all muscovite and biotite K/Ar ages (19–13 Ma), zircon and apatite fission track ages (19, 10 Ma, respectively) indicate Early to Middle Miocene cooling of both metamorphic and magmatic rocks. The Late Cretaceous ductile exhumation under ductile conditions was responsible for extensional disintegration of the Eastern Alpine nappe pile, including the Bakony nappe as the highest unit. Miocene exhumation is connected to extrusion tectonics, rotation and rifting in the Pannonian Basin including the easternmost Eastern Alps.

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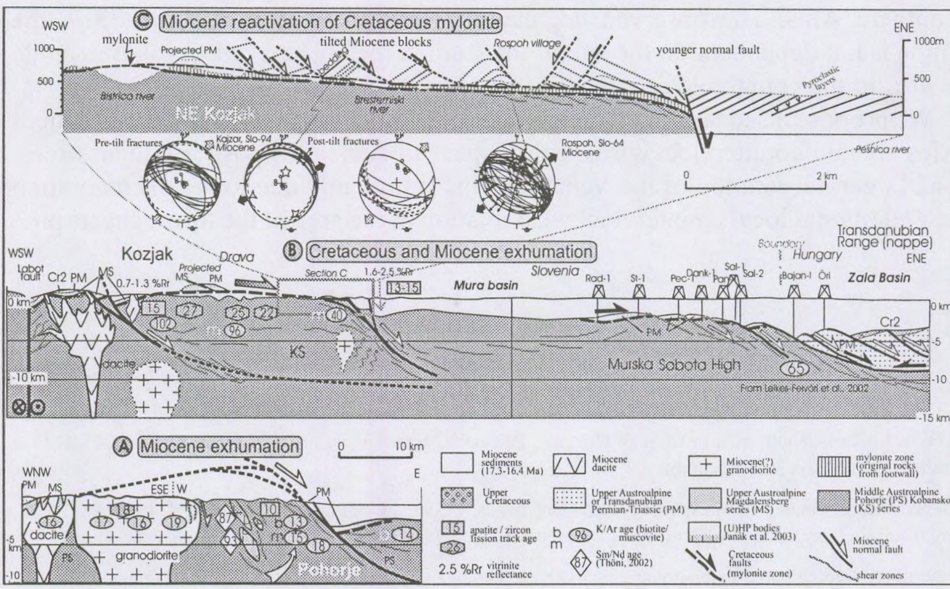

Figure 1. Cross sections across the Pohorje (A) and Kozjak (B) show main structures and projected geochronological data. Note different scale of C. Exhumation is Miocne in Pohorje and complex in Kozjak

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Tertiary rotations of the Venetian Alps and their foreland — tectonic implications of new palaeomagnetic data

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The palaeomagnetic study of 275 independently oriented samples from the Venetian Alps (eastern part of the Southern Alps) and their southern foreland (Colli Euganei) provided direct constraints for the rotation of the Adriatic block in the Tertiary, relative to Africa.

The high-quality palaeomagnetic directions observed on the uppermost Cretaceous – Palaeocene Scaglia sediments, Middle and Upper Eocene marls, and on two Palaeogene dykes from the Colli Euganei imply that the foreland, which represents the "autochthonous" Adriatic block, rotated 25° counterclockwise with respect to Africa in post-Eocene times.

Eocene through Middle Miocene sediments from the Venetian Alps must have acquired their natural remanence during and after the nappe stacking of the Southern Alps. The observed declinations are spread from 258° to 335°, the angle is not dependent on the age of the studied rock. The average rotation angle is 40°, in the counterclockwise sense.

We propose a scenario, in which both the Adriatic microplate and the Southern Alps rotated counterclockwise, with respect to Africa, in post-Langhian times. The larger net rotation of the Venetian Alps is probably due to the disintegration and additional local counterclockwise rotation in the area of the thrust sheets pile.

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Structural and Palaeomagnetic data from the border zone between Alps, Dinarides and Pannonian Basin (Medvednica and Samoborsko Gorje Mts., Croatia): Implications for geodynamic evolution of the area

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(with 1 figure)

In north-western Croatia there are several highly deformed pre-Neogene units of both Alpine and Dinaridic origin. During Neogene–Quaternary times, repeated transtension and transpression resulted in complex displacements of the pre-Neogene units. We carried out structural analysis and palaeomagnetic measurements in Medvednica in order to 1) correlate recently differently oriented pre-Neogene structures in the Dinarides and Medvednica; 2) reconstruct their original orientation 3) understand their meaning for the geodynamic evolution of the area.

As a result of structural analysis, we distinguish at least four deformational events (***D1–D4***) in pre-Ottnangian times. ***D1:*** Late Jurrasic – Early Cretaceous greenschist-facies metamorphism in the Medvednica Mt. It includes synmetamorphic, localy mylonitic foliation and lineation characterized by monoclinic fabric elements that indicate top-NE shearing. By accounting for subsequent rotations documented by palaeomagnetic data, the original shearing direction would be top-NNW, probably related to obduction of an ophiolite nappe over the eastern edge of the Dinaric shelf. ***D2:*** Cretaceous (post-Albian–pre-Senonian) shortening. This event produced syn-metamorphic tight to isoclinal folds in the metamorphic complex of Medvednica, accompanied by SE-dipping S2 axial plane cleavage and NE-trending L2 intersection (foliation/cleavage) lineation. When reconstructed to the original orientation, D2 structures trend NNW, thus indicating deformational event characterized by WSW–ENE-directed shortening. We suppose that during ***D2*** folding the metamorphic complex was structurally in the lower position with respect to the ophiolitic complex. ***D3:*** Palaeocene– Eocene top-WSW thrusting and folding, which produced recently SE-dipping thrusts and NW-verging folds accompanied by SE-dipping cleavage observed both in the low-grade metamorphic complex and in the Late

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Cretaceous – Palaeocene Gosau sediments. At outcrop scale, the mesoscale folds are isolated and cut by reverse faults, frequently developed in sets showing kinematic and structural pattern correlative to brittle-ductile shear zones, unambiguously indicating top-NW tectonic transport direction in the Medvednica and top-WSW shearing direction in Samoborsko Gorje. ***D4:*** Palaeogene–pre-Ottnangian pervasive reactivation of earlier (D3) SE-dipping penetrative surfaces in the Gosau sequences of Medvednica Mt. These surfaces act as oblique right lateral slip planes.

Palaeomagnetic declinations in all Neogene rocks showed ca 30° CCW rotation (Fig. 1). In Ottnangian somewhat greater, in Middle Miocene – Pliocene sediments somewhat smaller rotation was recorded. A similar CCW rotation is recorded in other areas of the Dinarides, as well as in Slavonian Mountains. In Senonian deposits ca 100° CW rotation was measured. All these declinations are interpreted as magnetizations during rock deposition.

Palaeomagnetic results from Miocene–Pliocene sediments in and around the Medvednica suggest a general bulk 30° CCW rotation, which may be related to the rotation of the Adriatic microplate. This also means that prior to Miocene the Dinarides were striking N–S and not NW–SE as now. Declinations measured in Gosau sediments from the Medvednica may be interpreted in terms of large CW rotation of pre-Ottnangian age. This rotation possibly affected the other inselbergs of Northern Croatia, too. Their different structural strike is therefore explained by this major rotation. When reconstructed, the structural transport directions and tectonic order is conformable to those experienced in the main body of the Dinarides. The large rotation is explained by the transpressive right lateral activity of the Periadriatic Line during Late Paleogene –earliest Miocene. We speculate that during pervasive right lateral shear a smaller crustal flake was torn off the Dinarides and was rotated and incorporated into the Zagorje–Transdanubian shear zone.

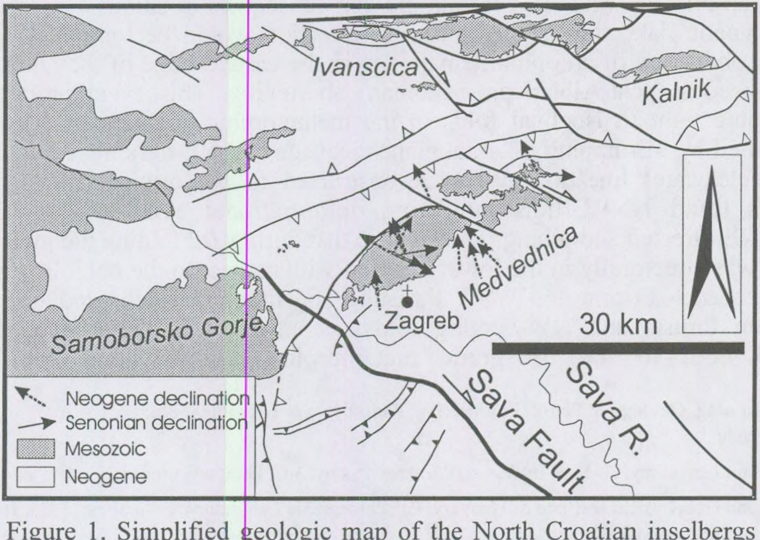

Figure 1. Simplified geologic map of the North Croatian inselbergs with measured Neogene and Senonian palaeomagnetic declinations. Main strike slip and thrust faults affecting Neogene are also indicated

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An APWP (Apparent Polar Wanderpath) for the Alpine-Adria Microplate

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Palaeomagnetic data (FWF P13566-TEC) from stratigraphic sections within the Northern Calcareous Alps (NCA), Southern Alps (SA), and Central Alps (CA) were used to construct an APWP for the area of Eastern and Soutern Alps.

Sites in NCA: Primary magnetisations aquired soon after deposition were recorded in two continuous stratigraphic sections covering the Late Triassic to Neocomian. Sites in Upper Cretaceous to Lower Oligocene sediments also yielded results.

Sites in CA. Oligocene dykes in the Ortler Campo and Ötztal basement units were sampled. Only one dyke carried a interpretable magnetisation.

Sites in SA. Permian magmatic rocks show a primary magnetisation as well as an overprint magnetisation that was interpreted to be of Tertiary age. A stratigraphic section extending from Liassic to Maastrichtian yielded results interpreted to be primary. An Eocene dyke shows results comparable to the results of a dyke in the Ortler Campo basement.

No block rotations of the NCA, CA, and SA relative to each other were observed. Therefore we propose an Alpine-Adria microplate, consisting of todays NCA, CA, and SA moving and rotating partly independently from Europe and Africa. There is no argument for an ocean separating NCA and SA, as propoesed by CHANNELL et al. (1992).

From 200 Ma to 145 Ma the APWP of the Alpine-Adria microplate closely resembles the APWP of Africa (BESSE & COURTILLOT, 2002). Both areas rotate counterclockwise relative to Europe. In the time between 145 Ma to 110 Ma the Alpine-Adria APWP shows a counterclockwise rotation of 50° relative to the African APWP. From 110 Ma to 60 Ma no further rotation relative to Africa can be recognized. Africa and the Alpine-Adria microplate rotate counterclockwise relative to Europe. Between 60 Ma to 20 Ma a clockwise rotation of 65° relative to Africa is shown by our APWP. Finally, after 20 Ma a counterclockwise rotation of 30° relative to Africa of the Alpine-Adria microplate is indicated by our data (see also THÖNY et al. (this volume)).

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The rotational movement of Africa relative to Europe are primarily controlled by the rates of opening of the North- and Central Atlantic. Rotational movements due to opening and closure of small oceanic basins in the area of todays Alps and the Mediterranean are superposed on the African rotation. The major differences of the Alpine Adria APWP to the African APWP are:

— 50° counterclockwise rotation in the Late Jurassic due to opening of the North Penninic Ocean

— 65° clockwise rotation during the closure of this ocean and Alpine continental collision in Paleocene to Early Miocene.

— 30° counterclockwise rotation of the Alpine-Adria microplate relative to Africa as a result of the opening of Tyrrhenian sea west of Appenine chain in the Miocene (see also THÖNY et al. – this volume).

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Late Badenian magnetostratigraphy of the East Slovakian Basin

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(with 1 figure)

The evaporites are considered to be an excellent time correlation marker. This is valid e.g. for Messinian evaporites of the Mediterranean. Likewise, the evaporites of Central Paratethys Middle Miocene have been considered as contermporaneous — Middle Badenian; the name of Middle Badenian substage Wieliczkian comes from a famous salt mine, Wieliczka in the West Carpathian foredeep in Poland. The Badenian Evaporites have a large areal extent: they begin at Opava and Koběrice in Upper Silesia and they continue in the foredeep of the Western, Eastern and Southern Carpathians. Evaporites extend also in the inner side of Carpathians in the Transcarpathian Basin (East Slovakian Basin and its continuation in Ukrainian Zakarpatie – Solotvino) and in the Transylvanian Basin (compare STEININGER et al. in PAPP et al. 1978).

The Badenian evaporites of East Slovakian basin are represented by the Zbudza Formation. The main evaporitic component of the formation is salt (NaCl), salt breccia and by lesser extent gypsum or anhydrite. The thickness of Zbudza Formation is about 100–300 m. This formation was the object of magnetostratigraphic investigation. The magnetic polarity fluctuation within the formation enables to correlate it with the upper part of the reverse chron C5ADr, then with the chrons C5ADn, C5ACr, C5Acn, C5ABr and C5ABn. The chrons mentioned correlate with the lower and middle part of the planktonic zone M7 (lineage zone of Gl. peripheroacuta) with the upper part of nannoplanktonic zone NN5 and lower part of NN6 zone. The age of Zbudza Formation time interval is »14.7–13.3 Ma (Fig. 1).

Thick delta and prodelta formations (ca. 2000 m) covering the Zbudza Formation originated in a relatively short time 13.3–13.0 Ma (0.3 Ma) of uppermost Badenian. This is not surprising because their sedimentation rate after

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decompaction is approximately 850 m/1000y. This value does not overpass the mean sedimentation rates of recent deltas including prodeltas (1500–2000 m/1000 y (Kukal 1964). The magnetostratigraphic study of the Zbudza Formation together with till now neglected biostratigraphic data of GASPARIKOVA (1963; foraminiferal assemblage) and more recent nannoplanktonic data from Badenian evaporites of the Carpathian foredeep (GAŽDICKA 1994, PERYT 1997) suggest a Late (and not Middle) Badenian age of Middle Miocene salinity crisis in the Central Paratethys.

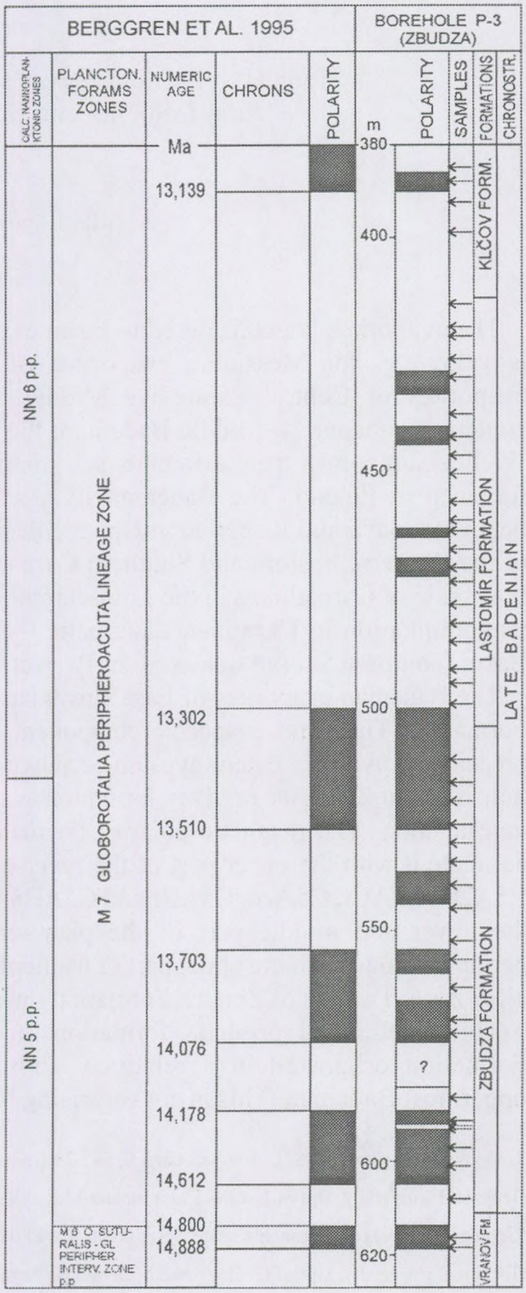

Figure 1. Correlation of magnetic polarity record from the upermost part of Vranov Fm., the whole Zbudza Fm. (evaporites), Lastomír Fm. (prodelta) and lower part of Klčovo Formation (delta fan) of East Slovakian basin with magnetic polarity and biostratigraphic Miocene time — scale of BERGGREN et al. (1995). The Zbudza Formation corresponds to the time interval ~14.7–13.3 Ma and must be considered as Late Badenian – Kosivian (a substage of the Central Paratethys chronostratigraphy)

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The displaced Dinaridic–Alpine transition in the Pannonian basement

János HAAS[1] and Sándor KOVÁCS[1]

Major Tertiary (pre-Middle Miocene) block movements lead to the formation of the postorogenic terrane collage constituting the Pannonian basement. As a result, units of Internal Dinaridic and South Alpine affinity can be found along the NW side of the WSW–ENE striking Mid-Hungarian (or Zagreb–Zemplin) Line, from NW Croatia and SW Hungary to NE Hungary (likely extending also to SE Slovakia). These are included into the term "Zagorje–Bükk–Meliata Zone" (ZBMZ) by PAMIĆ, 2003 and PAMIĆ et al., in press.

Detailed correlational works by Hungarian and Dinaridic geologists (HAAS et al., 2000; PROTIĆ et al., 2000; DIMITRIJEVIĆ et al. and FILIPOVIĆ et al., in press, submitted in 2001; PAMIĆ et al., in press) enabled a comparison and partly identification of these displaced fragments with corresponding Internal Dinaridic and South Alpine units. The preliminary results are summarized in HAAS & KOVÁCS, 2001.

On the SW, in the area of Alpine–Dinaridic–Pannonian triple junction, between the Periadriatic–Balaton and Mid-Hungarian Lineaments, in the Zagorje–Mid-Transdanubian (PAMIĆ & TOMLJENOVIĆ, 1998) or Sava Composite Unit (HAAS et al., 2000), fragments of South Alpine and Internal Dinaridic origin are juxtaposed. The non-metamorphosed nappes of the South Alpine South Karavanken and Julian–Savinja Units are thrust onto the Alpine metamorphosed complexes of the Medvednica and South Zala Units and the ophiolite melange of the Kalnik Unit, which is considered as a displaced prolongation of the Vardar Zone (PAMIĆ & TOMLJENOVIĆ, 1998; PAMIĆ, 2003).

On the NE, the Bükk Composite Unit (Bükk Parautochthon, Szarvaskő and Darnó Complexes), with its south-facing structure and typical Dinaridic development, represents a displaced fragment of the Dinarides. The Bükk Parautochthon shows a very close correlation with the Sana–Una and Jadar Block Terranes of the Dinarides (PROTIĆ et al., 2000; FILIPOVIĆ et al., in press), whereas the Darnó and Szarvaskő Complexes with the Dinaridic Ophiolite Belt (DIMITRIJEVIĆ et al., in press). Within the latter, the Jurassic carbonate turbiditic Mónosbél development can also be correlated with coeval parts of the Bosnian

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Flysch Zone (PAMIĆ, 2003; PAMIĆ et al., in press). These ophiolite complexes do not belong to the Meliaticum tectonostratigraphic unit, which is involved in a north-facing Austroalpine nappe system, thrust onto the Gemerides.

Both the Szendrő and Uppony Carboniferous have some equivalents in the Dinarides (FILIPOVIĆ et al., in press); the former with Austroalpine-type north-facing structure has a typical transitional development, with Devonian correlatable with the Upper Austroalpine Graz Palaeozoic, with Carboniferous flysch, which is a Carnic Alpine–Dinaridic facies (EBNER et al., 1998).

The Aggtelek—Bódva couplet in NE-most Hungary shows south-facing folds and thrusts, but also north-facing back-thusts (LESS, 2000; PÉRÓ et al., in the present volume). They represent a fragment of the North Tethyan margin, representing the shelf margin, slope and pelagic basin settings, or at least the southern margin of a microcontinent, like the Drina–Ivanjica Unit in the Dinarides, facing a southerly lying (according to present coordinates) oceanic domain. The Bódva Unit with its deep water carbonatic–siliceous Triassic has no equivalent in the Eastern Alps, but represents the NW-most occurrence of an Inner Tethyan specific development, which can be traced through the Inner Dinarides and Inner Hellenides (SKOURTSIS-CORONEOU et al., 1995) as far as Oman (BERNOULLI and KRYSTYN, pers. comm.).

Consequently, much of the Dinaridic–Alpine transitional features, both facial and structural, can be traced in NE Hungary, although considerably disturbed by Tertiary movements related to the Darnó Fault system. A 400–500 km dextral offset along the southern border of the Pelso Composite Megaunit is well constrained. As a result of block movements, there is a sinistral offset of similar scale between the Pelso and Tatro–Veporic system, which, however, should have been formed prior to Late Cretaceous nappe stacking (HAAS & KOVÁCS, op. cit.), probably even before the Late Jurassic Neotethyan oceanic closure (FRANK, in the present volume).

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The chert sequence of Uzlomac (Bosnia) Formation: a continental slope formation in front of the Dinaridic Upper Triassic – Jurassic carbonate platform

Nebojsa VASIĆ[1], Jovan OLUJIĆ[2], Lazar VUJNOVIĆ[2], and Stevan KARAMATA[3]

(with 2 figures)

Cherts, including radiolarites, occur in all ophiolitic belts of the Balkan Peninsula. They originated in oceanic realms, at continetal slopes and as members of volcanic-sedimentary formations. The place of origin, the source area of silica and the possibilities of input of material are shown by sedimentological features and geochemistry. The bedded chert sequence exposed at Uzlomac originated at the continental slope of Adria, i.e. on the NE margin of the Dinaridic marginal sea. The Dinaridic marginal sea existed from the Middle Triassic to the Late Jurassic and in this area its coast was a wide carbonate platform which prevented the transport of terrigenous material into the basin. It represents, for that reason, a very clean siliceous deposit mostly of biogenic provenience, but with radiolarians significantly resorbed and dissolved. The sedimentation of homogenous chert sequences was interrupted only when shocks of coarse carbonate material or of terrigenous material occured.

The chert sequence is composed of bedded cherts and radiolarites with rare interlayers of carbonate material in deep levels. Its age is Late Triassic (conodonts, at Nemila) to Middle – Late Jurassic (radiolarians, at Uzlomac).

In all analysed samples the variation of contents of all elements is small, and does not depend on the position in the geological column. Si is the main constituent and, because of always present clayish or limy admixture, Fe, K, Na, Mg, Mn, P, and S, followed by other minor compounds, are always present.

The following groups exist among the trace elements: (a) elements associted with clay minerals, the content of which increases with the content of Al are Ti, Sc, Y, Zr, V and Cr; (b) elements associted with carbonates and correlable with Ca are Sr and Ba, (c) Ni, Co, Cu, Zn and Pb, as elements with high affinity to sulphur have similar beheavior, (d) elements of extremely resistant minerals, transported as very fine grains, are Nb, as well as Y and Cr if the contents are higher.

Such a composition can be considered as characteristic for marine chert without continental or volcanic influence.

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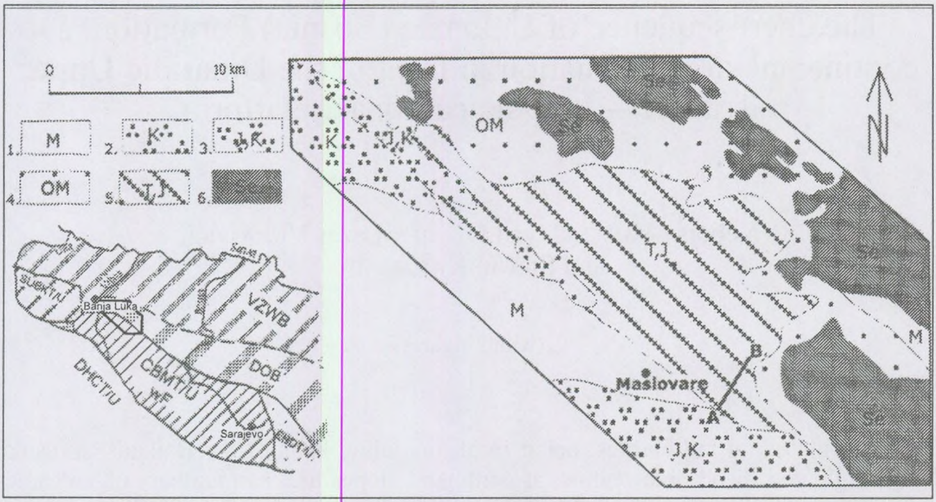

Figure 1. Geologic sketch of the area of Maslovare–Uzlomac, southeast of Banja Luka (Bosnia). At the left: geologic position of the area (after KARAMATA & KRSTIĆ, 1996, slightly sodified).

Legend: 1. Miocene lacustrine sediments; 2. Cretaceous flysch; 3. Jurassic–Cretaceous flysch; 4. Jurassic olistostrome Melange; 5. Upper Triassic to Jurassic cherts; 6. Ultramafics. A–B: the line along wich the sampling was performed. Abbr.: VZWB — Vardar Zone western belt; SUBKT/U — Sana–Una–Banija–Kordun Unit, until the aiddle of Cretaceous terrane; DOB — Dinaridic ophiolithe belt; EBDT/U — East Bosnian–Durnitor terrane, since Upper Jurassic unit; CBMT/U wF — Central Bosnian Mts. terrane, from Permian unit, with Mesozoic flysches at northeast; DHCT/U Dalmatian–Herzegovinian coffiposite terrane until addition to Adria, with post-Carboniferous cover

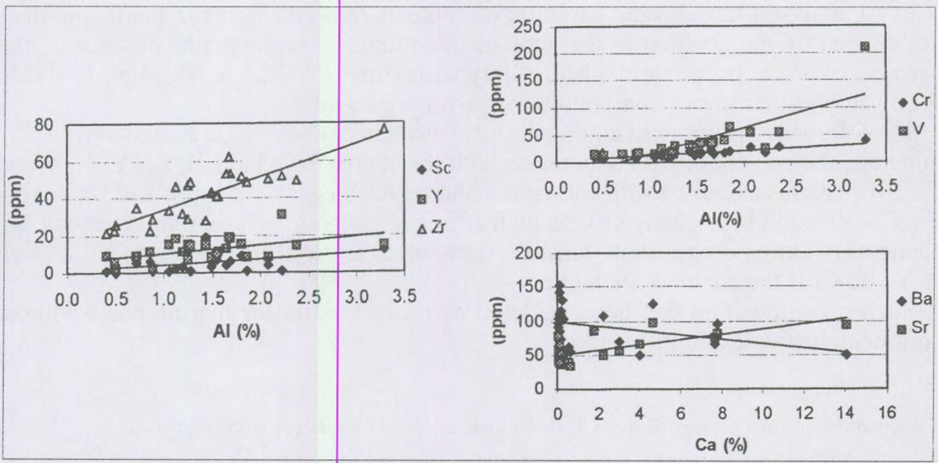

Figure 2. Al vs. Sc, Y, Zr, Cr, and V, i.e. elements associated to clayish minerals, and Ca vs. Sr and Ba in cherts from Uzlomac

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The geothermobarometry of Alpine amphibolites from the metamorphic sole of the Krivaja–Konjuh ultramafic massif (Dinaride Ophiolite Zone, Bosnia)

Dražen BALEN[1], Mevlida OPERTA[2] and Jakob PAMIĆ[3]

The metamorphic sole of Dinaridic ophiolites is frequently built up from compositionally different groups of amphibolites originated from ultramafic and mafic cumulates. In metamorphic sole of Jurassic Krivaja–Konjuh ultramafic massif (Dinaride Ophiolite Zone), several types of amphibolites commonly show granoblastic, porphyroblastic and nematoblastic textures of various grain size. Structure is mainly shown in foliation rarely in layering. Age of amphibolites is spanned between 174±14 and 157±4 Ma.

The varieties of these amphibolites are: (1) *amphibolite* with amphibole (Si 6.48–7.09, Mg 3.04–3.54, Fe2+ 0.29–1.31 p.f.u.) and plagioclase (21–47% An); (2) *garnet-amphibolite* and *clinopyroxene-garnet amphibolite* comprises garnet with composition X_{Alm}=0.384, X_{Sps}=0.020, X_{Prp}=0.370, X_{Grs}=0.224, amphibole (Si 5.90–6.36, Mg 2.75–3.28, Fe^{2+} 0.23–0.26 p.f.u.) and plagioclase (55–91% An). Some samples show kelyphite texture and some include clinopyroxene (diopside, Fs=0.108, En=0.409, Wo=0.484); (3) peculiar *corundum-bearing edenite–pargasite amphibolite* positioned in the most internal parts of the complex comprises amphibole (Si 6.34, Mg 3.42, Fe^{2+} 0.55 p.f.u.) enriched in edenite and pargasite components and anorthite-rich plagioclase (up to 91% An). The assemblage also includes xenomorphic corundum in the matrix and large centimetre sized corundum porphyroblasts with amphibole and plagioclase inclusions.

Thermobarometric calculations are performed using assemblages Grt+Hbl+Pl, Grt+Cpx and Hbl+Pl with reaction edenite + albite = richterite + anorthite in quartz-free rocks and also using Al and Si isopleths in Hbl.

In the *amphibolites* (1) calculated T values for rims are 670–730 °C for the edenite-richterite reaction. The *garnet-bearing amphibolites* (2) yielded 745–800 °C and 9.5–11.8 kbar for samples with kelyphite texture and 630 °C and 6.7–7.3 kbar for kelyphite-free samples while *clinopyroxene-garnet amphibolite* yielded 830 °C. Geothermobarometric estimations on the *corundum-bearing*

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amphibolites (3) yielded limiting P–T conditions of 620–830 °C and 6–10 kbar for amphibole and plagioclase inclusions with presumed equilibrium inside corundum porphyroblast and 4.5–8 kbar for the main metamorphic assemblage.

These estimates are thought to reflect the metamorphic conditions achieved during the Late Jurassic obduction of the hot upper mantle part of Krivaja–Konjuh ultramafic massif onto ophiolite mélange. The hot obducted ultramafic fragments acted as a heat source for metamorphism that transformed cumulate gabbro protolith into high-grade amphibolites.

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Exotic granites in the Cretaceous Pogari Formation overstepping the Dinaric Ophiolite Zone mélange in Bosnia

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New petrographic, geochemical and $^{40}Ar/^{39}Ar$ biotite and zircon fission track ages are presented here from the Pogari Formation of Bosnia which oversteps the Dinaric Ophiolite Zone mélange in central Bosnia. According to the existing models, ophiolitic rocks of the Dinaric Ophiolite Zone (DOZ) were generated during the Late Triassic(?) and Jurassic in MORB environments. During Tithonian/Berriasian times, they were emplaced and partly uplifted above the sea level due to obduction. The ophiolite mélange of DOZ, including large masses of peridotite tectonites, are disconformably overlain by Cretaceous overstep sequences, mainly constituting the Pogari Formation, which includes in the Zavidovići–Maglaj area redeposited exotic reddish granites which are not known from bedrock exposure in adjacent continental units. The stratigraphy of the overstepping Cretaceous sequence is supported by fossils documenting the continuous span from Tithonian/Berriasian to Maastrichtian. The ca. 1000 m thick Pogari Formation represents a clastic sequence which is mainly composed of unsorted and poorly sorted conglomerates grading into breccias which are interlayered with rare lithic sandstones and scarce marly shales. The clastic sediments laterally grade into massive fossiliferous Tithonian–Berriasian limestones. Middle portions of the sequence are composed of fossiliferous sandstones and marly shales which are conformably overlain by fossil-rich Cenomanian–Senonian limestones with marly shale interlayers. Sandstones are typical for orogenic sources including much framework constituents derived from metamorphic rocks. The conglomerates and breccias are the most common and characteristic rocks of the Pogari Formation. They are composed of serpentinite, gabbro, diabase, metabasalt, amphibolite, chert, shale, meta-sandstone and graywacke, i.e., the same rocks which are included as fragments in adjacent ophiolite mélange. The second group is represented by varieties of carbonate platform limestones with subordinate dolomites and subordinate recrystallized limestones to marbles and rarely pelagic limestones. Coarse-

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grained reddish granites make 20–50% of the detritus and thus, individually, represent the most common fragment in conglomerates. In lower parts of the section the reddish granites are particularly abundant and are cut in poorly sorted medium-grained conglomerates as huge weakly rounded blocks, up to 2 m in diameter, reminding to a “wildflysch”.

The clasts of exotic Maglaj granite are reddish rocks due to the red color of feldspars, mainly medium-grained (2–5 mm), massive in structure and extremely leucocratic. Major minerals are quartz, orthoclase, microperthite, albite, oligoclase (averaging An_{9-16}), dominant biotite and very rare muscovite; accessories are apatite, zircon, magnetite, ilmenite and hematite; secondary minerals are sericite, calcite, chlorite and limonite. Chemical compositions show that most of them are peralkaline and according some classifications they are rhyolitic. Based on the CaO versus FeO_{tot} analyzed granitoid rocks belong to I–type family. Rare earth elements show a relatively small enrichment of light rare earth elements and a pronounced negative Eu anomaly. Trace elements argue for highly evolved and fractionated granite magma suite. $^{40}Ar/^{39}Ar$ biotite ages from six samples range from 251 ± 2 to 256± 3 Ma, with an exception at 260 ± 2 Ma. These ages are interpreted to record cooling through ca. 300 °C in the continental source region. Three of $^{40}Ar/^{39}Ar$ biotite patterns display a small component of Ar loss due to possible thermal event younger than 235 Ma, indicating a possible low-grade thermal overprint.

Ca. 60 zircon grains from sandstones were dated by the fission track method. The majority of them was euhedral (37), ten grains were rounded and the rest subhedral or broken fragment. Their age distribution does not show any systematics. The isolation of the components was done by two basically different methods which gave similar results, a group of 160 ± 20 Ma, a minor group of 207 ± 5 Ma and 275 ± 37 Ma. The oldest group is similar to $^{40}Ar/^{39}Ar$ biotite ages of red granites. The second, Late Triassic group could represent a cooling event after Triassic rifting. The third group (160 ± 20 Ma) is clearly related to Jurassic obduction of the Dinaric Ophiolite Zone.

We suggest that the reddish granites derived from Late Variscan, post-collisional granite suite which may herald the transition to ongoing rifting. Consequently, the exotic red granite clasts are likely derived from a continental piece which underwent post-Variscan, mildly alkaline magmatism. Subsequent events, like Late Triassic and Late Jurassic cooling stages of the continental rocks, are recorded by low-temperature thermochronology.

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Late Cretaceous/Tertiary East Serbian mantle dynamics inferred from study of mantle xenoliths

Vladica CVETKOVIĆ[1], Hilary DOWNES[2], Dejan PRELEVIĆ[1] and Milivoje JOVANOVIĆ[3]

East Serbian Palaeogene mafic alkaline rocks contain various mantle xenoliths and xenocryst. Similar mantle xenolith-bearing alkaline rocks occur in Poiana Rusca (Romania). On the basis of their texture, modal composition and major element mineral chemistry and LA-ICP-MS trace element data on clinopyroxenes following groups of mantle xenoliths have been distinguished: dunite/harzburgite/lherzolite (D/HZ/L), clinopyroxene-rich lherzolite (Cpx-L), spinel-rich and spinel-poor olivine websterite (OWB_1 and OWB_2, respectively) and clinopyroxene megacrysts (Cpx-M). In addition, in D/HZ/L xenoliths frequent metasomatic pockets and veins mainly composed of clinopyroxene are observed. D/HZ/L mantle xenoliths represent the main lithosphere beneath East Serbia whereas all other types are subordinate mantle lithologies.

East Serbian subcontinental mantle is mainly harzburgitic recording previous processes of extraction of basaltic melts. A rather high degree of depletion, inferred from modal mineral composition and chemistry of present silicates, is not apparent from trace element contents in clinopyroxenes. Calculated temperatures (987–1190 °C) and pressure estimates (<2 GPa) suggest a high heat flow, likely related to Palaeogene alkaline magmatism. The highest temperature estimates approach the geotherms of the Styrian Basin and Persani Mts.

Formation of clinopyroxene-rich domains in the lithosphere occurred in response to infiltration of alkali melts, genetically and compositionally related to the host basanite magma. The same appears to be valid for numerous pockets and veins found in the D/HZ/L xenoliths. The differences in lithology of these xenoliths may be related to a possibility that pockets and veins are products of reactions in their incipient stages, Cpx-L and OWB_1 are much better equilibrated, whereas cpx±olivine megacrysts may represent fragments of deep-seated high-pressure cumulates of alkali mafic magma.

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The generation of OWB_2 xenoliths is probably related to the Cretaceous subduction processes and magmatism. Being much closer to the subduction trench these melts could not have reached surface but resided in the uppermost mantle or in the lowermost crust as precipitates of mafic/ultramafic arc-related magmas.

The study of East Serbian mantle xenoliths have provided better understanding of the upper mantle dynamics at the Cretaceous/Tertiary boundary. This part of East Serbia represented a fore-arc/arc region during Late Cretaceous and the mantle beneath was a supra-subduction zone even earlier. At the beginning of Tertiary cryptic and modal metasomatic processes occurred as precursors of mafic alkaline magmatism. These events marked the termination of collisional and onset of post-collisional tectonic regime which continued further on producing extensive Oligocene/Lower Miocene magmatism which was mainly confined to the area along the Vardar Zone.

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Geodynamic significance of the Tertiary ultrapotassic province from Serbia

Dejan PRELEVIĆ[1] and Vladica CVETKOVIĆ[1]

Serbian ultrapotassic rocks comprise lamproite affinity group (LAG) and kamafugitic affinity group (KAG), with LAG-rocks subclassified to primitive (P-LAG) and evolved E-LAG) subgroups.

The P-LAG samples are slightly silica undersaturated to saturated with Cr and Ni up to 800 and 500 ppm, respectively. The E-LAG rocks have SiO_2 up to 63 wt% and Cr and Ni contents 100 and 20 ppm, respectively. The former have elevated LILE (Cs, Rb, Ba, Th and U) and are depleted in HFSE. Their LILE/HFSE ratios resemble other Mediterranean-type lamproites. The lamproite of Bogovina (Carpatho–Balkanides) is slightly different from other LAG rocks from the Vardar Zone in having much less marked Ti-Nb and Ba troughs, lacking a Eu anomaly and displaying considerable depletion in HREE, with Lu_N below 10× chondrite. The E-LAG rocks show a large range of REE enrichment and are fractionated to different extents. They also show differences in the intensity of Eu anomaly. The LAG rocks vary widely with respect to $^{87}Sr/^{86}Sri$ vs $^{143}Nd/^{144}Ndi$ values, in the range 0.70735–0.71299 and 0.512515–0.512162, respectively. Pb isotopes of all the LAG rocks display no apparent variation in $^{206}Pb/^{204}Pb$ but with some variations in $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$. The LAG rocks plot above the depleted mantle line on $^{206}/^{204}Pb$ vs $^{207/204}Pb$ and $^{208/204}Pb$ diagrams and fall within the pelagic sediment field. They show Pb isotope values in agreement with EM II reservoir, while Sr and Nd isotopic ratios are not so extremely radiogenic and nonradiogenic, respectively.

Ugandites and leucite-basanites of the KAG are mostly ultrabasic and silica undersaturated with elevated CaO contents but never exceeding 11%. The KAG rocks display less pronounced LILE enrichment and LILE/HFSE fractionation compared to the LAG. This kind of incompatible elements distribution is similar to the Italian kamafugitic occurrences. The LREE concentrations are up to 500× chondrite. The spiderdiagram patterns are steep, without or with only a slight Eu anomaly and with low HREE, but mostly above 10× chondrite. The $^{87}Sr/^{86}Sr_i$ and $^{143}Nd/^{144}Nd_i$ range 0.70599–0.70655 and 0.51260–0.51258, respectively, whereas the Pb isotope compositions of the KAG rocks are very similar to Pb systematic

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of the LAG rocks. They reflect primary composition unaffected by low-pressure processes.

It is to be concluded that lithospheric mantle completely controls the Serbian ultrapotassic volcanism. The central Serbian lithospheric block, i.e. the Vardar Zone, has been the most productive source of ultrapotassic melts derived from a veined mantle source with metasomatic veins made up of a non-peridotitic assemblage comprising phlogopite and apatite. It is a unique example that all mineralogical and geochemical parameters, including the level of fertility of Cr-spinel and trace element and Sr-Nd-Pb isotopic systematics, offer sound evidence for the vein+wall-rock melts interaction. The easternmost block (Carpatho–Balkanides) is intruded by the geochemically different volcanics, also probably derived from the veined mantle, but with more complex isotopic history and/or different vein-mineralogy. Eventually, the volcanoes from westernmost block (Dinaric block=Apulia) may be regarded as counterparts of Italian low-silica "leucite-bearing" rocks, suggesting common pre-eruptive metasomatic and geodynamic history. Metasomatic assemblage is here homogeneously disseminated and represented with phlogopite, TiO_2-oxides and apatite.

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Deformation sequence in the Vardar Zone: surroundings of Jadar block; Serbia

Natasa GERZINA[1] and László CSONTOS[2]

(with 1 figure)

Field investigations in Central Serbia indicate a very complex defromation sequence implying the Drina–Ivanjica element, the Ophiolite belt, the Vardar Zone and the Jadar block of the Internal Dinarides. Obducted mélange and ophiolites occupie an original nappe position above both Drina–Ivanjica and Jadar. While the former is greenschist metamorphosed, the latter is only anchimetamorphic. The whole tectonic sandwich is covered by Late Cretaceous post-tectonic sediments, mostly turbidites. These might enlose ophiolite debris from exposed mélange and limestone breccias from adjacent platforms. The whole assemblage is then folded into often isoclinal folds, with steep limbs. At least two folding phases-directions can be separated; one seems to relate to E–W right lateral wrenching. The Late Senonian – Palaeocene sequence is thrust by the Jadar block. Thrusts are apparently flat and southwards directed. This thrusting might be related to one phase of folding.

Measured faults are dominated by both right and left lateral strike slip faulting. Sometimes evident thrust faults were very difficult or impossible to measure. Faults can be arranged into 4 subsets. The oldest phase (based on superposition criteria) is dominated by ENE–WSW right lateral faults and is assigned to Palaeogene, since it was not found in Early Miocene rocks. This is the result of NW–SE oriented compression. The second and third fault sets are dominated by NE–SW and N–S right lateral faults and are the respective results of WNW–ESE and NNE–SSW directed compression. The last field, where E–W left lateral and NE–SW normal faults dominate was generated by NE–SW compression. The last 3 phases affect Miocene rocks; the last stress field might have created a Middle to Late Miocene strike slip basin near Valjevo.

The Jadar block, very similar to Ivanscica and Medvednica in Croatia, Sana-Una in Bosnia and Bükk Mts in Hungary has an “exotic” position. It has a Dinaric margin, lower plate origin and a present day highest tectonic position above the same margin. The Drina–Ivanjica element, also of lower plate Dinaric margin origin is higher grade metamorphosed as Jadar, so a simple out of sequence thrusting of Jadar above itself and the ovelying original nappes cannot be plausible. Because of these incompatibilities we suggest a northwesterly origin of Jadar, in an original position close to Sana-Una. This implies a min. 250 km right lateral offset of Jadar along the Sava–Vardar belt. We suggest that this major slip occurred in the Palaeogene, prior

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to or synchronous with the southwards thrusting of Jadar along the then linear Sava–Vardar Zone. Studies in the Hellenides also evidence major right lateral shear along the Vardar Zone. It is suggested, that the Sava–Vardar Zone was kinked later, in Neogene, to acquire its present day shape.

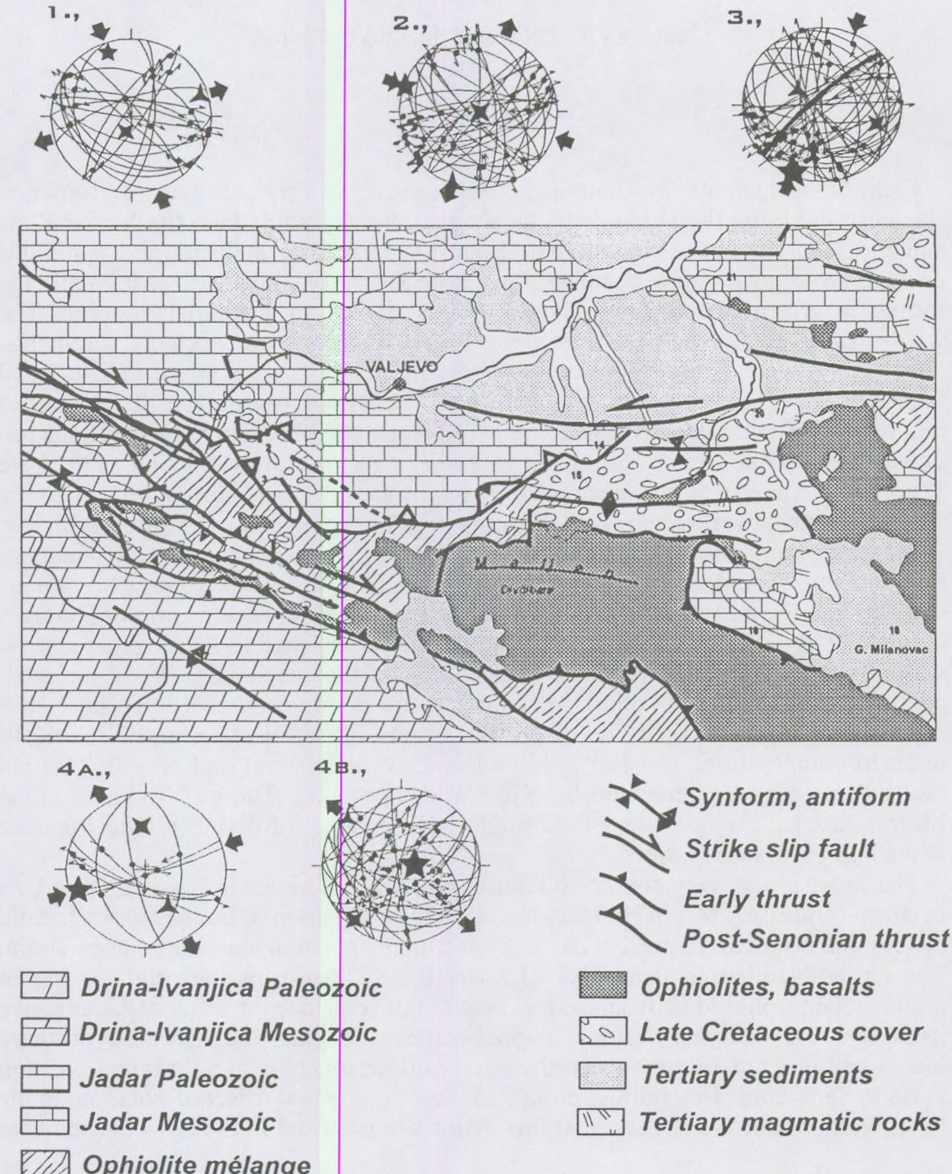

Figure: Geological map of the Jadar area with stressfield types in the order of appearance

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Evolution of the Vardar Ocean during Mesozoic

Stevan KARAMATA[1] and Dragoljub STEFANOVIC[2]

(with 1 figure)

In Central Serbia, there are fragments of Eurasia in the East (Moesian Plate) and of Gondwana in the southwest (part of Adria), with the terranes docked to them before the Permian (the Eurasian Unit or EAU and the Gondwana Unit or GU resp.) and relics of the oceanic lithosphere which was in between. These oceanic relics, presently ophiolitic belts, are remnants of the westernmost part of the Tethys or of the Vardar Ocean and the attached marginal seas.

In the Permian, the EAU and the GU were connected in the northwest and the Vardar Ocean represented a large embayment (e.g. SMITH & BRIDEN, 1977; ROBERTSON et al., 1996; STAMPFLI 2000, etc.). Both units were at the latitudes close to Equator but far from each other (different climate and flora).

During the Early and Middle Triassic, the conditions remained the same with WP volcanism with certain subduction signatures in the GU (KNEZEVIĆ & CVETKOVIĆ, 2000), which is an additional difference. In the Ladinian, the Dinaridic marginal sea (DOB) began to develop, which increased the distance between the GU and the EAU. The new western branch of the Vardar Ocean (VZWB) began to develop west from Kopaonik block and ridge unit (KBR). Later on, it become the main oceanic area in this region.

The differences of the Lower – Middle Jurassic brachiopod fauna of EAU and GU (RADULOVIĆ, 1995) are indicative for the distance of these units. At the end of that time, the closing of the DOB and of the main Vardar Ocean began, and these oceanic basins were both closed till the end of the Jurassic.

All units along this E–W transverse gradually drifted northwards slowly approaching each other. The EAU, with the added relics of the Main Vardar zone and the Kopaonik block and ridge unit was at 23–31° N during the Barremian to the Turonian, while the GU was at 30–33° N. It is important that Middle Cretaceous palynomorphs of European affinity were determined on the eastern side of the EAU while the ones of "central Tethyan affinity" were determined on the western side of the GU (DULIĆ, 1998). Accodingly these two main units were still far away at that time.

The GU and the EAU finally collided in the Late Senonian and the Vardar Ocean, as well as the inherited oceanic realms, was closed. All units along this E–W transverse were at 33–36° N at that time. The Oligocene sediments were deposited at 37–38° N.

From the latest Cretaceous, all the units rotated 5–10° CW in the west and up to 20° CW in the east. This is probably connected with formation of the Pannonian Basin and the Carpathian arc.

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These data show that all formations steady moved northwards until the present framework of the Balkan Peninsula has been established.

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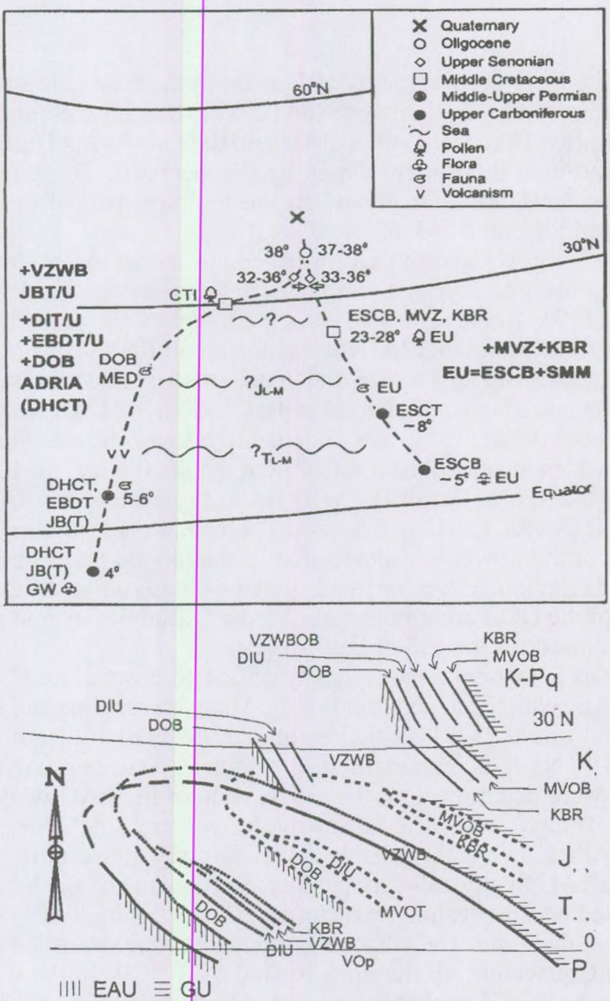

Figure 1. Simplified presentation of general northward movements of the units and their approaching and joining: Upper sketch — Data; B — Lower sketch — Schematic presentation of the units distribution.

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Structure of the Dinarides: a working model

László CSONTOS[1], Natasa GERZINA[2], Hazim HRVATOVIĆ[3],
Stefan SCHMID[4] and Bruno TOMLJENOVIĆ[5]

(with 1 figure)

During a series of field visits a model in the sense of a working hypothesis was developed for the Dinarides. This working model somewhat contradicts or modifies existing views. Our main points are given below.

1, Concerning a transect through Bosnia, there appears there are two belts with ophiolites (Central Dinaridic Ophiolite Belt and Eastern Dinaridic or Vardar Ophiolite Belt) but they resulted from obduction of just one ocean (Dinaridic Tethys) of Triassic–Jurassic age by the end of Jurassic – Early Cretaceous. No proof for the existence of a branch of "Vardar" that remained open up to Tertiary times was found in Bosnia or Central Serbia so far. Occurence of ophiolites in two and not only in one belt is due to out-of-sequence thrusting and later nappe re-folding. These subsequent structural events can be as late as Palaeogene-Neogene.

2, Final collision and closure of the Dinaridic Tethys Ocean occurred in Middle Cretaceous times. Occurence of ophiolites in younger formations are due to their reworking and redeposition from mélange and large ophiolite massifs already exposed on the surface since Late Jurassic – Early Cretaceous times. Late Jurassic obduction and mid-Cretaceous collision have to be separated into two different structural events. It is proposed that the Dinaric shelf was the lower plate and the Tisza (–Serbo-Macedonian) microcontinent was the upper one during Cretaceous collision.

3, The older part of the Bosnian flysch (Vranduk Fm) is of distal turbiditic-foredeep origin, grading eastwards- upwards into a more proximal facies. It was deposited on the active Dinaric margin and not on the passive margin as earlier proposed. Many Late Jurassic – Early Cretaceous dark turbidite formations can be correlated with the Vranduk Formation, including Rossfeld (Salzkammergut, Austria; Gerecse, Hungary), Lök and Mónosbél (Bükk Mts) Ostrc (Croatia). The stratigraphic underlayer might be Jurassic Radiolarite upon a distal parautochthonous Dinaric margin, or it might be sheared off this margin.

4, We separate the Late Cretaceous Ugar Fm (younger part of the Bosnian flysch) from Vranduk Formation, because there is a marked unconformity between the two

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turbidites. This unconformity marks the end of the "pre-Gosau" deformation of Early Cretaceous age, an event that so far largely remained unrecognised in the Dinarides. Their deformation styles and clastic material are different (syn-cleavage tight folds vs. open, rarely cleaved folds; basically clastic vs. marly-carbonatic material). The Ugar Formation represents a post-tectonic formation, together with other similar deposits of the Late Cretaceous, widespread in the whole Dinarides. This formation was deformed only by Tertiary structural events.

5, Durmitor is an out of sequence nappe rethrusting the former nappe pile and its Senonian cover onto Senonian, therefore its age is younger.

6, The Senonian–Palaeogene Posavina belt is a turbidite zone with coeval calcoalkaline acidic mafic magmatism. It is not necessarily related to any ocean closure. Instead, this belt might be related to intracontiental right lateral strike slip reactivation of an earlier collisional contact between Tisza and the Dinarides. This zone is tentatively correlated with similar rocks in Medvednica (Croatia) and the Szolnok Flysch Belt (northern margin of Tisza, Central Hungary). The former linear shear zone is now strongly disrupted by later microcontinent- and block-rotations.

7, The Tertiary evolution of the Dinarides is dominated by major rotations, right lateral strike slip faulting and southwestward thrusting. When reconstructed, the Dinaric structural belts and those of Tisza are aligned N–S. The External Dinarides are constantly shifted to the north, to indent into Europe at the Alpine sector. 500 km N–S shortening in the Alps is conveyed through right lateral N–S shear zones into subduction zone(s) in the External Hellenides. A Palaeogene westward thrusting is also a dominant feature. A first major period of CCW-rotation is in Late Palaeogene – Early Miocene times, followed by a second major period of CCW-rotation in Late Miocene – Pliocene.

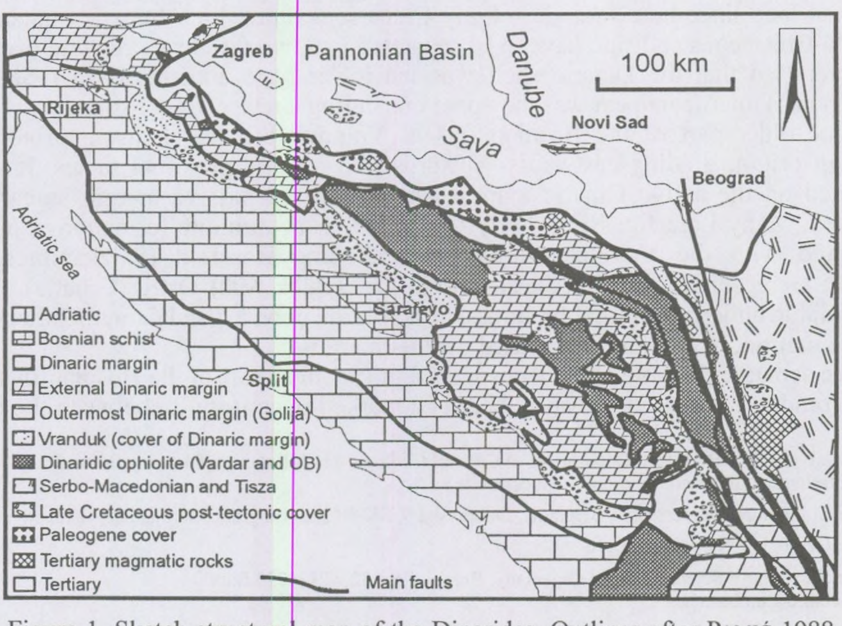

Figure 1. Sketch structural map of the Dinarides. Outlines after PAMIĆ 1988, reinterpreted

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The Permo–Triassic evolution of the Tethyan margins in the External Hellenides

Eric CHAMPOD[1], Stéphane KOCK[1], Bastien COLLIARD[1] and Gérard M. STAMPFLI[1]

(with 1 figure)

Three units are recognised at the base of the Cretan nappe pile (from internal to external) :

The Pindos Zone: In the area of Kalos Potamos (South Eastern Crete), the Pindos series is characterised by Triassic E-MORB and Volcanic Arc Basalts within the Priolithos Formation. The Upper Ladinian to Lower Carnian turbidites of the latter are interpreted as a synrift sequence of the Pindos back-arc basin.

The Tripolis Unit (Phyllites-Quartzites s.l.): On top of the nappe pile of Vaï (Eastern Crete), there is an andesitic and volcano-sedimentary sequence of Triassic age, coming from the Palaeotethyan volcanic arc. In the area of Chamezi (Eastern Crete), calc-alkaline volcanogenic deposits occur as well, but they are followed by a thick detritic series of Ladinian to Carnian ages. These massflows, laid in a tilted block environment, are interpreted as a synrift sequence. Pelagic and distal turbidites rest on top of the latter (postrift sequence). Therefore, these units demonstrate the opening of the Pindos back-arc basin within the Palaeotethyan volcanic arc, in Middle Triassic times. This fact is supported by the calc-alkaline and E-MORB signature of the volcanogenic deposits. In Chamezi, these Arc/Back-arc units are thrusted over the Variscan metamorphic unit (back-stop). At the base of the latter, there is a basement member of Cambrian to Triassic ages (ROMANO et al., 2002). Its terrigenous detritic cover is post-Variscan, as demonstrated by a jump in metamorphic conditions. Between this Variscan Unit and the “Relative Autochtonous”, there is a turbiditic and pelagic sequence of Early Permian to Middle Scythian ages. In Vaï, the base of the Ravdoucha Beds is also a turbiditic series, but it contains many olistoliths of radiolarites, andesites, OIB basalts and basement blocks. The external position and the sedimentation processes of these series allow us to consider them as remnants of a Permo–Triassic Fore-arc basin.

The Talea Ori Unit: The “Relative Autochtonous” corresponds to the Palaeotethyan southern margin (lower plate). Near Bali, a strong Neotethyan northern margin affinity has been recognized in its stratigraphy, with its Permo–Carboniferous base constituted by dark synrift sandstone deepening upwards. A large fusuline limestone platform corresponds to the postrift thermal subsidence.

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An Upper Triassic conglomerate and an angular unconformity are regarded as consequences of the Cimmerian collision.

The Cimmerian event also affects the upper plate, as demonstrated in Eastern Crete by Cimmerian thrusts, basement conglomerates and flysch. The high metamorphic condition recorded by the conodonts in the Ravdoucha beds testify of the Cimmerian metamorphism. In Vaï, it is demonstrated that the suture zone was sealed by the Norian platform of Tripolitza, which means that the Palaeotethys final closure is Late Carnian to Early Norian.

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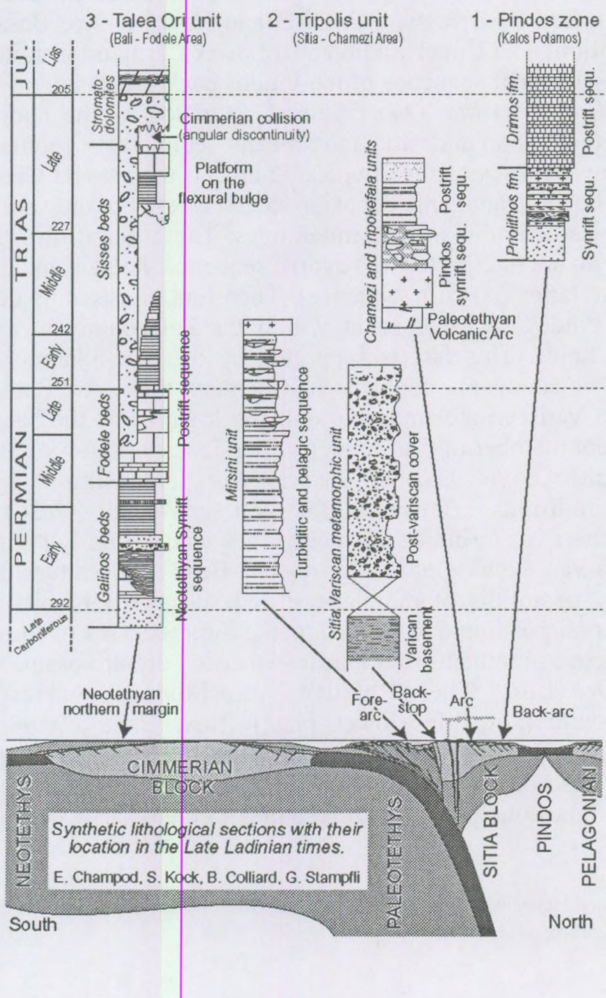

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Eastward-directed shearing during nappe emplacement in the Calabrian–Peloritan Arc

Federico ROSSETTI[1] and Gianluca VIGNAROLI[1]

(with 1 figure)

This contribution is addressed to define the kinematics of the Alpine orogenic phase in the Calabride Complex, based on integrated geological, structural and petrographical investigations carried out in two selected areas of the Calabrian–Peloritan Arc. The study mainly focuses on the definition of the nappe architecture of the two regions and the definition of the P-T-deformation paths of the main tectonic units.

In the Sila Piccola Massif (central Calabria), the Calabride Complex consists of pre-Alpine basement continental slices overprinted by Alpine metamorphism, equilibrated under low-grade greenschist to blueschist conditions. Stable mineral assemblages during the Alpine stage are Na-amphibole + lawsonite + albite + chlorite + phengite/paragonite. These mineralogical associations provide *P-T* estimates of 0.6–0.8 GPa for pressure and temperature less than 350 °C. Alpine metamorphism is associated with a transpositive *S-L* fabric associated with a mean ENE-trending stretching direction. Sections normal to main schistosity and parallel to stretching lineations (*X-Z* sections of the finite strain ellipsoid) systematically show asymmetric features, with kinematic indicators showing a top-to-the-ENE sense of shear.

The Peloritani Mountains (north-eastern Sicily) consist exclusively of stacked continental-derived units (pre-Alpine crystalline basement and Alpine cover rocks). The lowermost units (Mandanici, S. Marco d'Alunzio and Alì units of LENTINI et al., 2000) provide evidence for a progressive ductile-to-brittle shearing during south-eastward piling up. In the Mandanici and S. Marco d'Alunzio units, Alpine deformation obliterates the pre-Alpine assemblages with the development of a plano-linear fabric (S-L tectonites), whose intensity increases approaching the main tectonic boundaries. Syn-kinematic metamorphic assemblages are equilibrated within the low-grade greenschist facies. Main stretching lineations are provided by chlorite + albite + quartz + white micas composite associations and strike from NW–SE to NNW–SSE. Shear sense criteria are consistent with a top-to-the-SE/SSE tectonic transport. Semi-brittle deformation is the dominant structural feature in the Alì Unit, where the

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development of metric fault gouges is commonly observed in top-to-the-SE/SSE reverse fault zones.

The described structural pattern documents a first-phase Alpine compressional deformation, associated with orogenic wedge formation and nappe stacking. The tectonic transport related to this early deformation stage is constantly directed towards the Apennine foreland: i.e. the Adriatic and Ionian plates. This kinematic framework supports an "Apennine-type" eastward-directed compressional structuration of the Calabrian-Peloritan Arc as a whole.

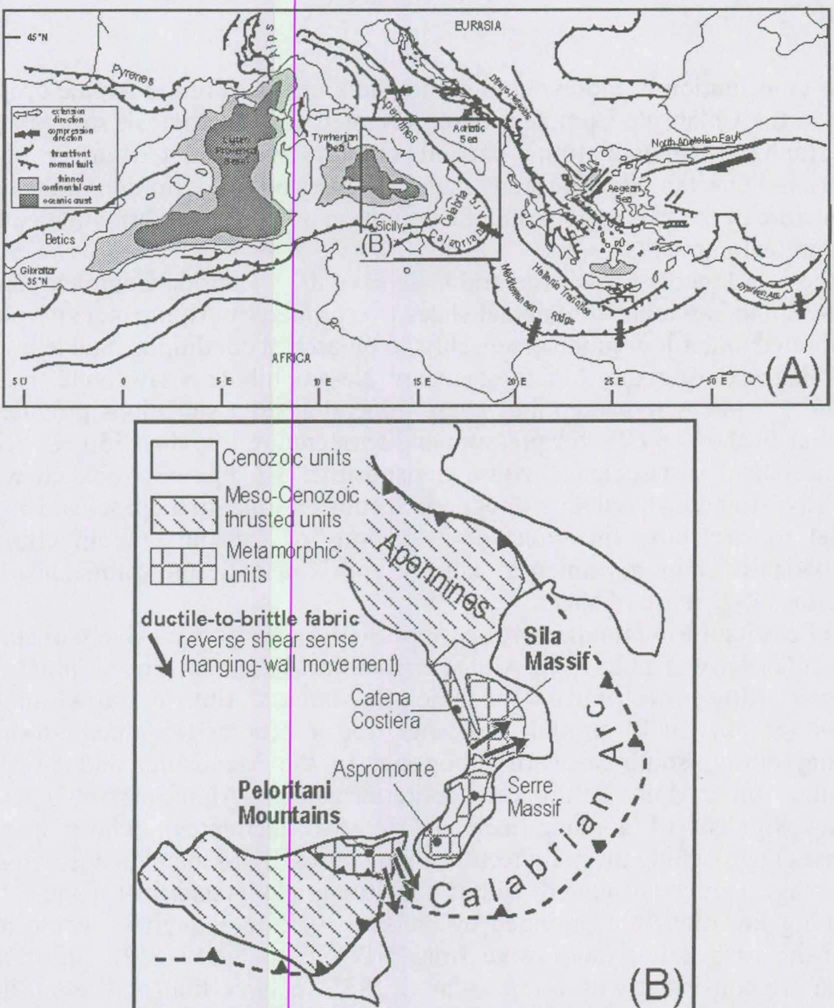

Fig. 1 - (a) Synthetic tectonic map of the Tyrrhenian-Apennines system (modified after *Jolivet et al., 1998*). (b) Geological sketch map of the Calabrian Arc. Arrows indicate the reverse ductile-to-brittle shear senses detected in the basement units piled up in the Calabrian Arc nappe stack.

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Pleistocene horst of Northern Backa

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(with 2 figures)

A Neotectonic horst in the Northern Backa was recognised by several methods: borehole analysis, sedimentological and palaeontological data, geophysical surveying, surface mapping and, in first place, geomorphologic features, like direction of the water currents. The horst structure is located above central part of the Northern Backa Plateau, named Telecka.

Morphological analysis shows very straight courses of the rivulets, having direction NNW–SSE as the faults in subsurface. They are often knee bended, like Krivaja (meaning — Bended) rivulet according to a set of perpendicular, secondary faults. On the geological section, a slight folding of the horst structure is visible, but the most part of it is tilted and therefore slanting toward the East. Highest point of Backa Plateau lies just outside of locality Bajmok to NW.

Geophysical data repeat the above mentioned pattern, indicating greater and greater displacement downwards. This means that all the faults are of synsedimentary character, and some of them bifurcated or multifurcated close to the surface.

On the section the westernmost limb of the fault swarm is covered by the Würmian loess with sand intercaltions; it lies uncomfortably over the lower part of Upper Pleistocene. In the main part of Telecka, loess is washed off the horst itself, so Middle Pleistocene silts with toothed *Planorbis planorbis, Bithynia crassitesta, Virgatocypris* and others reach the surface.

The middle part of the horst, around Bajmok, was emerged from the Pannonian Lake by the end of Pliocene. There are some micromammal habitats, (Sb–6), filled by dark silt. Also the Lower Pleistocene, accordig to ostracodes, should be thin there. To the east of Bajmok two faults are indicated, deep in and under the Neogene (different geophysical metods). One is relatively close to the town of Bajmok following Krivaja course. The other roughly follows the course of the Cik brook. Both are marking the eastern border of the horst being not only of Pleistocene age but lasting for very long time.

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