Berichte der Geologischen Bundesanstalt, 99

11th Workshop on Alpine Geological Studies & 7th European Symposium on Fossil Algae

Abstracts & Field Guides

Schladming, Sept. 2013

Redaktion: Ralf Schuster

Cover image: Sölk marble from the base of the Weiße Wand, Walchental (Styria, Austria)

Impressum:

ISSN 1017-8880

A-1030 Wien, Neulinggasse 38
www.geologie.ac.at
Wien, September 2013

Medieninhaber, Herausgeber und Verleger: GBA, Wien
Redaktion: Ralf Schuster (Geologische Bundesanstalt)
Technische Redaktion; Christoph Janda (Geologische Bundesanstalt)
Umschlag Monika Brüggemann-Ledolter
Druck: Riegelnik, Offsetschnelldruck, Piaristengasse 19, A-1080 Wien

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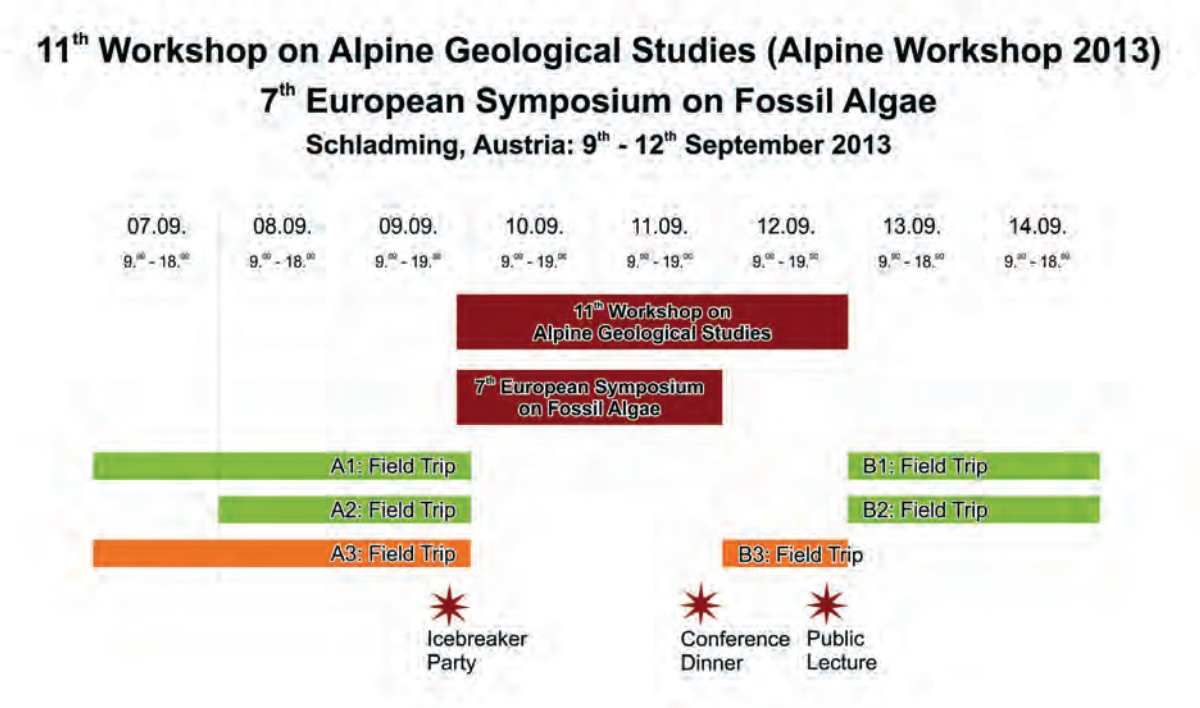
Content

Organisation & Time Schedule



11th Workshop on Alpine Geological Studies

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Montanuniversitaet Leoben, Department of Applied Geosciences and Geophysics
Geological Survey of Austria

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11th Workshop on Alpine Geological Studies

Theme	Tuesday, 10. September	Wednesday, 11. September	Thursday, 12. September
T1 Tectonostratigraphy: Triassic-Neogene tectonostratigraphy in the Alpine Carpathian Dinaride realm	Oral: 9:30 - 15:00 (Blue) Poster (Orange)	Poster (Orange)	Poster (Orange)
T1 Tectonostratigraphy: The Alps-Apennine junction	Poster (Orange)	Poster (Orange)	Oral: 9:00 - 17:45 (Blue) Poster (Orange)
T5 Stratigraphy and facies	Oral: 15:00 - 17:30 (Blue) Poster (Orange)	Poster (Orange)	Poster (Orange)
T6 Metamorphic processes	Poster (Orange)	Oral: 9:00 - 10:15 (Blue) Poster (Orange)	Poster (Orange)
T7 Geomorphology and landscape evolution	Oral: 17:30 - 18:00 (Blue) Poster (Orange)	Poster (Orange)	Poster (Orange)
T8 Modelling and application	Poster (Orange)	Oral: 11:00 - 12:15 (Blue) Poster (Orange)	Poster (Orange)
T9 Geophysics/Seismics/ Petrophysics	Poster (Orange)	Oral: 14:00 - 15:15 (Blue) Poster (Orange)	Poster (Orange)
T10 Georesources/Applied geosciences	Oral: 16:30 - 17:30 (Blue) Poster (Orange)	Poster (Orange)	Poster (Orange)

	Tuesday, 10. September	Wednesday, 11. September	Thursday, 12. September
9:00	OPENING CEREMONY	Tropper, P. et al.: How good do simple experiments using natural rocks reproduce natural observations and theoretical calculations: Selected examples ranging from high-P to high-T settings	Vannucchi, P. & Molli, G.: The Alps/Apennines boundary: Structures and kinematics of interfering orogens and comparison with other modern analogues
9:15			
9:30	Miladinova, I. et al.: Middle Triassic eclogite in the Rila Mountains (Rhodope Upper Allochthon, Bulgaria): A vestige of Palaeotethys subduction?	von Niederhaeusern, B. et al.: Permian metamorphism and magmatism in the ...	Manatschal, G. et al.: Alternative models to explain the evolution of ...
9:45		Lanari, P. et al.: PT-t estimates in low-grade metamorphic terrains, a key to ...	Ballevre, M. et al.: Geometry, kinematics and P-T paths of the Money ...
10:00	Cao, S. & Neubauer, F.: Geodynamic and structural controls on the exhumation ...	Cvetkovic, V. et al.: Late Cretaceous bimodal igneous association of the ...	Manzotti, P. et al.: The structure and P-T evolution of the Dent Blanche ...
10:15	Wagreich, M. et al.: The St. Veit Klippenzone in Vienna - missing piece in ...	REFRESHMENT BREAK	Scheiber, T. et al.: Crystalline nappes in the Cental Alps: Case study Suretta ...
10:30	Plasienka, D.: Jurassic and Lower Cretaceous tectonics of the Western ...		REFRESHMENT BREAK
10:45	REFRESHMENT BREAK		
11:00		Keynote lecture: Willingshofer, E. et al.: Analogue modelling of continental subduction with laterally changing subduction polarity	Cavargna-Sani, M. & Epard, J.L.: Structure and kinematics of the northern ...
11:15	Borojevic Sostaric, S. et al.: The origin and age of the metamorphic sole from ...		Pleuger, J. & Podladchikov, Y.: Possible amounts of tectonic overpressure in ...
11:30	Van Gelder, I.E. et al..: From orogenic buildup to extensional unroofing ...	Carminati, E. et al.: Subduction flip in the Mediterranean and the asymmetry of ...	Gnos, E. et al.: Dating Alpine brittle deformation with hydrothermal monazite
11:45	Heberer, B. et al.: Oligocene and Neogene tectonic processes in the southeastern ...	Zerlauth, M. et al.: Thermal modelling of an external Unit of the Eastern Alps ...	Glotzbach, C. et al.: Early exhumation of the Aiguilles Rouges and Mont ...
12:00	Koever, S. & Fodor, L.: New constrains to the Mesozoic structural evolution of ...	Burn, M. et al.: Mobility within the subduction channel: Correlation of P-T-D-t ...	Herwegh, M. et al.: Strain localization history of the Simplon Fault Zone ...
12:15	Georgiev, N. et al.: A review of magmatic zircon ages from the Rhodope ...	LUNCH BREAK	Mosar, J. et al.: Tectonics in the Swiss Molasse Basin
12:30	Marton, E. et al.: Tectonic models for Adria and the External Dinarides in the context ...		LUNCH BREAK
12:45	LUNCH BREAK		
14:00	Haupert, I. et al.: Evolution and reactivation of basement highs at ...	Bokelmann, G. et al.: Large-scale deformation of the Eastern Alps from seismic anisotropy	Rabin, M. et al.: Plio-Quaternary deformation of the Jura mountain belt ...
14:15	Fodor, L.I. et al.: Jurassic to Early Cretaceous basin evolution of the northern ...		Favaro, S. et al.: Development of nappe stacking in the eastern Tauern ...
14:30	Andric, N. et al.: Study of the thermal history of the Miocene Jarando basin ...	Bianchi, I. et al.: The lithosphere-asthenosphere boundary below the Eastern ...	Scharf, A. et al.: Late Oligocene to Miocene exhumation and cooling history ...
14:45	Csaszar, G.: Two separated Lower Cretaceous basins in the Transdanubian Range ...	Vouillamoz, N. et al.: Micro-seismic characterization of the Fribourg Lineament ...	Woelfler, A. et al.: 3D termo-kinematic modelling of a crustal-scale low-angle ...
15:00	Richoz, S. et al.: News from the Upper Triassic in the Northern Calcareous Alps (Austria)	Abednego, M. et al.: Analysis of microseismicity in the Fribourg area ...	Pomella, H. et al.: The central Alps - eastern Alps boundary in western ...
15:15		POSTER SESSION + REFRESHMENT BREAK	Ortner, H. & Kilian, S.: In-sequence and out-ofsequence thrusts: Nappe ...
15:30	Gorican, S. et al.: Mesozoic stratigraphy and general structure of the Julian Alps ...		POSTER SESSION + REFRESHMENT BREAK
15:45	POSTER SESSION + REFRESHMENT BREAK		
16:00			
16:15			
16:30	Missoni, S. et al.: Carnian-Norian tectonics and seawater from Silicka Brezova ...	Birk, S. et al.: Thresholds in karst catchments: The example of the Lurbach ...	Neubauer, F. et al.: Emplacement mechanisms of evaporite mélanges ...
16:45	Grabowski, J. et al.: Magnetic susceptibility and spectral gamma ray stratigraphy of ...	Pauritsch, M. et al.: Relict rock glaciers - complex aquifer systems in alpine ...	Schorn, A. & Neubauer, F.: The structure of the Hallstatt evaporite body ...
17:00	Decarlis, A. et al.: Stratigraphic architecture and correlation of rifting-related deposits ...	Simic, V. et al.: Listvenite from Serbia as gemstone resource	Schuster, R. et al.: Lithostratigraphy and internal structure of the Austroalpine ...
17:15	Neumeister, S. et al.: Source rock investigations and organic geochemistry of a ...	Trajanova, M. & Zorz, Z.: The abandoned Remshnig mine, occurrence of rare ...	Stuewe, K. et al.: What happened 5 million years ago in the Alps?
17:30	Robl, J. et al.: Base level changes and landscape response in the Eastern Alps ...		Bartel, E.M. & Neubauer, F.: A ductile shear zone terminating a brittle ...
17:45	Bichler, M.G. et al.: Landscape evolution north of the Sonnblick (Salzburg) during ...		CLOSING CEREMONY

7th European Symposium on Fossil Algae

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7th European Symposium on Fossil Algae

Theme	Tuesday, 10. September	Wednesday, 11. September
T1 Calcareous algae	Oral: 9:30 - 11:30 (Grey) Poster (Orange)	Field Trip in the nearby NCA
T2 Microbial carbonates	Oral: 11:30 - 15:45 (Grey) Poster (Orange)	

	Tuesday, 10. September	Wednesday, 11. September
9:00 9:15 9:30 9:45 10:00	Bucur, I.I.: Mesozoicdasycladalean algae from Romanian Carpathians: Diversity, environment and palaeogeographic context	Field trip to the nearby Northern Calcareous Alps (Includes: transportation, lunch packets)
10:15	Mastik, V.: Silurian non-calcified algal flora from the Kalana Lagerstaette, Estonia	
10:30	Bucur, I.I.: Lower Cretaceous calcareous algae form the Khur area, Central Iran	
10:45 11:00	REFRESHMENT BREAK	
11:15	Bucur, I.I.: Calcareous algae from the olistoliths at Poiana Zanoaga, northern part of Piatra Craiului Syncline	
11:30 11:45 12:00	Riding, R.: Stromatolites in reefs past and present	
12:15	Pretkovic, V.: Microbial carbonates in Miocene reefs in the Mahakam Delta in East Kalimantan, Borneo, Indonesia	
12:30	Suarez-Gonzalez, P.: A coastal paradise for Aptian microbialites (Early Cretaceous, N Spain)	
12:45	LUNCH BREAK	
14:00	Tosti, F.: Microbial carbonate reef components in the mid-Triassic Italian Dolomites: A biogeochemical approach	
14:15	Riding, R.: Cyanobacterial ‘whiting’ origin of Devonian-Mississippian carbonate mud mounds?	
15:45	POSTER SESSION + REFRESHMENT BREAK	

Abstract Volume

Emile Argand Conference

(11th Workshop on Alpine Geological Studies)

7th - 14th September 2013

Schladming, Austria

Editorial:

Ralf Schuster
Geologische Bundesanstalt
Neulinggasse 38
1030 Vienna, Austria

Analysis of microseismicity in the Fribourg area (Western Swiss Molasse Basin)

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This study presents an analysis of microseismicity in the Fribourg area (Western Swiss Molasse Basin), a region that has recently displayed increased microseismicity (KASTRUP et al., 2007). Arrival time data of these earthquakes were used in a non-linear probabilistic earthquake relocation approach and to refine an existing three-dimensional (3-D) P-wave velocity model of the Fribourg area.

Two mini-arrays (seismic navigating systems/SNS) have been deployed since 2010 to enhance seismic monitoring of the Fribourg Lineament within the Fribourg area. A comprehensive local catalogue of microseismicity was build using recordings of the two SNS and of nine permanent stations of the Swiss Digital Seismic Network and the Swiss Strong Motion Network operated by the Swiss Seismological Service (SED). Events were detected on all traces by sonogram analysis, a non-linearly scaled and noise-adaptive spectrogram (SICK et al., 2012). It allows the detection of very low magnitude events, for which signal to noise ratio is minimal (JOSWIG, 2008).

Events were relocated using the non-linear probabilistic earthquake location software NonLinLoc (LOMAX et al., 2000). This approach requires consistent arrival time picking including uncertainties as well as a velocity model for the area. Initial arrival time picking was done using sonogram analysis. Arrival time picks were subsequently readjusted and its uncertainties were assigned according to New Manual of Seismological Observatory Practice (BORMANN, 2012). An initial 3-D P-wave velocity model was designed on the basis of controlled-source seismology data in the area (MEIER, 2009) and of a 3-D P-wave velocity model of Switzerland (HUSEN et al., 2003).

Since 2001, 314 were events detected in the Fribourg area, of which 112 events were detected routinely by the SED. In total 185 high-quality events were integrated in a local earthquake tomography analysis to refine the initial P-wave velocity model. Relocation of the events using the new tomographic model, yields on average smaller location errors as given by the volume of the 68 % confidence ellipsoid. Most of the events locate in the sedimentary cover, at depths shallower than 2500 m in the NNW and 4500 m in the SSE of our study region. The number of events located in the sedimentary cover is increasing by at least 3.5 % using our approach.

BORMANN, P. (2012): New Manual of Seismological Observatory Practice (NMSOP-2), IASPEI, GFZ German Research Centre for Geosciences, Potsdam.

HUSEN, S., KISSLING, E., DEICHMANN, N., WIEMER, S., GIARDINI, D. & BAER, M. (2003): Probabilistic earthquake location in complex three-dimensional velocity models: Application to Switzerland, J. Geophys. Res., 108.

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KASTRUP, U., DEICHMANN, N., FRÖHLICH, A. & GIARDINE, D. (2007): Evidence for an active fault below the northwestern Alpine foreland of Switzerland, Geophys. J. Int., 169, 1273-1288.

LOMAX, A., VIRIEUX, J., VOLANT, P. & BERGE, C. (2000): Probabilistic earthquake location in 3D and layered models. – In: THURBER, C.H. & RABINOWITZ, N. (eds.): Advances in seismic event location, Kluwer Acad., Norwell, Mass., 101-134.

MEIER, B. (2009): 2D Seismik Interpretation im Gebiet Fribourg und Berner Seeland, Report Interoil E&P Switzerland AG, for Resun AG, Zürich.

SICK, B., WALTER, M. & JOSWIG, M. (2012): Visual Event Screening of Continuous Seismic Data by Supersonograms, Pure Appl. Geophys.

Study of the thermal history of the Miocene Jarando basin (Southern Serbia)

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The Jarando basin is located in SSW part of Serbia and belongs to the internal Dinarides. It was formed during the Miocene extension affecting the whole Alpine-Carpathian-Dinaride system (SCHMID et al., 2008). In the study area Miocene extension led to the formation of a Studenica core-complex (SCHEFER et al., 2011) with the Jarando basin located in the hanging wall of the detachment fault.

The Jarando basin is characterized by the presence of bituminous coals, whereas in the other intramontane basins in Serbia coalification did not exceed the subbituminous stage within the same stratigraphic level. Furthermore, the basin hosts boron mineralization (borates and howlite) and hydrothermal-sedimentary magnesite, which indicate elevated temperatures.

Possible heat sources in the study area are magmatic activity, core-complex formation and burial of sediments. The intense Tertiary magmatic activity is represented by Oligocene I-type Kopaonik granodiorite, Miocene S-type Polumir granitoid, volcanics (SCHEFER et al., 2011) and subsequent hydrothermal fluid flow. The juxtaposition of warmer footwall units against cooler hanging wall units via rock uplift and exhumation of the Studenica core-complex could produce high heat flow in the Jarando basin.

This paper is aimed at providing new information about the thermal history of the Jarando basin. The vitrinite reflectance was measured for 11 core samples of shales from one borehole and 5 samples of coal from an underground mine. Fifteen core samples from three boreholes and 10 samples from the surrounding outcrops were processed for apatite and zircon fission-track analysis.

VR data reveal a strong post-depositional overprint. Values increase with the depth from 0.66-0.79% to 0.83-0.90%. Thus organic matter reached the bituminous stage and experienced temperatures of around 110-120˚C (BARKER & PAWLEWICZ, 1986). All zircon grains from samples are older than the age of sedimentation. FT single grain ages for apatite scatter between 45 Ma to 10 Ma with a general trend towards younger ages with depth. The mean track length varies from 9.90±2.45μm to 12.32 ±2.23μm. Both the spread in single grain ages and the bimodal track lengths distribution clearly point to partial annealing of the detrital apatites. The temperatures given from the VR data and thermal modeling indicate short-lived thermal event around 15-12 Ma. The VR values and apatite FT modeling suggest two paleo-thermal events, heating and subsequent cooling. We correlate the thermal event with the extension and core-complex formation followed by the syn-extensional intrusion of the Polumir granite. Later cooling from 10 Ma onwards is related to basin inversion and erosion.

Acknowledgments: This research was financed by the DOSECC Research Grant and by the Ministry of Education and Science of the Republic of Serbia (Projects 176006, 176016 and 176019). The authors are grateful to Prof. Dr. Vladimir Simic for his support, constructive comments and suggestions, and to the RKU Ibarski Rudnici uglja (Ibar Coal Mines) for providing cores and samples from the Jarando basin.

BARKER, C.E. & PAWLEWICZ, M. J. (1986): The correlation of vitrinite reflectance with maximum temperature in humic organic matter. In: Lecture notes (eds. G. Buntebarth and L. Stegena), Earth Sciences, 5. Palaeogeothermics Springer-Verlag, Berlin, 79-93.

SCHEFER, S., CVETKOVIĆ, V., FÜGENSCHUH, B., KOUNOV, A., OVTCHAROVA, M., SCHALTEGGER, U., SCHMID, S.M. (2011): Cenozoic granitoids in the Dinarides of southern Serbia: age of intrusion, isotope geochemistry, exhumation history and significance for the geodynamic evolution of the Balkan Peninsula. - International Journal of Earth Sciences, 5: 1181-1206.

SCHMID, S., BERNOULLI, D., FÜGENSCHUH, B., MATENCO, L., SCHEFER, S., SCHUSTER, R., TISCHLER, M., USTASZEWSKI, K. (2008): The Alpine-Carpathian-Dinaridic orogenic system: correlation and evolution of tectonic units. - Swiss Journal of Geosciences, 101: 139-183.

Quartz vein formation during decompression and recrystallization in the Venediger Nappe Complex and Eclogite Zone of the southern Tauern Window (Eastern Alps): Fluid Inclusions linked with structures

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The Variscian Basement (Venediger Nappe Complex) and the Eclogite Zone are parts of the Subpenninic Units of the Tauern Window in the Eastern Alps. The investigated area, located in the southern Tauern Window along the Frosnitztal (Eastern Tyrol), shows asymmetric domino boudin structures with quartz-filled vein necks within the Venediger Nappe Complex. The amphibolite host rocks are surrounded by a layered penetrative foliation consisting of leucocratic melts (leucosomes) which can be linked with the Permian-Carboniferous intrusion of the Zentralgneis. Quartz samples are taken from the leucosomes and from the boudin neck structures.

In the Eclogite Zone concordant quartz layers occur beside carbonate-bearing micaschists and a penetrative foliation consisting of omphacite + garnet + epidote/zoesite + glaucophane. Three generations of fluid inclusions have been distinguished. On the basis of the textural occurrence and rheological characteristics, the chemistry of the metamorphic fluid during recrystallization of the leucosome layers and quartz-filled vein neck formation is reconstructed. It can be shown that during recrystallization and decompression the grade of salinity increases from about 6 to 15 mass% accompanied with a small change in the aqueous system H_2O-NaCl-$MgCl_2$±$CaCl_2$. This change occurred at estimated maximum P conditions around 850 MPa and temperatures of 500-550°C (fluid inclusion generation 1). Subsequent healing of micro-cracks postdates recrystallization in the range between 600 and 350 MPa (fluid inclusion generation 2). Restricted to the boudin necks a late fluid generation of primary character consisting of CO_2-H_2O-NaCl chemistry indicates entrapment conditions between 250-300 MPa which is linked with a late stage quartz vein precipitation in the boudin necks (fluid inclusion generation 3). These late veins are not recrystallized and contain conjugate microcracks that are different to earlier cracks which healed in recrystallized quartz aggregates (intragranular versus transgranular plane characteristics). In this late quartz vein generation fluid inclusion decrepitation features indicate isobaric cooling at the latest stage of the PT-evolution of the Venediger Nappe Complex.

Fluid Inclusions from a concordant folded quartz layer in the Eclogite Zone are compared to the fluids in the Venediger Nappe Complex but significantly different in their chemistry and densities. They are dominated by the N_2-CH_4-H_2O system and texturally arranged along intragranular planes within totally recrystallized quartz grains. The fluid chemistry of ca. 90 mol% N_2 can be related to the breakdown of K-bearing minerals like feldspar and mica during retrogression of the eclogitic host rock. Additionally a rare occurrence of pure aqueous inclusions is observed along cracks. Calculated low densities are indicative for reequilibration and leakage due to decompression and recrystallization.

Geometry, kinematics and P-T paths of the Money window (Western Alps): lower-pressure rocks overthrusted by higher-pressure ones?

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In the Western Alps, the polycyclic, eclogite-bearing units of the Gran Paradiso and Dora-Maira are thrusted over monocyclic, lower-grade units that contain as a diagnostic suite a sequence of graphite-rich sequences long ago thought to derive from Carboniferous sediments (Money and Pinerolo, respectively).

In detail, the Money window exposes in the Valnontey valley (Gran Paradiso massif, Western Alps) a sequence of clastic sediments and volcanics that are intruded by a granitoid body (Erfaulet metagranite). Two types of clastic sequences have been recognized. The first one essentially consists of greyish (i.e. graphite-rich) micaschists and polygenic metaconglomerates, reworking quartz veins, granitoids and some mud clasts. The second one is made of monogenic conglomerates (consisting essentially of quartz veins, with rare granitic pebbles), with a few interbedded graphite-rich micaschists. The two sequences are separated by fine-grained biotite-amphibole gneisses that display alkaline chemistry, and by albite-bearing gneisses and amphibolites. Although still uncertain, the few observed polarity criteria (graded bedding in the former conglomerate layers) are consistent with sequence 1 being older than sequence 2. In addition, this would be coherent with the transition from essentially polygenic to monogenic conglomerates (implying closer sources and /or higher relief for sequence 1 with respect to sequence 2) and a transition from graphite-rich to graphite-poor sediments (recording the climate change at the Carboniferous to Permian boundary). La-ICPMS U-Pb geochronology on detrital zircon grains and on the volcanics will be performed in order to test this hypothesis.

Detailed mapping and structural analysis has been made within the Money window, allowing recognizing four main stages of Alpine deformation. The first one is only identified as relic foliation (S1) in the cores of albite and garnet porphyroblasts, defined by the alignment of quartz, chloritoid and rutile. The second one is associated to a pervasive foliation (S2) that is parallel to the main lithological boundaries. This foliation is defined by garnet-chloritoid-white mica-rutile, and testifies to an early high-pressure event. The stretching lineation (L2) associated to this event has an E-W trend.

The third one is associated to a large-scale folding (F3) of the volcano-sedimentary sequence, and it is characterized by flat-lying axial plane with nearly E-W fold axes. The S2 schistosity is microfolded (crenulated) in the weaker lithologies, i.e. in the two clastic sequences, where a new mica-chlorite-ilmenite foliation develops. Because the F3 fold axes have a nearly E-W trend, they are almost parallel with the L2 stretching lineation. However, a minor angle is observed between the L2 stretching and the F3 fold axes, suggesting that the folds are non-cylindrical at a kilometer scale. 3D modeling of the geometry within the Money window will be displayed.

The thrust contact that separates the Money Unit from the overlying Gran Paradiso Unit predates this F3 folding event, because the mylonites at the base of the Gran Paradiso Unit are folded. Detailed petrological models will be performed in order to check the pressure difference between the hangingwall (Gran Paradiso Unit) with respect to its footwall (Money Unit). The consequences of these data with respect to existing models for the Alpine collision will be discussed.

A ductile shear zone terminating a brittle strike-slip fault: The gypsum-dominated Paluzza-Comeglians shear zone as western extension of the Fella-Save fault, Southern Alps

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Compressive and extensive horsetails are common structures on the lateral termination of brittle strike-slip faults, which forms within the shallow continental crust. Here we report another possibility, the lateral termination of a brittle strike-slip fault in a formation-parallel low-temperature ductile shear zone within sulphatic, gypsum-dominated evaporites. In the Southern Alps, over a distance of ca. 35 km, a steeply to gently S-dipping foliation, a subhorizontal stretching lineation and pure shear-dominated porphyroclast systems developed within the S-dipping Lower Bellerophon Formation of uppermost Permian age. Subordinate σ-clasts indicate dextral shear. The main-stage foliation is often overprinted by shear band structures, which also consistently indicate dextral shear along the shear zone. Open to tight faults form at several stages during shear zone development, and mainly refold the mylonitic foliation. Open folds are sometimes associated with reverse faults indicating final N-S shortening. Together, the structures within the Paluzza-Comeglians shear zone indicate transpression, which accommodated dextral displacement of the Fella-Save fault in the east.

Acknowledgements: The research was funded by the Austrian Science Fund (FWF): P22,110 (Aldi-Adria-project).

Analyzing hydrogeological properties of fault rocks and fracture networks in fault zones in carbonate rocks

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Around 60 % of the drinking water for Austria's capital Vienna comes from springs at the N and NE of the Hochschwab Massif. Hydrogeological flow properties in the Hochschwab Massif are essentially governed by karstified fault zones. We investigated sinistral strike-slip fault zones exposed in the Upper Triassic Wetterstein Fm., which formed at shallow crustal depth during the process of eastward lateral extrusion of the Eastern Alps in the Oligocene and Lower Miocene.

In detailed structural field-work we analyzed fault zone anatomy and distinguished zones of certain hydrogeological properties within the fault core and the damage zone. Fault rock classification, fracture network analysis and estimates over their spatial distribution in outcrop studies were supplemented by porosity and permeability measurements from representative samples. Additionally, thin-sections have been investigated with optical microscopy, cathodoluminescence and electron microscopy using backscattered electron imaging and focused ion-beam techniques.

The results show that by trend fault zones in dolomite lack a distinct, single fault core and masterfault but show multiple branching, minor fault cores that interlock in the 3D geometry of the outcrop. Fault zone formation in dolomite is accompanied and influenced largely by fluid interaction producing large volumes of cemented fault rock. In contrast fault zones in limestone have a definite fault core characterized by a distinct masterfault and delimited cataclastic fault rock associated. There is no evidence for spacious cementation processes.

Porosity values of fractured rocks show an exponential increase with increasing fracture densities, with an average effective porosity of 5 % for intensely fractured rocks. Fault rocks such as cataclasites show variable values of effective porosity (2% -6%) due to differences in their micro-structural fabric. The analytical methods provide an insight on deformation processes and features such as grain size reduction, cementation and recrystallization, and point out porosity and permeability differences due to deformation mechanisms and cementation events.

2D thermo-mechanical modeling of basement-cover deformation with application to the Western Alps

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The external crystalline massifs of Western Alps and the Helvetic sedimentary nappe stack result from the deformation of the European passive margin during the Alpine collision. This area has been studied extensively for the past hundred years. However although the geometry and tectonic structures are well documented, the mechanical behavior of the rocks during nappe stacking and basin inversion is still highly debated. The aim of this study is to reproduce the first order tectonic structures of the Western external Alps. We use a 2-D thermo-mechanical finite element model with visco-elasto-plastic rheology formulation to simulate the deformation of half-graben structures during collision. We systematically investigate the control of (1) the rheology, i.e. ductile vs brittle; linear vs power-law viscous rheology, and (2) the boundary condition, i.e. pure shear vs simple shear. Geometry and finite deformation patterns in both basement and sediments are then compared to cross-sections, finite strain ellipses and cleavage orientation from published field data. Orientation and distribution of plastic shear bands in the model are compared to fault distribution from field data and sand box analogue models.

Alpine evolution of the central Aar-massif (Grimsel section)

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The Aar-massif represents a polycyclic basement window representing a part of the inverted former European continental margin. The exhumation and cooling history of the Aar-massif have been already intensively discussed in the literature using fission track and U-Th/He data. However, the thermal and structural situations in the Aar massif in its adjacent tectonic units (e.g., Gotthard unit in the south, Helvetic nappes in the north) during Alpine peak metamorphic conditions (Tmax) are less clear. The maximal temperatures in the Aar massif are similar in age and level as in direct south oriented Gotthard unit and the trend can be followed towards the South into the Lepontine dome (i.e. in Oligocene-Miocene Barrovian metamorphism), a situation which is fundamentally different to other external massifs of the Western Alps (e.g., Aiguille Rouge-, Mont Blanc-, Pelvoux-massifs).

Several problems exist for the reconstruction of Tmax in such basement units: (1) the lithologies (mainly granitoids) are not ideal for P-T estimates based on conventional mineral assemblages, and (2) the timing of mineral equilibration is not clear (mixing of pre-Alpine and

Alpine temperatures). These problems in mind, we compiled metamorphic and isotope age data of the Aar massif in a central cross-section. We add own data using different geothermometers solely collected in Alpine shear zones (e.g., Ti-in-biotite, calcite-dolomite thermometry).

The available P-T conditions in the Grimsel area indicate conditions of ~450°C and 6.5 kbar, which is similar or only slightly lower as in the adjacent southern units (Gotthard units). Such elevated temperatures are found up to the central region of the Aar-massif and therefore no substantial change in temperatures from the southern to the central part is indicated. In contrast, the northern part of the massif shows fundamental lower Tmax (~250°C). These Tmax data suggest a change in the temperature field gradient from south (more constant) to north (relative steep).

The Grimsel area requires exhumation from depths of ~18 km since the Miocene, which is consistent with age and metamorphic conditions in the units further south (the thick skinned units of the Lepontine dome). The northern area shows much less vertical transport and is related to the physical emplacement conditions of the Helvetic meta-sedimentary units (thin skinned, fold and thrust belt). This variation and the related difference in vertical transport from south to north have to be connected to an array of numerous vertical shear zones inside the Aar-massif. Several of these shear zones show a steep transport direction, but also strike slip shear zones exist.

Despite the localized deformation in the individual shear zones, their large number and spatially homogeneous distribution is capable to accommodate uplift and exhumation on the scale of the entire Aar massif in a distributed manner. In other words, temperature offsets between individual shear zones are too small to be detected but in light of the whole Aar massif the shear zone arrays bring different former mid crustal levels to today's exposed position at the surface.

The lithosphere-asthenosphere boundary below the Eastern Alps and the effect of eastward extrusion

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The Eastern Alps (EA) are the result of the European and Adriatic plates convergence. The architecture of this portion of the Alpine collision has been furthermore affected by a lateral (east directed) tectonic extrusion caused by the retreating subduction of the nearby Carpathians. Analysis of Ps and Sp receiver functions from datasets collected by permanent and temporary seismic stations, located in the EA, show the presence of a low velocity layer (LVL) at depth. This LVL might indicate the velocity drop that the seismic waves undergo passing through the asthenosphere, and it testifies a sudden lateral thickness change of the lithosphere. The detected thinner lithosphere is bounded by the Bohemian Massif to the north, and by the Lavanttal fault to the South-west. The detected asthenosphere is deeper (100-130 km) below the North Calcareous Alps, and shallower (70-80 km) below the Vienna Basin and Styria Basin. Unraveling the depth extent of the coherent rigid lithosphere moving over a weak asthenosphere helps deciphering the decoupling determining plate motions and tectonics of the EA. For the first time in the area the Lithosphere-Asthenosphere Boundary is imaged with such a clear depth variation, reflecting the depth extent of the dextral extrusion of the EA towards the Pannonian Basin.

Landscape evolution north of the Sonnblick (Salzburg) during the Alpine Lateglacial

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The area north of the Hoher Sonnblick, in the Austrian province of Salzburg, offers unique opportunities to study landscape forming events (glacial advances, glacial retreats and mass movements) since the Last Glacial Maximum (LGM). The field work revealed unique relationships of cross-cutting landscape elements.

These include multiple moraines and a till cover of a dominant glacial stadial overlying a giant landslide (0.4 km^3, largest in the province of Salzburg), which is then topped by a younger landslide of smaller dimension. The landslide events (13ka BP and 10ka BP), as well as the glacial advance (12.5ka BP) and retreat (11ka BP) were dated using the 10Be method. To establish an extensive chronology, six 10Be samples from the landslides, twelve 10Be boulder samples and two ^{10}Be polished bedrock samples related to glacier history were processed. Furthermore, ^{14}C samples were taken at suitable sites to augment the ages gained by exposure dating. The combination of the evidence found in the field and a detailed geological map, concentrating on Quaternary features, with ^{14}C dating and ^{10}Be dating made it possible to reconstruct the glacial chronology and the landscape evolution of the study area between 21ka BP and 1850 AD with special focus on the time between 14ka and 10ka BP.

Based on mapping and dating, we modeled the glacial dynamics of the Younger Dryas (Egesen stadial) glacier system and its relation to the prominent landslides (old: Allerød interstadial; young: Preboreal) from the onset of the ice advance to the retreat phase.
Detailed sedimentary evidence allows us to constrain the starting position of glaciers before the Younger Dryas advance, as well as reconstructing a confluence situation of the two local glaciers (Goldbergkees and Pilatuskees), producing a glacier system with a maximum surface area of 10 km^2. Furthermore, distinctive shaped moraine ridges allow us to shed some light on the glacier conditions during stabilization phases during the retreat phases of the Egesen. In addition, surface models revealed a reconstituted glacier geometry for the Egesen-age Goldbergkees.

We employed various methods for calculating Equilibrium-Line-Altitudes (Maximum Elevation of Lateral Moraines, Toe-to-Headwall-Altitude Ratio, Area x Altitude, Area x Altitude Balance Ratio, and Accumulation Area Ratio) and compared them to already available data from western Austria and Switzerland. With this data, we are able to reconstruct temperature and precipitation change of the local climate and glacier dynamics during the maximum of the Younger Dryas in the central part of the European Eastern Alps.

With our multiple-dated Egesen (Younger Dryas) glacier system as a solid basis, we critically discuss the correlation of Lateglacial to Holocene stratigraphy with our study area and other inner-alpine areas, based on high resolution climate archives in the North Atlantic region, which have been targets of palaeoclimate research.

Acknowledgements: Great thanks to the Sonnblickverein, the University of Vienna, the Geological Survey of Austria and the ETH Zurich.

Thresholds in karst catchments: the example of the Lurbach karst system

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Threshold behavior in hydrological systems generally involves a qualitative change of either a single process (process threshold), the response of the system (response threshold), or the functioning of the system (functional threshold) (ZEHE & SIVAPALAN, 2009). The transition from laminar to turbulent flow provides an example of threshold behavior at the process level, which occurs when the ratio of inertial forces to viscous forces (represented by the Reynolds number) exceeds an empirical threshold value. This transition, for instance, occurs in karst aquifers where water flows rapidly through solution conduits, and it is known that it may strongly influence the hydrological response of the springs draining these aquifers. Assessing if and under which conditions this leads to threshold behavior at the response level, however, is not straightforward, as the spring response is governed by the interaction of several processes and flow components. One example of a response threshold is provided by the Lurbach System (Austria) where the sinking stream Lurbach, which under low-flow conditions only resurges at the Hammerbach spring, additionally supplies a second spring, the Schmelzbach outlet, once a given threshold discharge is exceeded. Interestingly, this threshold appears to have changed after a flood event in 2005, presumably because of the plugging of flow paths with sediments or collapse material. Flow duration curves, master recession curves, and the thermal response of the Hammerbach spring have markedly changed since then, suggesting that a sudden qualitative change in the hydrological functioning was triggered by this flood event (functional threshold). This example demonstrates that thresholds in karst catchments are closely connected to geomorphologic processes, such as sediment transport, and climatic factors, such as the occurrence of extreme events.

Acknowledgments: This work was funded by the Austrian Academy of Sciences (project “Global models of spring catchment) and by the Austrian Science Fund (FWF): L 576-N21.

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Serpentinite slices within a tectonic zone at the base of the Juvavic nappe systems (Eastern Alps, Austria): petrography and geochemistry

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Near to Unterhöflein (Lower Austria/Austria) at the eastern margin of the Eastern Alps several tectonic slices of serpentinites occur within a highly tectonised zone composed of schist of the Werfen Formation and different Triassic limestones and dolomites. The tectonic zone is situated at the base of the Juvavic nappe system of the Austroalpine unit. In a similar position basic magmatic rocks are known from several other localities, mostly occuring within evaporitic sediments of the Permian Haselgebirge (GRUBER et al., 1992; SCHORN et al., 2013). Further between the Juvavic nappe system and the underlying Tirolic nappe system tectonic slices of the Meliata unit occur, which represents remnants of the Neotethys oceanic domain (MANDL & ONDREJIKOVA, 1993).

The largest serpentinite body, 400 to 100 meters in size, was investigated by petrological (X-ray diffraction) and geochemical (X-ray fluorescence) methods. The primary mineral composition was olivine + orthopyroxene + clinopyroxene + chromite. Olivine is completely replaced by chrysotile which shows the typical mesh-structures. Some grains of clinopyroxene are preserved, whereas the main part and the orthopyroxene were transformed into lizardite. Within some pseudomorphs after orthopyroxene the former cleavage and twin lamella are visible. Chrome spinel is mostly transformed into magnetite. Further Mg-rich chlorite, talc and hydrogrossular appear.

The mineral compositions of the former peridotites were recalculated by an interative method using a dataset of typical chemical compositions for fresh harzburgite and lherzolite and geochemical analyses of the serpentinites. The results indicate harzburgites as precursor rocks of the serpentinites.

According to SCHORN et al. (2013) the basic rocks from the Haselgebirge represent remnants of the Permian to Lower Triassic rift of the Meliata ocean. However, it is difficult to exhume mantle rocks to the surface with the proposed mechanism without creating a deep marine basin. However, the latter is not indicated by the evaprites and the overlying Triassic shelf sediments of the Juvavic nappes. In any case a relation of the harzburgites to westward propagation of initial rifting of the Neotethys ocean seems to be the most convenient explanation for the investigated rocks.

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Large-Scale Deformation of the Eastern Alps from Seismic Anisotropy

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Internal deformation in the Eastern Alps is documented by seismic anisotropy, and we report here observations from SKS shear-wave splitting. Together with earlier observations from the Western Alps, these observations present one of the clearest examples yet of “mountain chain parallel fast orientations” worldwide, with a stunningly simple pattern of fast orientations, nearly parallel to the trend of the mountain chain. This simple pattern (of deformation) appears to be in contrast with the complex surface geology of the Alps. Regarding the pattern, we make a number of important observations: there are rapid spatial variations of fast orientation in certain parts of the Alps while there is little variation in others. Where fast orientations vary (Western Alps and the Tauern-Window region), they do so with nearly constant spatial rotation rate. In the Eastern Alps, the fast orientations do not “connect” with neighboring mountain chains, neither the present-day Carpathians, nor the present-day Dinarides, but rather with an intermediate orientation.

There is a clear jump of fast orientations across the Tauern Window, by about 45 degrees, somewhat similar to the geometry of the Adriatic indenter. In the very east, where lithosphere is thin, and where we most likely observe asthenospheric anisotropy, the anisotropy is consistent with eastward extrusion toward the Pannonian basin, if we assume that the anisotropy recorded relative motion of the surface with respect to the deeper Earth moving coherently with the Central Alps. An eastward extrusion has been suggested before, based on the pattern of seismicity, surface geology, and more recently geodesy. It appears that much of the deformation associated with the eastward extrusion is accommodated within the asthenosphere. This suggests that the entire lithosphere is escaping to the east, not only the crust.

The origin and age of the metamorphic sole from the Rogozna Mts., Western Vardar Belt: New support for the one-ocean model for the Balkan ophiolites

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This study reports new geochronological and petrochemical data from the metamorphic sole beneath the Rogozna Mts., Western Vardar ophiolite belt. The Rogozna metamorphic sole is located at the base of an Ibar serpentinite nappe and consists of (i) high-grade andalusite–garnet–sillimanite gneisses and cordierite-bearing hornfels (mostly listwanitized), (ii) medium-grade pyroxene amphibolites and hornfels, amphibolites, amphibolite schists and metagabbros and (iii) low-grade micaschists and talc-chlorite schists. Selected samples of the Rogozna amphibolites and talc-chlorite schists were subjected to the electron microprobe, SEM-EDS, $^{40}Ar/^{39}Ar$ analysis and whole-rock geochemistry. The Rogozna amphibolites are medium- to fine-grained rocks with nematoblastic texture and pronounced foliation. They consist of green amphibole (~70 vol.%) with variable silica contents (6.4 to 7.8 Si a.p.f.u.), as well as Mg# (molMg/[Mg+Fe_{tot}]; 0.53 to 0.77) and variably albitized plagioclase (~30 vol.%; Ab_{24}–Ab_{98}). Amphibolites are overprinted by a retrograde assemblage containing actinolite, epidote, clinochlore, sericite, chlorite and magnetite. The amphibolites formed due to metamorphism of two basaltic suites: subalkaline/tholeiitic and alkaline. Subalkaline/tholeiitic amphibolites possess low Zr, Nb, Y, Th, Hf, TiO_2 and P_2O_5 values and a LREE-depleted patterns typical for the N-MORB to BAB (back-arc basalt) origin. Alkaline amphibolites show elevated concentrations of Zr, Nb, Y, Th, Hf, TiO_2 and P_2O_5 with a LREE-enriched patterns typically displayed by ocean island basalt (OIB). Amphibolites crystallized during intra-oceanic thrusting at temperatures between 685 ºC–765 ºC and at a depth of 12–17 km. $^{40}Ar/^{39}Ar$ cooling ages of amphibole range from 165–170 Ma and slightly postdate the sole formation. The Rogozna talc-chlorite schists are related to retrograde greenschist-facies metamorphism after amphibolite facies conditions. They consist of talc (Mg-rich minnesotaite), chlorite (diabantite), serpentine and white mica pseudomorphs after amphibole and MORB-type Cr-Al spinel, surrounded by Al- and Mg- poor ferrit-chromite. The occurrence of ferrit-chromite is related to earlier, amphibolite facies metamorphism. Chlorite pseudomorphs after amphibole were formed at ~415 °C, whereas low-K white mica from the assemblage cooled below the argon retention temperature in a time period of ~95–105±25 Ma. The studied metamorphic rocks of the Rogozna Mts. underlying the Ibar serpentinite massive represent, therefore, typical products of metamorphic sole. The amphibolites are of igneous origin, displaying subakaline/tholeiitic and alkaline geochemical affinities. The protoliths of subakaline/tholeiitic amphibolites originated in a N-MORB or BAB setting. The alkaline group of amphibolites are analogous to E-MORB or OIB and their protolith derived from fragments of seamounts or islands from the lower oceanic plate. Maximum P-T conditions of the formation of the Rogozna Mts. metamorphic sole were 685–765 ºC and 4–6 kbar (corresponding to a 12–17 km thick overburden). The Rogozna Mts. metamorphic sole experienced rapid cooling below the closure temperature of hornblende and actinolite between 164.9±1.3 and 170.0±1.4 Ma. Intra-oceanic thrusting must have started maximum 5 m.y. earlier, between 170 Ma and 175 Ma. The greenschist-type retrograde assemblage was

formed after medium-grade metamorphic conditions at ~415 °C. A weakly constrained Cretaceous age (95 and 105±25 Ma) obtained from white mica within talc-chlorite schists is related to the westward obduction of the Vardar ophiolites over the Adria continental margin.
Data reported in this study clearly suggest that there is no essential difference in the emplacement age of the Dinaric and West Vardar ophiolite belts, supporting the interpretation involving a single Mesozoic ocean in the Balkan sector.

Tectonometamorphic record in the cover sequences of the western Tauern Window, Eastern Alps

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The Tauern Window in the Eastern Alps represent a tectonic window within Austroalpine crystalline nappes. The window is formed by the Venediger (Zentralgneiss) nappe system forming large scale antiformal dome structure with preserved Mesozoic cover sequences. This system is overlain by the Subpenninic nappes (namely Modereck and Wolfendorn nappe and Eclogite zone) distinguished from the rest of the nappes by discrete deformation record. The Subpenninic nappes are overlain by the Penninic nappes represented by the Glockner nappe, Reckner Ophiolitic Complex and Matrei zone.

In the studied area, the Venediger duplex is composed of nappes of late Variscan/Permian Tux Gneiss and Zillertal Gneiss with its post-Variscan (Permo-Carboniferous and Mesozoic) cover sequences (VESELÁ et al., 2011). The Subpenninic nappes in the hanging wall are represented by the Modereck and Wolfendorn nappes which are overlain by the Glockner nappe being part of the Penninic units (SCHMID et al., 2013). The nappes alltogether were previously named as Lower Schieferhülle, Upper Schieferhülle and their P-T conditions of up to blueschist facies were described by SELVERSTONE (1988, 1993).

Our detailed structural and petrological study focused mainly on the cover sequences represented by the post-Variscan cover and Subpenninic nappes and their tectono-metamorphic evolution with respect to the Central gneiss complexes.

The cover sequences consist mainly of schists, amphibolites and quartzites and they show dominant NW-dipping fabric in the northern and central parts of studied area and S-dipping fabric in the western part. The observed stretching lineation plunge to the W-SW. This dominant fabric is subsequently folded by open to tight folds with steep E-W trending axial planes and axes gently plunging to the W. The rocks were later affected by cleavage showing dip-slip kinematics with lineations perpendicular to fold axes.

The overlying Glockner nappe (former Upper Schieferhülle) is composed of deformed greenschists and marbles, which are together folded by large-scale open folds with NW trending fold axes and lineations and steep NW dipping cleavage in fold planes.

The metamorphic overprint observed in the cover sequences is characterized by occurence of garnet. These garnets show decrease in spessartine and sometimes also grossular component, while almandine and pyrope increase towards the rim. The core to rim increase in XMg documents the overall prograde growth of these garnets. An attempt is made to characterize this prograde evolution of a garnet by means of thermodynamic modelling.

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Mobility Within the Subduction Channel: Correlation of P-T-D-t Stages Amongst Tectonic Fragments

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Numerical models of subduction channels indicate that tectonic mixing may be an important process. Opinions diverge with regards to possible origins of fragments, amplitudes of internal mobility, and temporal scales of such mixing processes. Recent work in the Sesia Zone of the Western Alps shows that the HP-evolution was substantially more long-lived and complex than previ¬ously established (e.g. RUBATTO et al., 2011). Significantly different HP-stages have been identified in different slices of the Eclogitic Micaschists Complex (EMC; REGIS, 2012), providing evidence of differential movements of HP-fragments, with subduction- and exhumation-related stages being recorded. The size, geometry, and ultimate provenance of fragments are in the focus of our present research.

We report on methods refined to relate petrochronology to structural data. Detailed analysis of local phase equilibria using X-ray images (XMapTools software) yields local P-T equilibrium conditions; these are combined with in situ U-Th-Pb dating for growth zones in allanite and zircon. Careful microstructural details (e.g. on deformation fabrics, mineral inclusions) and REE-distribution data are used to document an integrated HP-record for single samples. Provided that corresponding time intervals were recorded in several tectonic units, it appears thus possible to correlate HP-stages and deformation.

Results are shown for HP-fragments from several tectonic units in the internal Western Alps, with examples ranging from the eastern parts of the Sesia Zone right across to the Austroalpine klippen units now resting atop Piemonte-Liguria oceanic units:

- In eastern parts of the EMC (Mombarone area) HP-micaschist equilibrated at 1.9-2.0 GPa and 540-550 °C contains allanite dated at 85.8±1.0 Ma; zircon shows rims at ~75 Ma and 70-60 Ma, these reflect growth during decompression, but still at pressures >1.4 GPa.
- Further west (Val de Lys), micaschists from the EMC show a HP foliation (ECL-BLS facies) and weak (GRS facies) retrogression. Several generations of phengite, garnet, glaucophane (±early omphactie) and allanite are distinguished, plus quartz, epidote, chlorite, and titanite (rimming rutile). Growth zones in garnet and allanite correspond to distinct HP stages. Preliminary Th-Pb age data for allanite from in situ LA-ICP-MS analysis show 80-74 Ma for cores and 68-62 Ma for rims. These ages compare well with the two HP stages (HP1: ~75 Ma; HP2: ~65 Ma) REGIS et al. (subm.) found in several samples of the Fondo slice of the Sesia Zone, from which pressure cycling was inferred.
- Leucocratic gneiss from the Glacier-Rafray klippe shows assemblages with amphibole-phengite-epidote-plagioclase-titanite-quartz. Complex growth zoning in phengite allows us to establish a relative, but detailed P-T path. Replacement of phengite by chlorite adds late-stage information. When combined with published P-T data an absolute P-T path can be constructed. Dating of the HP-stage(s) is underway.

The analysis of the fossil continental margin between the Sesia Zone, the Piemonte Zone and the external klippen may have significant implications. Several stages and scenarios for the evolution of this margin need to be reconsidered, from pre-collisional rifting, formation of an OCT zone, through polyphase subductive processes to the juxtaposition of fragments during collision or exhumation.

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Geodynamic and structural controls on the exhumation of Cenozoic metamorphic core complexes: Application to the Alpine-Carpathian-Hellenic orogenic belt

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Metamorphic core complexes (MCCs), particularly Cordilleran-type MCCs, represent typical the thick ductile/viscous material within the middle to lower crust and the mechanically strong upper crust within highly extensional tectonic setting. In the extensional setting, the rheological stratification is particularly the presence of a thick layer of highly ductile material, which results in an upward motion of the viscous material during progressive exhumation. Extensive studies of metamorphic core complexes have highlighted a fundamental problem that the relationship between the mylonitic rocks in the footwall of the ductile low-angle detachment fault at its top, and the brittle-deformed to undeformed hangingwall unit. The exhumed metamorphic rocks typically record a progressive change from ductile to brittle behaviors during decompression. As such, MCCs also reflect highly localized extensional strain on the scale.

As exemplified in the Alpine-Carpathian-Hellenic (ACH) orogenic belt, the exhumations of such MCCs are controlled by several processes including: (1) the retreat of the subduction zone, (2) extensional gravitational collapse of previously shortened lithosphere, (3) continental strike-slip component of tectonic plate movement, and (4) rheological stratification of the extending crust in post-orogenic settings. Our examples mainly include the Naxos MCC in the Aegean Sea, and Rechnitz and Tauern MCCs in the Eastern Alps, which represent Cordilleran-type MCCs. Cordilleran-type MCCs are exhumed virtually parallel to the regional extension direction. Such cases are common in post-collisional settings with extension of previously over-thickened lithosphere, or as in the case of the Aegean Sea, in a back-arc basin setting, which formed due to the retreat of a subduction zone.

Here, we propose a scheme between several possible end-member type cases of exhumation mechanisms of MCCs, e.g., classification of different detachment modes (e.g., rolling hinges, initial low-angle detachment) and contribution of pure-shear vs. simple-shear modes of exhumation. In these cases, upward motion along a detachment (ductile low-angle normal fault) and internal ductile thinning imply gradual exhumation with the youngest exhumation along a rolling hinge at the trailing edge of the MCCs.

Deformational styles at all scales are dominated by extensional structures similar to those documented in numerous MCCs. In all cases investigated by us, the level of the ductile low-angle normal fault is controlled by the presence of thick successions of calcite-dominated lithologies (e.g., calcite marble, calcareous phyllite), which are rheologically weak at low temperatures. These lithologies are overlain by quartz- and feldspar-rich lithologies in the upper hangingwall unit, which remains brittle during deformation. One of the most important meanings to occur in these low grade metamorphism rocks is the new recrystallized assemblage formed the lower the strength of the rock, active representing a matrix-controlled interconnected weak layer rheology. Strain partitioning results in preservation of high-temperature microfabrics, minerals and textures with low-grade mylonitic shear zones. As a result, grain size reduction associated by fluids circulating within shear zones leads to rock softening, which results in strain localization, weak rock rheology and the overall thermal structure of the crust.

Acknowledgements: This work is financially supported by the Austrian Science Fund (FWF)-Lise Meitner program, grant no. M1343 to SC.

Differential compaction and early rock fracturing in the Triassic Esino Limestone high-relief carbonate platform (Central Southern Alps): field evidence and numerical modeling

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Syndepositional fractures are important features in high-relief, steep-slope carbonate systems as they control the occurrence of platform-margin collapse events, drive the generation of early diagenetic fluid flow systems and development of karst networks and may enhance permeability. Studies on modern and fossil carbonate systems recognized the importance of early (syndepositional) fractures, which can be generated by different processes (gravitationally controlled fractures, antecedent-topography controlled fractures, and tectonically controlled fractures).

In this study we focus on the generation of margin-parallel, gravitationally-induced early fractures driven by compaction of basinal sediments prograded by early-cemented high-relief carbonate platforms with steep slopes. Compaction is most effective when brittle early-lithified sediments prograde over unconsolidated basinal deposits.

Numerical models were used to investigate the effects of differential compaction on strain development and early fracturing in early-cemented high-relief carbonate platform, prograding onto basinal sediments, whose thickness increases basinward. Results show that basinal sediment compaction induces stretching of internal platform and slope strata in prograding platforms. When sediments are early cemented, such extensional strain is accommodated by the generation of syndepositional fractures. The amount of stretching is predicted to increase from the oldest to the youngest layers, due to the thickening of the compactable basinal sequences towards the external parts of the platform. Stretching is also controlled by the characteristics of the basin: the thicker and the more compactable the basinal sediments, the larger will be the stretching.

To test this model on a real case, ad hoc computations were dedicated to the Ladinian-Early Carnian carbonate platform of the Esino Limestone (Central Southern Alps, Italy), up to 800 m thick and with a top to basin relief of more than 500 m. This platform, after a prevailing initial aggradational stage, rapidly progrades on thinly-bedded fine-grained resedimented limestones. This case study is favorable for numerical modelling, as it is well exposed and both its internal geometry (inner platform, reef and prograding steep clinostratified slope deposits, consisting of reef-derived breccias) and the relationship with the adjacent basin can be fully reconstructed, as the Alpine tectonic overprint is weak in the study area. Furthermore, rapid early cementation processes affect the carbonate platform facies, so that conditions for creation and preservation of early fractures occurred. Evidence for early fracturing (fractures filled by fibrous cements coeval with the platform development) is described and the location, orientation and width of the fractures measured. The fractures are mainly steeply dipping and oriented perpendicularly to the direction of progradation of the platform, mimicking local platform margin trends.

The integration of numerical models with field data gives the opportunity to quantify the extension triggered by differential compaction and predict the possible distribution of early fractures in carbonate platforms of known geometry and thickness, whereas the interpretation of early fractures as the effects of differential compaction can be supported or rejected by the comparison with the results of ad hoc numerical modelling. The obtained models on generic platforms further indicate that strain induced by differential compaction is strongly geometry- and lithology-dependent.

Subduction flip in the Mediterranean and the asymmetry of Alps and Apennines

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Geological (magmatological and tectonic) observations and numerical models are used to constrain and describe the last 50 Myr evolution of the Central-Western Mediterranean. Both oceanic and continental lithospheric plates were diachronously consumed along plate boundaries with different styles of evolution and polarity of subduction. The hinge of subducting slabs converged toward the upper plate in the double-vergent thick-skinned Alps-Betics and Dinarides. The hinge diverged from the upper plate in the single-vergent thin-skinned Apennines-Maghrebides and Carpathians orogens. The mass deficit caused by the lithosphere retreat was compensated by passive asthenosphere upwelling and by the opening of several back-arc basins. The magmatic evolution of the Mediterranean area cannot be easily reconciled with simple magmatological models proposed for the Pacific subductions. This is due to synchronous occurrence of several subduction zones that strongly perturbed the chemical composition of the upper mantle in the Mediterranean region and, above all, to the presence of ancient modifications related to past orogeneses.

In our reconstruction, the W-directed Apennines-Maghrebides nucleated along the retro-belt of the Alps, following a subduction flip. The origin this process is investigated with 2D thermo-mechanical models. In particular we focus on the influence of mantle flow relative to the overlying lithosphere on subduction dynamics. We obtain that, for mantle flow supporting the slab, as occurred in the Alps, an initial stage of slab steepening is followed by a stage of continuous decrease in slab dip. This slab shallowing eventually leads to mantle wedge closure, subduction cessation and slab break-off, possibly driving to subduction flips.

As a result of the described geodynamic evolution, Alps and Apennines developed highly asymmetric. The Alps have higher morphological and structural elevation, two shallow, slow subsiding foreland basins. The Apennines have rather low morphological and structural elevation, one deep and fast subsiding foreland basin. While the Alps sandwiched the whole crust of both upper and lower plates, the Apennines rather developed by the accretion of the upper crust of the lower plate alone. Alpine relics are boudinated in the hangingwall of the Apennines, stretched by the Tyrrhenian back-arc rifting. Relative to the upper plate, the subduction hinge moved toward it in the Alps from Cretaceous to present, whereas it migrated away in the Apennines from late Eocene to Present, apart in Sicily where since Pleistocene(?) it reversed.

We investigated the origin of part of these asymmetries using 2D and 3D viscoelastic models. In particular we analyzed the dependency of the stress field of slabs and overriding plates on geometry (dip of the slab) and kinematics (velocity of convergence between upper and lower plates and their absolute velocity with respect to the underlying mantle) of subduction zones. We obtain that, although the state of stress in slabs and overriding plates is controlled also by other processes, down-dip compression in the subducting slab and extension in the overriding plate are enhanced by mantle flow opposing the direction of the dip of the slab, whereas down-dip extension in the slab and contraction in the overriding plate are favoured by mantle flow in the same direction of the slab dip (i.e., sustaining it). We conclude that the asymmetry of Alps and Apennines is primarily controlled by the slab polarity with respect to the westward drift of the lithosphere.

Structure and kinematics of the northern Adula nappe (Central Alps, Switzerland) and its emplacement in the Lower Penninic nappe stack

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The Adula nappe belongs to the Lower Penninic domain of the Central Alps. It consists mostly of pre-Triassic basement rocks containing also numerous eclogites. The Adula nappe has the peculiarity to comprise several cover occurrences within the basement. The nature of the deformation experienced by the nappe reveals a complex history with several deformation phases.

The purpose of our study is a better understanding of the Alpine kinematics of the northern Adula nappe with a special focus on the early deformation phases responsible for the nappe emplacement. This study is mainly based on a detailed geologic mapping of several representative key-areas in the Northern Adula nappe. It has been also extended to a multi-scale structural analysis of the nappe at a broader scale.

We recognized that the nappe emplacement is associated with two phases of deformation. The early Ursprung ductile deformation phase is characterized by folds that are compatible with a top-to-the-south shearing. The Zapport phase is partially contemporaneous with the Ursprung phase. It produces the main structural features of the nappe by ductile north directed shear and forms two generations of isoclinal nappe-scale folds. These folds are revealed by a detailed mapping in areas preserved by later deformation. The Zapport phase folds are complex synclines cored by the sedimentary cover at the front of the nappe.

In the Eastern transect of the Central Alps, the Adula nappe and the nappes derived from paleogeographic domains located south of the Adula domain (hyper-extended margin) are mostly emplaced by detachment and basal accretion in the Alpine accretionnary prism. In contrast, the Adula nappe and the other nappes located northward in the paleogeography are derived from a coherent European slab and form fold-nappes. The specific paleogeographic position of the Adula domain at the leading edge of a coherent European slab explains why this unit was subducted to depth sufficient to form eclogites. This leads the Adula nappe to act as a major shear zone during the nappe emplacement.

Two later deformation phases postdate mainly the nappe emplacement. The Leis and the Carassino deformation phases are principally characterized by NW-vergent folds. These deformations affect the nappe front formed during the previous nappe emplacement phases.

Two separated Lower Cretaceous basins in the Transdanubian Range, Hungary and their relation to the Eastern and Southern Alps

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The Transdanubian Range is the only tectonic unit where the original connection between the North- and the South-Alpine facies connection is preserved. The first signal for the stop of the more or less uniform development of the Transdanubian Range occured at the end of the Triassic. In the Bakony Mts continued the deposition of the platform carbonates in the Hettangian while the Gerecse (Eastern part of the Range) has been raised above the sea level at the end of the Triassic, the sedimentation started there in the Late Hettangian. Further on in the Jurassic the successions of the Bakony and the Gerecse Mts are similar. The basin is fragmented by submarine highs in the Early Jurassic. The sedimentation is more or less continuous in the basins while on the highs highly lacunose and condensed. Thanks to the rifting process of the Penninic ocean the tendency in both areas is the deepening till the end of the Middle Jurassic but the subsidence in the Bakony area was quicker than in the Gerecse. The result is that the first area became deep bathyal while the other one only shallow bathial.

Based on the Jurassic and Cretaceous formations in the axial (synclinal) part of the Transdanubian Range the Gerecse Basin is separated completely from the Bakony one in the Early Berriasian albeit the process started in the Late Tithonian already. In the South Bakony the pelagic Tithonian Szentivánhegy Limestone is replaced upward by the Maiolica or Biancone facies (Mogyorósdomb Limestone Fm) typical for the Southern Alps, while in the Gerecse the change is more complicated. In the Eastern Gerecse the Szentivánhegy Limestone is substituted by the Bersek Marl in the Early Berriasian while it lasted in the Western Gerecse until the Valanginian. As a consequence the formation of the Felsővadács Breccia as a product of an event at the boundary of the Berriasian/Valanginian it is found in the Bersek Marl in the Eastern Gerecse and in the Szentivánhegy Limestone in the Western Gerecse.

The result of the Eastward shallowing tendency is that the Berriasian-Hauterivian Mogyorósdomb Limestone is replaced by a crinoideal, ammonite and bivalve-bearing, highly condensed Borzavár Limestone restricted only for the Zirc Basin. The Biancone facies in the Southern Bakony turns into grey marl facies such as in the Karawanken.

The Lower Cretaceous in the Gerecse Mts is dominated by a coarsening upwards flysh type siliciclastic succession similar to the Rossfeld one and in part to the Inner Dinarides.

The two basins must have been united temporalily for the fist time in the Late Aptian when the crinoidal Tata Limestone covered the entire Bakony Mts and the Vértes Foreland and in part the Vértes Mts as well. This limestone is proved to be in the Tatabánya Basin and intercalated in the Lábatlan Sandstone as well.

The two basin separated again in the Early Albian (Austrian tectonic phase) when the whole Bakony Mts and is western continuation has been raised, strongly eroded, katsified and bauxite accumulated, as far as the sedimentation is continued in the Gerecse and in part of the Vértes Foreland. On the Western margin of the Gerecse and partly on the Vértes area restricted basinal facies developed which interfinger with the lower rudisted Urgonian limestone restricted for a few km broad zone only.

The large part of the Albian bauxite is covered by fluvial, lacustrine and later brackish-water – predominantly pelitic and marly sediments (Tés Clay Fm) in the Bakony Mts. The marine invasion came from the Gerecse the northern foreland of which platform carbonate existed since the Berriasian. The Tés Clay is overlain by the beds of the 2nd Urgonian limestone succession which was deepening step by step. In the Late Albian - Cenomanian time the entire Transdanubia Range but at least ist synclinal part has been flooded again thanks to the global sea level rise. After a long period when the fundamental differences between the two part of the Transdanubian Range North-Alpine and the South-Alpine origin ceased.

Late Cretaceous bimodal igneous association of the northern Kozara Mts. revisited: New geochemical data serving for refined geodynamic interpretations

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The recent interpretations suggest that the Sava-Vardar (SVZ) is a relic of the youngest Tethyan realm in the present-day Balkan area, which left behind after Upper Jurassic closure of the West and East Vardar domains. The SVZ supposedly represents the last suture between the Tisza/Dacia and Dinarides acting as upper and lower plate, respectively. One of the best exposed SVZ segments is found on the Kozara Mts. (northern Bosnia and Herzegovina). We here report and discuss new geochemical data on igneous rocks of the northern Kozara Mts. in order to further constrain their geotectonic setting and with special emphasis on the petrogenetical link between the basic and acid rock suite.

The northern Kozara Mts. bimodal igneous association is thrust onto the West Vardar ophiolites of the southern Kozara Mts. and is unconformably overlain by Late Cretaceous-Paleogene fluvial siliciclastic sediments. It consists of isotropic to layered gabbro, diabase dykes and basaltic pillow lavas and hyaloclastites, as well as of relicts of rhyodacite-rhyolite lava flows and extrusions and subordinate small-scale granitoid intrusions representing basic (BS) and acid suite (AS), respectively. We analyzed 13 samples of the BS and 11 samples of the AS on major and trace element concentrations (including rare earth elements – REE) in the ACME Laboratories Ltd. Vancouver (Canada). A vast majority of the studied rocks show silica contents <53 wt % or >64 wt % SiO_2. The BS and AS rocks show different trends on Harker's diagrams with SiO_2 as index of differentiation. Thus, Al_2O_3, P_2O_5 and TiO_2 contents in the BS rocks mostly increase with increasing silica concentrations, while in the AS rocks the opposite trend is observed. On the chondrite- and primitive mantle-normalized diagrams for REE and incompatible trace elements, respectively, the BS rocks show relatively flat to moderately light-REE enriched patterns with no or weak negative Eu-anomaly. The AS rocks exhibit steeper patterns and have distinctively more pronounced Eu- and Sr- negative anomalies. Compared to the known intra-ophiolitic granitoids from the Eastern Vardar Zone, the AS rocks show geochemical similarities to oceanic plagiogranites.

These new geochemical data confirm earlier opinions that the BS rocks of the northern Kozara Mts. neither derived from pure mid-ocean ridge basalts (MORB) nor from volcanic arc basaltic magmas. This conclusion appears to be robust even taking into consideration that most BS rocks crystallized from evolved magmas. Moreover, it is suggested that the BS primary magmas probably correspond more to enriched MORB (or to MORB+EMORB) than to typical ocean island basalts. On the other hand, geochemical characteristics of the AS rocks indicate that their primary magmas most probably originated via partial melting of the altered gabbros from the lower oceanic crust. Main geodynamic implications of our study are, first, that it confirms the oceanic nature of the northern Kozara Mts. rock assemblage, and second, that it could have formed within an anomalous ridge setting similar to present-day Iceland. We therefore challenge previous interpretations that the northern Kozara Mts. ophiolites are relicts of an oceanic plateaux from a wide oceanic area.

Acknowledgements: This study is supported by the Ministry of Science and Education of the Republic of Srpska.

The Meliata and Piemont-Ligurian rifted margins: stratigraphic record and tectonic evolution of polyphase rift systems

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The Late Permian to Late Jurassic paleogeographic evolution of the Alpine domain was strongly controlled by the formation of polyphase rift systems. If these rift systems are the result of a single, long lasting rifting event or if they are generated by two distinct rift pulses is still a matter of debate. Recent studies seem to agree on the second hypothesis, supporting two distinct rift events: one Early-Middle Triassic (Meliata s.l.) and one Early to Middle Jurassic (Piedmont-Liguria s.l.). Nevertheless major incertitude arises on the interpretations of the evolution of the former rifting, which leads to either multiple or one single, continuous ocean branch. This uncertainty is mainly due to the successive orogenic overprint related to the formation of the Alpine belt and of the Western Mediterranean domain. The aim of this work is to explore how rifting events are recorded by the stratigraphic and structural evolution using both the vast existing literature and own observations. Selected areas belonging to different paleogeographic domains in the Alpine realm (Southalpine, Briançonnais s.l. and Austroalpine) will be studied in order to define relevant time-marker levels to map and correlate the temporal and spatial evolution of rift events. With this “basinal” approach we point to major tectonic events, filtering smaller-scale tectonics and minor environmental controlling factors on sedimentation. Our final goal is to identify the “fingerprints” for major rifting events that may enable to map the location and timing of hyper-extended domains. The evaporitic successions, the onset of thick carbonate platforms, their demise or drowning, the iron-manganese hardgrounds sedimentation (that may represent a response of hydrothermal circulation associated with hyper-extension) may correspond to correlable and mappable residues of large-scale rift events. These observations, together with data of the subsidence history, exhumation of basement rocks and magmatic evolution may provide a major, well-constrained framework that can be used to compare the evolution of the Alpine domain with that of present-day rifted margins.

Stratigraphic architecture and correlation of rifting-related deposits of potential conjugate distal margins: the Ligurian Prepiedmont-Piedmont (I) and the Lower Austroalpine (CH)

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Major rifting within the Alpine domain was active since the Late Triassic and led to the exhumation of subcontinental mantle and the formation of an embryonic oceanic domain during Late Middle Jurassic time (~165Ma). The rift history is recorded in several sectors of the Alpine belt, where complete pre- to postrift successions are preserved. These successions record the evolution of different sedimentary basins, showing different architectures and sedimentary evolutions. Today they are preserved in different Alpine domains and at different structural levels in the Alpine nappe pile as a result of the Alpine collision. In this work, we focus on the sedimentary successions of different domains of the former distal rifted margins: those belonging to the Ligurian Prepiedmont and Piedmont domains, outcropping in the Ligurian Alps in Italy (European margin) and those belonging to the Lower Austroalpine exposed in the Central Alps in SE Switzerland (Err, Bernina units; Adria margin). We chose these domains because of the completeness and the correlatability of the sedimentary successions. We aim to test if, with a certain degree of approximation, these areas can be considered as part of a former "conjugate" rift system and if sedimentation shows evidence of continuity along composite sections across these domains. The two margins are characterized by sudden drowning of a Late Triassic to Early Jurassic shallow-water carbonate platform into a Lower Jurassic carbonate ramp. In the Ligurian Prepiedmont the drowning event is dated as Lower Hettangian to Lower-Middle Sinemurian and it is characterized by the deposition of discontinuous condensed deposits (Fe-Mn hardgrounds). This level has a good correlation potential through both the sections. The following external-platform to ramp carbonates deposited in different basins, more or less subsident (e.g. Arnasco-Castelbianco). Locally, they are followed by huge amounts of coarse breccias, fed by the progressive activation of fault-scarps during the ongoing deformation in highly subsiding troughs. At the same time, ramps with moderate gravity flows formed in the areas directly facing the future exhumation zone (i.e. Lencisa, Bardella sections) testifying its progressively deepening trend. The sedimentation was interrupted by successive episodes of condensation, in the Upper Sinemurian and in the Pliensbachian. At the scale of the basin, these events show quite a good correlation considering selected areas. Successively, accommodation space was created especially above the major exhumation fault(s). The portion of the margin closely-facing the exhumation area was dismembered in blocks, (extensional allochthons; e.g. Piz Alv, Piz Bardella) while just above the main exhumation area, a depression formed (outer trough) hosting a composite sedimentation made up of deep water deposits (calcschists) and slices of exhumed serpentinite (Montaldo Unit). Thus, despite of all the complications that may be introduced considering local basin subdivision, the general stratigraphic framework in the two study areas is pretty well comparable and shows a first-order similar evolution of the sedimentation during the initial stage of rifting, beginning to clearly differentiate only after the exhumation stage. In addition, we recognize some new elements for a more accurate stratigraphic correlation of synrift deposits. These data lead us to consider that the studied sections can be approached as "conjugate" domains within an evolving rift system, with a good degree of continuity in stratigraphy and in sedimentological features.

Geochronology of Alpine shear zones in the Mont Blanc region using $^{40}Ar/^{39}Ar$ step-heating and Rb-Sr microsampling techniques

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Timing of deformation in the Mont Blanc massif in the western Alps and the understanding of its structural evolution, especially with regard to its recent exhumation, remains a matter of debate. Ductile deformation in the Mont Blanc region lasted from Oligocene to Late Miocene times, resulting in the development of the Helvetic nappe stack, with the Mont Blanc massif forming a crustal-scale fold-nappe. Generally NW-directed thrusting interacts with dextral transcurrent movements related to the Rhône-Simplon fault along the Chamonix valley and the Val Ferret on the internal side of the Mont Blanc massif. This case study presents geochronological data from 11 sample locations collected at 6 key areas in the Mont Blanc-Aiguilles Rouges region, which represent different stages in the tectonic evolution of the area. The $^{40}Ar/^{39}Ar$ step-heating method on white mica and the Rb-Sr microsampling method on texturally-controlled, µg-sized white mica - calcite pairs in textural equilibrium were applied to samples collected from individual low-grade shear zones with the aim of obtaining direct constraints on ages of deformation from synkinematically grown or recrystallized minerals. The results are critically assessed with respect to cooling versus neocrystallization ages and their assignment to distinct periods of tectonic activity in the Mont Blanc area is discussed. The sampled shear zones are low-grade mylonites and phyllonites and because of their deformation temperatures most of the ages obtained are interpreted to reflect neo-/recrystallization of synkinematic minerals, therefore giving deformation ages. Steep and often conjugate shear-zones in the Chamonix zone between the eastern margin of the Aiguilles Rouges massif and the western margin of the Mont Blanc massif overprint the main Alpine fabric related to NW-directed shear. Ages from such shear zones indicate a change from intensive NW-directed shearing between Mont Blanc and Aiguilles Rouges massifs to more coaxial deformation between the two massifs around 14.5-15 Ma. This is interpreted to be related to a collective updoming of the two massifs from Middle Miocene times. In the Mont Chétif basement slice on the eastern side of Mont Blanc, dextral + E-side up oblique-slip to transcurrent movements dominate, with a tendency toward a stronger strike-slip component with time. Rb-Sr microsampling ages of 27-30 Ma from the Mont Chétif reflect early stages of deformation in the study area in the footwall of the Penninic thrust in Oligocene times, whereas Early Miocene $^{40}Ar/^{39}Ar$ ages (18-20 Ma) from the same sample are interpreted to reflect cooling below the closure temperature of the $^{40}Ar/^{39}Ar$ system of white mica. However, the youngest sample from the Mont Chétif basement yielded a Late Miocene age, suggesting that subsequent folding that overprints the shear zone must have taken place after 9.5 Ma. One age spectrum from Col de la Seigne of 28-35 Ma fits well with Oligocene activity along the Penninic thrust. A NW-verging shear zone between the Mont Blanc granite and Mont Blanc paragneiss, close to Champex-Lac and coinciding with the Faille du Midi, yields ages between 15-20 Ma. The age results provide key time constraints for our new model for the structural and temporal evolution of the Mont Blanc area during the Neogene.

Development of nappe stacking in the eastern Tauern Window with special attention to new Rb/Sr biotite and $^{40}Ar/^{39}Ar$ white mica ages, and peak-temperature data

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The Tauern Window (Eastern Alps) exposes a Paleogene nappe stack comprising European derived units (Subpenninic units) and Penninic units (Glockner, Matrei nappes) below the Austroalpine units. The Subpenninic units form the cores of two domes at the eastern and western ends of the Tauern Window. Our work focuses on the Eastern Tauern Dome where a peak-temperature of c. 612° C was recorded in the core of Subpenninic units and c. 500°C was measured at its rim in contact with the Penninic nappes. Peak temperatures at the contact of the Penninic units with the Austroalpine nappes are ≤ 450°C. Grt-st, grt-bt and bt-wm thermometers yield temperatures in the range of 596 to 630°C, calculated for a mean pressure of 9.2 kbar obtained with the chl-bt-ms geobarometer. These temperatures lasted at least until 25.4 ± 2.5 Ma according to a $^{147}Sm/^{144}Nd$ formational age on garnet that overgrew the main foliation related to nappe stacking but that predates doming.

The Eastern Tauern Dome is itself divided in two smaller domes (Sonnblick, Hochalm) and the intervening tight Mallnitz synform. Reddy et al. (1993) proposed that the Sonnblick Dome cooled earlier than the Hochalm Dome based on distinct clusters of Rb/Sr biotite ages in the cores of the Sonnblick and Hochalm domes. However, when combined with this existing dataset, our new $^{87}Rb/^{86}Sr$ biotite ages point to simultaneous cooling of the domes to below the closure temperature of this isotopic system (300°C). $^{87}Rb/^{86}Sr$ biotite ages decrease from 23-20 Ma in the northwest to 19-16 Ma in the southeast and do not vary in a transect across the Mallnitz Synform. Also, $^{87}Rb/^{86}Sr$ white mica ages range from 30-26 Ma to 25-20 Ma and apatite fission track data young in the same direction. A SE-ward increase in the intensity of mylonitic shearing along strike of the Mallnitz Synform is interpreted to be a manifestation of stretch faulting that was kinematically linked to top-E to–SE directed normal faulting along the central part of the Katschberg Shear Zone System (KSZS, SCHARF et al., 2013). We attribute the SE-ward decrease of the $^{87}Rb/^{86}Sr$ biotite cooling ages to an increased component of tectonic unroofing towards the eastern and southern margins of the Tauern Window. Moreover, new $^{40}Ar/^{39}Ar$ laser ablation data on individual mica grains in a transect oriented perpendicular to the central part of the KSZS yields ages between 31 and 13 Ma in the footwall. Nine samples were analyzed and their microstructural setting brackets the ending of rapid exhumation. The ages lead to the conclusion that ductile shear along the KSZS started sometime before 20 Ma at a temperature of more than 470°C and ended no later than 17 Ma at the contact of the KSZS with the Austroalpine unit above.

The consideration of structures in the Tauern Window combined with our new garnet age constrains duplex formation to have occurred before 25 Ma. Moreover, there is no difference in the cooling histories of the Hochalm and Sonnblick domes, indicating that the Eastern Tauern Dome was exhumed as a single unit during doing and coeval extensional exhumation in the footwall of the KSZS. Shearing along the KSZS started no later than 20 Ma and ended at about 17 Ma. The onset of rapid cooling related to fast exhumation is still poorly constrained, but probably began no earlier than 21 Ma according to stratigraphic criteria in the Giudicarie Belt of the Southern Alps (SCHMID et al., 2013).

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Jurassic to Early Cretaceous basin evolution of the northern Transdanubian Range: structural influences of two oceans

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The northern Transdanubian Range (TR), Hungary occupied a paleogeographical position between the Neotethys and Alpine Tethys during the late Jurassic and early Cretaceous. Structural events in the two oceanic domains strongly controlled the basin evolution.
We used field structural measurements, mapping, sedimentological and stratigraphical analysis to date the succession, reconstruct the basin geometry and structural evolution. To place structural data in Alpine frame, an 80–50 counterclockwise Cenozoic rotation should be considered.

Jurassic basin evolution started with differentiation of the Triassic carbonate platform in the Sinemurian. Syn-sedimentary dykes and faults prove extensional deformation related to early rifting events of the Alpine Tethys. The direction of extension was NNE–SSW at present position. Different Jurassic successions indicate map-scale faults: WNW–ESE trending normal, and N–S striking transfer faults with oblique-slip. As the revival of Early Jurassic faulting, nodular “Ammonitico rosso” and Bositra limestones deposited in syn-sedimentary half-grabens.

In geodynamic models, late Middle to Late Jurassic times were marked by the subduction of the Neotethys Ocean. For the TR, such models would mean N–S to NE–SW directed compression. However, direct structural observations indicate extensional or transtensional deformation. Observations can be consistent with a model that Late Jurassic extension could form on the bended part of the slab subducting to N or NE. The obducting Neotethyan oceanic crust and related nappes thrust over this downbended slab.

Long-lasting carbonate sedimentation stopped in the late Berriasian. The following Valanginian to Aptian basin evolution was dominated by clastic input from the approaching Alpine–Carpathian–Dinaridic nappe pile containing Neotethyan ophiolite and accreted passive margin rocks. The subsidence of the basin was caused by the increasing load of the emerging orogenic wedge. The TR remained on the southern side of this flexural basin during the Valanginian-Hautrivian. The instable slope was deformed by large slides with northern or north-eastern vergency. The more southerly located forebulge was marked by strongly reduced carbonate sequence.

In the Barremian to Aptian coarse clastics dominated over the marl deposition. Sedimentation took place in form of submarine fans. The orogenic wedge approached but still did not reach the TR clastic basin. After sedimentation ceased, the northern TR was gently folded and faulted by N–S or NE–SW compression in the earliest Albian.

As a major change, the whole TR was deformed by NW–SE compression. Large-scale NE-trending folds and thrust faults were completed from Albian to Coniacian (113–86 Ma). As part of this phase, the TR thrust over different Alpine nappe units and integrated to the Austroalpine system.

This structural evolution suggests that the TR changed completely its structural position: it was on the lower plate in the Jurassic–early Cretaceous and became the highest unit in the “Mid-Cretaceous” phase. This needs a major reorganisation of the subducting and overriding plates. We follow earlier suggestions that a major strike-slip fault operated during this time. The large shift placed the TR and its Neotethys-related foreland-type Early Cretaceous basin in the rear of the subduction, in the highest position.

Acknowledgements: The research was supported by the grant OTKA K 68453.

Late Miocene depositional units and syn-sedimentary deformation in the western Pannonian basin, Hungary

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The Pannonian Basin system is due to late Early to Mid-Miocene lithospheric extension and related crustal faulting between 19 and 11.6 Ma. The faults bounded more or less isolated sub-basins with few hundred meters of marine sediments while the intermittent basin highs were marked by a reduced sedimentation or erosion.

At the beginning of the Late Miocene, the sedimentation has been changed and the brackish Lake Pannon developed. Between 11.6 and 9.7 Ma the former basin highs were progressively inundated and the surface and volume of the lake increased. Since 9.7 Ma onwards clastic input via extensive fluvial networks progressively filled the lake, large scale normal regression took place.

Late Miocene deposition pattern, facies relationship and coeval structural geometry and kinematics, as well as their influence on sedimentation was studied by the help of surface structural, sedimentological and palaeontological observations, by 2D and 3D seismic reflection data sets. Our research extended into the Transdanubian Range (TR), the largest high in the Miocene, and sub-basins W, S and SE of it.

The transgressive phase resulted in in a spatially variable facies pattern. Deep lacustrine marls of large thickness accumulated in the deep sub-basins and condensed marls in the less than 100 m deep waters covering the basement highs. This lithofacies is characteristic along the western margin of the TR during 9.5–9 Ma. The clastic input reached the western Pannonian basin from the NW and N. As rivers entered the lake deltas of ca. 20–50 m thick coarsening upwards successions were formed. These shelf deltas prograded towards basin-margin-slopes of several hundred meters high in the deep sub-basins, and also towards flooded basement highs where slopes were missing. Deltas were prograding across both type of areas, but above deep basins deltaic successions has a large thickness, while on highs a reduced sequences.

Systemathic mapping of shelf-to-basin clinoforms clearly indicate the influence of basement highs which deflected slope progradation into a direction sub-parallel to highs. These basement highs were partly inherited from the syn-rift deformation, however, seismic sections clearly demonstrate active syn-sedimentary faulting during the transgressive phase and partly during slope progradation, ca. between 11.6 and 8.5 Ma. Fault-controlled abrasional gravels and fault breccias are found along the margins of TR, were most likely coeval with the flooding of highs and and might have occurred between 9.5 and 8.8 Ma. Surface measurements suggest an E–W to ESE–WNW extensional (transtensional) stress field in agreement with seismic fault mapping. South from the TR, thickness of basinal marls decreased above E–W trending active transpressional ridges between ca. 12 and 9 Ma. After the ceasion of deformation during slope progradation between 9 and 8 Ma, growing of E–W trending anticlines started from 8 Ma. However, regional subsidence counterbalanced anticlinal growth and deltas overstepped folds.

Acknowledgements: The research was supported by the grant OTKA K 81530, Hungarian Horizon and MOL Plc. companies.

Garnet systematics of a polymetamorphic basement unit: Evidence for coherent exhumation of the Adula Nappe (Central Alps) from eclogite-facies conditions

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The Adula Nappe in the Central Alps is derived from the former continental margin of the European Plate that was subducted beneath the Adriatic Plate during the Alpine orogenic cycle. It consists of pre-Mesozoic basement (various gneisses with layers of garnet-micaschist, and bodies of mafic and locally of ultramafic rocks) and few Mesozoic cover rocks. High-pressure and ultra-high-pressure conditions are preserved in eclogite and ultramafic rocks but are apparently not recorded in the gneisses that build up the bulk of the nappe. It is unclear whether the unit constitutes a tectonic mélange that is compiled of rocks with different Alpine PT histories or wether it represents a coherent unit that was subjected to eclogite facies conditions as a whole. Within the nappe, eclogite-facies conditions and post-peak pressure amphibolite-granulite-facies conditions display increasing peak temperatures between 500 °C and >750 °C from north to south.

We present Lu-Hf garnet ages and detailed garnet chemistry of eclogite samples from several locations throughout the Adula Nappe. Samples from the central Adula Nappe are characterised by the presence of two populations of garnet. A first generation yields a Variscan Lu-Hf age and a second one an Alpine (Late Eocene) age, a result already established at the locality Trescolmen and here shown for more locations. In eclogites from the southern Adula Nappe, Alpine metamorphic conditions completely reequilibrated Variscan assemblages and garnet reveals exclusively Eocene Lu-Hf ages. In contrast, garnet is almost unaffected by Alpine metamorphism and is consistently of Variscan age in the northern Adula Nappe. Hence, the degree of Alpine metamorphic overprint and an associated re-equilibration of the Lu-Hf system is maximal in the southern part of the unit and decreases towards the north. Isotopic ages are in line with microstructural observations and major-element maps of garnet. Element maps display fully equilibrated garnet in the southern Adula Nappe, i.e. garnet with a homogeneous composition due to diffusive reequilibration during Alpine metamorphism. In the central nappe, relicts of an older, partly reequilibrated Variscan garnet generation are overgrown by a second Alpine generation with perfectly preserved prograde zoning and no diffusive overprint at all. Towards the north, the Alpine generation becomes less abundant and is absent in the northermost eclogite sample.

Eocene garnet ages are about the same through the entire nappe, 35-38 Ma. This and the continuous gradient of Alpine metamorphic overprint in high-pressure assemblages strongly suggest that the Adula Nappe essentially remained coherent during Eocene high-pressure metamorphism and exhumation despite very intense deformation. The gneissic host rocks of eclogites very likely experienced the same high-pressure metamorphic conditions but did not completely equilibrate, and later re-equilibrated during exhumation (see also abstract by KURZAWSKI et al., same volume).

A review of magmatic zircon ages from the Rhodope Metamorphic Complex: tectonic implications

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The Rhodope Metamorphic Complex is a stack of thrust sheets assembled during a protracted history of tectonic deformation during the Mesozoic and Cenozoic. Most studies on the geology of the Rhodope Metamorphic Complex (including the Rhodope Massif and the Serbo-Macedonian Massif) are regional investigations and address local problems. As a result the number of local nominations and tectonic subdivisions made large scale tectonic interpretations difficult. JANAK et al. (2011) proposed a simplified tectonic subdivision, merging all the known units of the Rhodope Metamorphic Complex into four super units (allochthons), namely the Lower (LA), Middle (MA), Upper (UA), and Uppermost Allochthon (UMA).

Due to the scarcity of distinctive lithologies, geochronological characterization is particularly important and the amount of data is rapidly increasing. The majority of zircon U/Pb ages obtained by conventional ID-TIMS, SHRIMP or LA-ICP-MS from orthogneisses, amphibolites, and metagabbros rather date protolith formation than metamorphism. Another important group of zircon ages comes from syn- to posttectonic plutons that crosscut the metamorphic section and thus can also be used as reliable markers for the restoration of the geodynamic evolution of the Complex.

We review the available zircon age data in the framework of the allochthon subdivision scheme. In the LA, alpine granitoids are less than 34 Ma old and postdate stacking of the nappe pile. The MA additionally contains Late Cretaceous (70 - 65 Ma), Late Paleocene-Early Eocene (57 – 53 Ma) and Middle-Late Eocene (46 - 37 Ma) granitoids. Tertiary and Late Cretaceous granitoids are also found in the UA. Orthogneiss protoliths in the LA are mostly Variscan/Late Variscan (319 to 270 Ma) with a few older samples. In the MA, this age group occurs as well but most are 164 to 136 magmatic arc granitoids. In the western part of the UA (Vertiskos, Ograzhden), 460 to 432 orthogneiss protoliths occur. In the eastern Rhodopes both Variscan and Jurassic protoliths occur in units presently attributed to the UA (Kimi, Kardzhali units) but these series may also contain parts of the MA. Protoliths of mafic rocks are around 570 Ma (UA), 470 to 430 (UA and MA), 312 - 253 Ma (UA and MA), and ca. 160 Ma (MA, UMA).

The age distribution provides constraints for the paleogeographic reconstruction. It is compatible with a model where the units were stacked by Late Cretaceous to Palaeogene southwestward thrusting, the UA representing Europe, the LA Apulia, and the MA comprising elements of the Vardar Ocean (160 Ma ophiolite), adjacent magmatic arcs (Late Jurassic granitoids), and possibly Pelagonian continental and Pindos-Cyclades oceanic crust. The UMA comes from the Vardar Ocean and associated arcs as well but was thrust towards north onto Europe already in the Late Jurassic to Early Cretaceous.

Acknowledgements: This research was supported by the Bulgarian National Science Fund, grant № DMU-0358.

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Distinguishing different generations of deformation structures by structural and magnetic fabric analyses: examples from the Central gneiss (Tauern window) and Tschigotgranodiorite (Eastern Alps)

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The classical methods of structural geology prove the polyphase tectonometamorphic history of rocks mostly relying on relationships between different generations of foliations, lineations and folds. In schists and paragneisses due to their varied and finer grained composition, the relationships between different generations of foliations and lineations are easier to define. In contrary, the monotonous and coarse-grained orthogneisses make this task more complicate and it is often difficult to distinguish between different generations of structures.

The anisotropy of magnetic susceptibility (AMS) is a standard method for structural investigations of undeformed and deformed igneous, sedimentary and metamorphic rocks. In deformed rocks and shear zones AMS can reveal the position of the finite-strain axes. In such cases the principal axes of the magnetic ellipsoid ($K_{max} \geq K_{int} \geq K_{min}$) are in agreement with the X, Y and Z strain axes (i.e. with the stretching lineation and mylonitic foliation). On the other hand the magnetic lineation (K_{max}) can parallel the intersection of two different planar fabrics. In these cases the pole to the magnetic foliation (K_{min}) coincides with the mylonitic foliation pole (Z axes) but the other two axes of the magnetic ellipsoid K_{max} and K_{int} can differ from X and Y strain axes.

We have studied two different orthogneiss bodies, the Central Gneiss of the Tauern Window and the Tschigot Granodiorite, hosted by the Texel Unit. Both orthogneisses belong to units which underwent a polyphase tectonometamorphic evolution. On outcrop and sample scale the studied rocks show strain partitioning and intensive deformation being localized in cm to decametre wide shear zones. While the sheared parts are characterized by a strong and coherent mylonitic foliation, intensity of deformation varies significantly in the surrounding rock. Within the shear zones there is perfect agreement between the AMS and structural data. There Kmax and the measured stretching lineation are parallel and the pole of Kmin fits the pole of the mylonitic foliation. The less deformed parts are more complicated due to the presence of different generations of competing foliations and lineations. By combining structural and AMS data we distinguish between different foliations and lineations some of which are not observable at outcrop scale. Thus, some lineations which due to the field observations were assumed as stretching lineations, after the interpretation of AMS data are reinterpreted as intersection lineations. The latter is the intersection of either two macroscopically defined foliations or a macroscopically defined foliation and an optically invisible but magnetically defined foliation.

The parallelism between magnetic and field structures in the shear zones shows that the intensive shearing fully overprints and reorients the preexisting structural and magnetic features. In less deformed orthogneisses combination of structural and AMS data can be used to decipher macroscopically undetected penetrative features and thus to detect different generations of deformation.

Acknowledgements: This research is funded by Autonome Provinz Bozen-Südtirol, Project title: The potential of AMS (Anisotropy of Magnetic Susceptibility) studies in polyphase deformed rocks.

Early exhumation of the Aiguilles Rouges and Mont Blanc massifs, European Alps

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Although the exhumation history of the external crystalline massifs of the European Alps has been studied in detail, little is known about the timing and kinematic of the initiation of exhumation. Here we present new zircon fission track, apatite fission track and apatite (U-Th-Sm)/He data from the central Aiguilles Rouges massif, collected from the NW prolongation of the densely sampled Mont Blanc tunnel transect. This profile together with another densely sampled profile through the NW Aiguilles Rouges and Mont Blanc massif along the Rhône valley are used to investigate the (early) exhumation history of the Mont Blanc and Aiguilles Rouges external crystalline massifs. We use a variety of methods with increasing complexity and parameterisation to infer the exhumation history: (i) the age-elevation approach, (ii) transdimensional inverse thermal modelling, (iii) 1D thermal-kinematic modelling, and (iv) state-of-the-art 3D numerical-kinematic modelling (Pecube).

Age-elevation relationships yield apparent exhumation rates of ≤0.05 km/Myr between 230 and 23 Ma, increasing to ≥0.4 km/Myr since 15 Ma. The low slope of >23 Ma old zircon fission track ages is interpreted to be the result of prolonged stay within the partial annealing zone during burial due to nappe emplacement. The timing of initiation of exhumation most likely happened between 23 and 15 Ma. Transdimensional inverse thermal modelling results further suggest that burial due to nappe emplacement must have occurred rapidly during less than 10 Myrs. According to 1D thermal modelling exhumation of the external crystalline massifs initiated before 20 Ma at rapid rates (~1 km/Myr) and decreased before 10 Ma to moderate rates (~0.4 km/Myr). 3D thermal kinematic-modelling reveals that the thermochronological data are best fitted with a burial/exhumation scenario with rapid burial (~0.6 km/Myr) from ~33 Ma to ~20 Ma followed by rapid exhumation at ~1.3 km/Myr until 10 Ma and final exhumation at ~0.6 km/Myr up to present. Modelling further reveals a strong gradient in burial and early exhumation normal to the orogen, whereas burial/exhumation rates are lowest in the external Aiguilles Rouges massif and approximately half as much as in the Mont Blanc massif.

Deciphering the driving forces of short-term erosion in glacially impacted landscapes, an example from the Western Alps

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Tectonic uplift is the main driver of long-term erosion, but climate changes can markedly affect the link between tectonics and erosion, causing transient variations in short-term erosion rate. Here we study the driving forces of short-term erosion rates in the French Western Alps as estimated from in-situ produced cosmogenic 10Be and detrital apatite fission-track thermochronology analysis of stream sediments. Short-term erosion rates from 10Be analyses vary between ~0.27 and ~1.33 mm/yr, similar to rates measured in adjacent areas of the Alps. Part of the data scales positively with elevation, while the full dataset shows a significant positive correlation with steepness index of streams and normalized geophysical relief. Mean long-term exhumation and short-term erosion rates are comparable in areas that are exhuming rapidly (>0.4 km/Myr), but short-term rates are on average two-three (and up to six) times higher than long-term rates in areas where the latter are slow (<0.4 km/Myr). These findings are supported by detrital apatite fission-track age distributions that appear to require similar variations in erosion rates. Major glaciations strongly impacted the external part of the Alps, increasing both long-term exhumation rates as well as relief. Based on our data, it seems that glacial impact in the more slowly eroding internal part is mainly restricted to relief, which is reflected in high transient short-term erosion rates. The data further reveal that normalized steepness index and ridgeline geophysical relief are well correlated with (and could be used as proxies for) short-term erosion, in contrast to slope, corroborating studies in purely fluvial landscapes. Our study demonstrates that climate change, e.g. through occurrence of major glaciations, can markedly perturb landscapes short-term erosion patterns in regions of tectonically controlled long-term exhumation.

Dating Alpine brittle deformation with hydrothermal monazite

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Alpine clefts (open fissures) are tectonically formed cm- to meter-sized voids that become filled with hydrothermal fluid. Interaction of cleft-filling fluid with wall rock results in mineral dissolution/precipitation, alteration of the wall rock, and repetitive crystallization of minerals on the cleft walls. Dating monazite from such clefts thus provides a possibility to attribute an age to an exhumation-related brittle structure. Moreover, unlike thermochronometers, the ^{232}Th-^{208}Pb system of monazite is not affected by diffusion and yields a crystallization age.
Two cleft monazites and minerals from the cleft wall have been studied using an electron microprobe at the University of Copenhagen. U-Th-Pb isotope analyses of monazite were subsequently performed on a Cameca IMS1280 SIMS instrument at the Swedish Museum of Natural History (Nordsims facility).

Deformation in the study area located in the Baltschieder Valley, Aar Massif, Switzerland, has been subdivided into three main events: (D1) main thrusting including formation of a new schistosity; (D2) dextral transpression; and (D3) local crenulation including a new schistosity. The two younger deformational structures are related to a subvertically oriented intermediate stress axis, which is characteristic for strike slip deformation. The inferred stress situation is consistent with observed kinematics and the opening of such clefts. Therefore, the investigated monazite-bearing cleft formed at the end of D2 and/or D3, and dextral movements along NNW dipping planes.

The two investigated, millimetre-sized hydrothermal monazites from a late D2 cleft are characterised by high Th/U ratios typical of other hydrothermal monazites. Despite mineralogical changes in the cleft wall, the bulk chemistry of the system remains constant at the decimetre scale. Thus the mineralogical changes require redistribution of elements via a fluid over distances of a few centimetres. ^{232}Th/^{208}Pb monazite ages are not affected by excess Pb and yield growth domain ages between 8.03 ± 0.22 Ma and 6.25 ± 0.60 Ma. These crystallization ages are younger than ^{40}Ar/^{39}Ar ages obtained on white mica from ductile shear zones of the Aar Massif in the Grimsel area and younger than ^{40}Ar/^{39}Ar-dated 13.7 ± 0.1 Ma to 11.0 ± 0.1 Ma old phyllonites (mylonites) outcropping near Baltschieder. Monazite crystallization in brittle structures is in this case coeval or younger than 8 Ma old zircon fission track data, and hence occurred at temperatures below 280°C.

Mesozoic stratigraphy and general structure of the Julian Alps (eastern Southern Alps, NW Slovenia)

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The study area is part of the zone of overlap between the Southern Alps and the Dinarides. This zone is to the north bounded by the Periadriatic Fault and extends south to the South Alpine front, where the Southern Alps are in a direct thrust contact with the

External Dinarides. The Sava Fault, a branch of the Periadriatic fault system, separates the Julian Alps from the South Karavanke Mountains and the Kamnik-Savinja Alps.
The Julian Alps have classically been subdivided into the Tolmin nappes and the overlying Julian nappes. The Tolmin nappes consist of three superposed E-W trending south-vergent nappes. The sediments are typically deeper marine (shale, chert, pelagic limestone, calcareous turbidites) from the Middle Triassic volcano-sedimentary succession up to the Campanian-Maastrichtian flysch. These Mesozoic rocks exhibit a considerable thermal overprint.

The Julian nappes originated from various paleotopographic units that started to differentiate in the Late Carnian. Small scale half-grabens did exist in the Middle Triassic but the entire area was then uniformly covered by the Schlern Formation. From bottom to top (and from NW to SE) we distinguish three major tectonic units. (1) The Tamar Nappe is characterized by Upper Carnian to Rhaetian carbonates rich in organic matter and chert nodules. (2) The Krn Nappe has the largest areal extent and mainly consists of the Dachstein limestone. Middle Jurassic deposits are cherts and calcareous turbidites or condensed Rosso Ammonitico limestone. (3) The Pokljuka Nappe is composed of deep-water Upper Triassic to Lower Cretaceous deposits. The most distinguishing stratigraphic unit is the Valanginian-Hauterivian flysch-type deposits that suggest a correlation with relatively internal tectonic units of the Northern Calcareous Alps and Dinarides. The Zlatna Klippe in the central part of the Julian Alps is structurally well differentiated but stratigraphically less distinctive, because it is composed only of the Schlern Formation and older rocks. Its position on top of the Krn Nappe suggests that the Zlatna Klippe is part of the Pokljuka Nappe.

The Julian nappes are dissected by parallel reverse faults oblique to the Sava Fault. Fault-propagation folds are the most commonly observed structures along these faults. The NE-SW striking faults east of the Vrata-Trenta line are characterized by SE vergent folds, whereas the folds and the steepened beds west of this line have the same orientation but the opposite vergence. South of Bohinj, i.e. closer to the Tolmin nappes, the faults are NW-SE trending and the associated folds are S to SW vergent. This pattern suggests an overall pop-up structure and CW rotation of internal smaller-scale fault blocks. A number of later normal faults have been observed, with down throw ranging from a few meters to several hundred meters.

The three-stage Paleogene to early Neogene deformation history, generally postulated for the eastern Southern Alps, is well recognized in the Julian Alps. The Dinaric phase was characterized by nappe emplacement, presumably towards west, perpendicularly to the orogen. During the Insubric transpressional phase, doubly-vergent reverse faults and CW rotation of fault blocks characterized the rheologically stiffer Julian nappes. At the same time the entire stack of the Julian nappes may have been transported southward on top of the Tolmin nappes and individual slices of the Tolmin nappes were imbricated. The subsequent short-lasting extensional phase near the end of the Early Miocene caused subsidence along steep normal faults in the Julian nappes and exhumation of the deeply-buried Tolmin nappes.

Magnetic susceptibility and spectral gamma ray stratigraphy of the Tithonian – Berriasian limestones in the Carpathians of Poland and Hungary – paleoenvironmental implications

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Magnetic susceptibility (MS) reflects para- and ferromagnetic mineral content in sedimentary rocks and is often applied as a correlation tool and, integrated with geochemical methods, as a useful palaeoenvironmental proxy. Field gamma ray spectrometric measurements determine the content of radionuclides: ^{40}K, ^{238}U and ^{232}Th. Integrated MS and spectral gamma ray (SGR) logs are presented from several marine pelagic sections of Tithonian – Berriasian age from the Carpathian area of Poland (Tatra Mts, Pieniny Klippen Belt) and the Pannonian Basin (Transdanubian Range, Mecsek Mts). All sections are reliably dated by calpionellid stratigraphy. Sections in the Tatra Mts, and the Transdanubian Range are additionally calibrated with magnetostratigraphy. MS in the Polish sections correlate well with K, Th, Al, Ti and other lithogenic elements and therefore might be used as a measure of lithogenic influx into basins. MS low that occurs in the lower to middle Berriasian (magnetozones M18r to M17r) correlates with high sea level, while MS highs in the upper Tithonian/lowermost Berriasian (M20r to M19n2n) and upper Berriasian (M16n) match the low sea level. High sea level coincides with a slight oxygene deficiency evidenced by elevated U/Th ratio. Some second order changes might be interpreted as climatic events; for example subtle MS increase within M17n which might represent humidity increase. The same interpretation might be applied for the section studied in the Mecsek Mts (Tisza unit) which encompasses most of the Berriasian. Sections in the Transdanubian Range reveal a different MS pattern without significant MS contrasts around the Jurassic/Cretaceous boundary. These results suggest that instead of the eustasy, the climatic conditions might have been the main factors controlling MS and SGR signal in the studied sections.

Acknowledgements: The project was performed and financially supported within a frame of Hungarian – Polish bilateral cooperation 2011-2012, Methodology of magnetostratigraphic correlations in the Jurassic-Cretaceous sediments of Carpathians in Poland and Hungary).

3D Modeling of the Fribourg Area - Western Swiss Molasse Basin

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This study focuses on the structural style of the western Swiss Molasse Basin near Fribourg (west of Bern, Switzerland). We are elaborating a 3D geological model with Move Software (Midland Valley) covering an area of 1700 km2 around the city of Fribourg. Based on 2D seismic line interpretations and deep borehole data (SOMMARUGA et al., 2012) three dimensional seismic horizons are built. Horizons correspond to the following stratigraphic boundaries: Near Base Tertiary, near Top Late Malm, near Top Early Malm, near Top Dogger, near Top Lias, near Top Trias, near Top Muschelkalk and near Base Mesozoic. Surface bed dip data from the Geological Atlas 1:25'000 (swisstopo) are included so as to improve orientations of geological strata. Fault surfaces in Tertiary and Mesozoic cover as well as in Pre-Mesozoic basement rocks are constructed based on seismic interpretations (SOMMARUGA et al., 2012), geological cross-sections (Geological Atlas 1:25:000, swisstopo) and hypocenter positions (VOUILLAMOZ & ABEDNEGO, in prep.). Due to the lack of continuous seismic reflectors in Tertiary Molasse sediments, an appropriate mapping of fault structures in the latter is difficult. As a consequence Mesozoic fault surfaces are extrapolated through Tertiary Molasse sediments based on mapped surface fault structures (Geological Atlas 1:25'000, swisstopo; IBELE, 2011). 3D seismic horizons are depth converted based on a 3D heterogeneous P-velocity model of the Fribourg area (ABEDNEGO, in prep.).

The model shows a kinematic decoupling of Tertiary and Mesozoic units along a detachment horizon in Triassic evaporites. A second decoupling can be observed along the base Tertiary horizon in the south of the study area, probably linked to the thrust front of Subalpine Molasse. East of the city of Fribourg, several N-S-striking, en echelon type normal faults in Mesozoic and Tertiary units can be observed. Faults form a zone of 20 km length from N to S. The zone is called the “Fribourg zone”. Faults root in listric bends within middle Triassic evaporites forming a graben or half-graben structure. Triassic evaporites show an important thickening beneath the Fribourg zone. Mapping of fault structures at surface give evidence for left-lateral reactivation of the Fribourg zone under the NW-SE compressional stress field in Neogene times. Correlation of mapped structures does not indicate the presence of large scale fault surfaces exceeding a length of 1 – 3 km (IBELE, 2011). The location of fault traces between 2D seismic lines is speculative in the central part of the Fribourg zone due to a gap of seismic data. Recent studies on present earthquake activity show an enhanced recurrence of low magnitude earthquakes (ML 0 to 4.3) along the Fribourg zone (VOUILLAMOZ & ABEDNEGO, in prep.; KASTRUP et al., 2007). It is therefore proposed, that the Fribourg zone is formed by an assemblage of multiple small scale fault surfaces rather than a few large scale faults. The Fribourg zone forms the eastern border of a N-S striking, low amplitude syncline, called the “Fribourg structure”. The N-S-alignment of the Fribourg structure deviates from the overall NE-SW trend of fold axis in the region. Triassic evaporites show a thinning beneath the Fribourg structure.

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The Gran Paradiso massif: an upside down lower crust?

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At the structural top of the Gran Paradiso (GP) orthogneiss dome, on its W- and NW-margins, seemingly layered or, at any rate, strongly flattened formations comprise greenstones, quartzites, as well as Al-rich whiteschist seams (BERTRAND, 1968). From their peculiar mineral assemblage, including margarite and magnesiochloritoid, CHOPIN (1977) inferred a premonitory estimation of ~1 GPa peak-pressure for the Alpine metamorphism of a part of the Internal Crystalline Massifs (ICM), i.e. Monte Rosa and GP. Soon after (CHOPIN, 1984), his seminal discovery of >3 GPa coesite in Dora Maira (DM, next ICM massif to the S) was from a chemically similar rock, again associated to metagranites, alike the GP whiteschist layers. In both cases, from the Al,Mg-rich chemistry those authors invoked a sedimentary origin, either as a bauxite or as an evaporite level. However this hypothesis of an upper crustal origin has been questioned. SCHERTL & SCHREYER (2008), based on geochemical investigations, have proposed instead that those whiteschists would have been leucophyllite shear zones inside the granites, secondarily metasomatized at depth.

Underlying DM coesite-units to the E, the conglomeratic Pinerolo unit is analogous by its position and by its rock-types to the conglomeratic Money unit that underlies the GP orthogneiss dome. Both metaconglomerate units were unaffected by eclogitization. Overlying DM as well as GP, eclogitized metamafic units (VZSFO = Mt.Viso and Zermatt-Saas-Fee Ophiolite) comprise subordinate calcschists. VZSFO are in their turn tectonically overlain by Combin-type units composed of dominant calcschists and subordinate ultramafic rocks. All those ultramafic-bearing units were classically supposed to be of oceanic origin, representing the Jurassic Piemont Ocean.

Protolith age data comprise mostly Permian to Late Upper Carboniferous ages (310 to 265 Ma) for the orthogneiss (BERTRAND et al. 2005). This is also the radiometric age range for the Ivrea mafic body, a verticalized, Permian, lower crust wedge. The Gneiss du Charbonnel Formation, consisting of interlayered felsic levels of unknown origin in the VZSFO, nearby GP massif, also yielded zircons of Permian age, as is also the case for the Lanzo peridotites. Gabbros of the latter Lanzo zone yielded Jurassic ages (KACZMAREK et al. 2008), correlated to the radiolarite ages at the base of the calcschists, and representing the age of the oceanization (MOHN et al., 2010).

A suggested vision of the ICM would hence them to be an upside down Permian crust of S-Alpine origin representing a lateral equivalent to the Ivrea body. More speculatively, parts of the presently overlying eclogitized mafic units of the VZSFO might represent parts of their related upper mantle. Thin marble levels previously considered as Triassic deposits, between GP and VZSFO, might instead represent layered lower crust remnants.

Abundant zircon crystals found in the Al,Mg-rich whiteschist of western GP margin are presently being investigated, regarding their age(s) of crystallization as well as their mineral inclusions. Field data might also help better defining the relationships of the GP whiteschist with its host-rocks.

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Evolution and reactivation of basement highs at hyper-extended rifted margins: the example of the Briançonnais domain in the Alps and comparisons with modern analogues

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The development of new reflection and refraction seismic techniques enabled to image the crustal architecture of deep-water rifted margins. The new data show that in addition to the classical tilted blocks rifted margins are formed by a large variety of different types of crustal blocks/structures, including micro-continents, continental ribbons, H-blocks and extensional allochthons. This large variety of structures suggest a complex rheological, thermal, and subsidence history of rift systems that is recorded by the tectonic, magmatic and sedimentary processes occurring during rifting. Since rifted margins may eventually be reactivated and become part of an orogenic system, understanding their rift architecture may also be a key to understand the final structure of internal parts of collisional orogens. Distal parts of rifted margins are often at deep-water and sealed by thick post-rift sediments, which makes that these highs are difficult to drill. That's why we combine the study of seismic sections with that of field analogues exposed in the Briançonnais domain in the Alps. Mapping the pre-Alpine and Alpine structures of this domain and properly define their stratigraphic and tectonic evolutions provide important insights into the tectonic evolution of distal rifted margins during their formation and subsequent reactivation.

The Briançonnais domain forms the most distal part of the European margin. In contrast to the Adriatic margin that was the focus of many studies investigating the architecture and evolution of the Jurassic margin, much less is known about the structure and evolution of the conjugate Pre-Piemontais/Briançonnais domains. To better understand their evolution during rifting, we reviewed the existing structural, stratigraphic and age data of these domains from Liguria/Italy, across the French Alps to Grisons in Switzerland. We propose new constructed sections across the Briançonnais domain that forms the basis to discuss the rift-related tectono-stratigraphic and subsidence evolution of this domain. This study will enable to compare the along and across strike stratigraphic architecture of the Pre-Piemontais/Briançonnais domains and to compare them with those made at seismic sections imaging deep-water rifted margins (e.g. Campos (S-Atlantic), Newfoundland (N-Atlantic) and eastern Indian margin).

The first results show that the principal Alpine structures in the Briançonnais domain reactivated mainly pre-Alpine structures. The structural evolution and the change in vergence across the Briançonnais domain are likely controlled by the crustal architecture of the former rifted margin. The stratigraphic architecture and its relation to basement structures within the Pre-Piemontais/Briançonnais domains suggest the abrupt juxtaposition of crustal domains of different crustal thickness with strong lateral changes of the top basement architecture. These relations are very similar to that observed along present-day rifted margins. This complex, 3D architecture of the European margin may have played an important role for the distribution of post-rift sedimentary systems as well as for the reactivation of the European margin during the Alpine convergence.

Internal structure of cataclastic faults along the SEMP fault system (Eastern Alps, Austria)

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In this study three different sites along the ENE-trending, sinistral Salzach-Ennstal-Mariazell-Puchberg [SEMP] fault zone were investigated with respect to brittle fault zone evolution and fault re-activation. All sites crop out in Triassic carbonates (Ladinian Wetterstein limestone/ -dolomite). Simultaneously (re-) activated faults were investigated with focus on fault-slip data and structural inventory of each individual fault zone.

Configuration of (internal) structural elements, fault core thickness, strike direction and slip sense in addition to particle analysis of fault core cataclasites add up to three different fault types (Fault type I, II and III).

Fault type I is classified by a complex internal fault core structure with thicknesses up to several 10s of meters and generally evolve in a strike direction of maximum shear stress (τmax). Type II faults, characterized by cataclastic fault cores with thicknesses up to 1m, as well as type III faults (thin solitary cataclastic layers) evolve sub-parallel to the main fault direction and in orientation according to R, R' or X shear fractures with variable (σn / τ) ratio.

Progressive development from type III to type II and type I faults is consistent with increasing displacement and increasing fault core width.

Fault type classification and related paleostress analysis provides evidence from field observation compared to theoretical and analogue models of Mohr-Coulomb fracture evolution.

Changing fluid chemistry during continuous shearing in cataclastic fault zones along the SEMP fault system

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Brittle fault rock samples from carbonate shear zones along the Salzach-Ennstal-Mariazell-Puchberg fault system (SEMP) have been analysed using cathodoluminescence microscopy (CL), microprobe analysis and stable isotope composition. The combination of these analytical methods provides an insight into comminution processes and fluid chemistry. The reconstruction of the evolution of fluid chemistry leads to a chronological classification of five fluid phases with respect to fluid chemistry, CL behavior and related structural processes. Initial cataclasis is accompanied by dedolomitization processes along crystal borders and intragranular fractures derived by Ca-rich fluids (Phase P1). Subsequent fluid phases (P2-P5) are characterized by variable Fe- (and Si-content) and therefore variable CL behavior.

Microprobe element mappings support the discrimination of Fe-enriched, non luminescent phases and Ca- and Mn-enriched fluids with bright luminescent calcite precipitations. Fe-enriched carbonates and Fe-hydroxide precipitation indicates fluid circulation in deeper parts of the stratigraphic sequence. These fluids are assumed to be derived from underlying clastic sequences of the Werfen Formation. Stable isotope signatures (δ13C and δ18O) indicate mainly meteoric origin of penetrating fluids and variable amounts of fluids in the fault zone.

Oligocene and Neogene tectonic processes in the southeastern Alps and northwestern Dinarides: constraints from new (U-Th-Sm)/He apatite ages

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The AlDi-Adria project aims at deciphering the late-stage orogenic evolution for the northern edge of the Adriatic microplate, i.e. the Friuli orocline and its surrounding regions by a combination of structural studies, subsidence analysis and low-temperature thermochronology. Results will form the base for studying the large-scale surface response to deep-seated lithospheric processes, a number of which have been debated for the study area, e.g. slab break-off, slab delamination, orogenic shortening and lateral extrusion. First results from apatite (U-Th-Sm)/He dating (AHe) in combination with existing apatite fission track age constraints allow us to derive some regional patterns of deformation and exhumation in the Southalpine units/Dinarides and phases of fault movement along the PAF. Here, we discuss those constraints on tectonic processes from old to young events.

Only very limited low-temperature thermochronological data are available south of the Periadriatric Fault (PAF). Oligocene AHe ages were derived for samples from the inner portions of the External Dinarides (Fužine). Similar ages were found even in the southernmost Austroalpine units (e.g. the Reifnitz tonalite). Together, these ages are interpreted as belonging to a regional scale deformation event, which caused large-scale low-amplitude folding due to shortening mainly directed to the stiff interior of Adria. The PAF was also initially activated during this stage. Tonalites intruded into the eastern PAF during Early Oligocene (ca. 34 to 32 Ma; GENSER & LIU, 2010) forming a zone of weakness immediately activated as fault zone.

A major phase of dextral shear along the PAF is indicated by cooling ages of ca. 16 to 20 Ma, attributed to lateral extrusion of the Eastern Alps (e.g., RATSCHBACHER et al., 1991). A new Ar-Ar biotite age of 19 Ma from a mylonitic gneiss from the PAF near Kupitsch with a similar age corroborate this phase of exhumation and deformation.

We find latest Miocene/Pliocene AHe ages of ca. 7 – 5 Ma Ma for an Oligocene tonalite just north of the easternmost Periadriatic Fault. Similar ages were recently reported from the Lavanttal fault by WÖLFLER et al. (2010) and ascribed to fault activity and hydrothermal fluid circulation causing rejuvenation. Since our samples do not show any alteration fabrics we interpret them to indicate final uplift, which is supported by the young relief in this area: To the north, the Klagenfurt basin has been overridden by the Karawanken Mountains during Pliocene-Quaternary times. Formation of the Sava fold belt in the south is also of similar age. A denser network of low-temperature data is needed to refine these preliminary patterns and more results from ongoing apatite fission track and AHe work will be presented.

Acknowledgements: We acknowledge funding of the AlDi-Adria project by the Austrian Science Fund (FWF, grant no. P22,110).

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Mapping the transition between the eo-Alpine HP-nappe system and the Ötztal-Bundschuh Nappe system using garnet zoning types and geothermobarometry

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The investigated area is situated west of the Penninic Tauern Window directly at the already proposed transition between the Ötztal Nappe as part of the Ötztal-Bundschuh Nappe System and the Schneebergzug as part of the Koralpe-Wölz high pressure Nappe System. Aim of this study is to compare garnet major element zoning linked with pseudo-sections from different types of metapelites to be able to distinguish between polymetamorphic and monometamorphic units. Polymetamorphism means combinations of Variscan, Permian and eo-Alpine events which are related to the Ötztal Nappe (Variscan and Eo-Alpine) and the Texel Complex (Varsican, Permian and Eo-Alpine). Monometamorphism means eo-Alpine and is related to the Schneeberzug. Texel Komplex is together with the Schneebergzug part of the Koralpe-Wölz high pressure Nappe System.

Two main types of pre-Alpine garnet zoning patterns in the cores, type-1 and type-2 and two main types of eo-Alpine garnet zoning in the rims, type-3 and type-4 have been observed. Type-1 shows typical prograde zoning with decreasing XGrs (Grs30 to Grs8) and bell-shaped XSps patterns, as well as increasing XAlm (Alm60 to Alm70) and XPyp (Prp5 to Prp12) from the inner core close to the rim. Type-2 is characterized by homogeneous contents of XGrs (Grs8-10), XAlm (Alm70-75), XPyp(Prp10-15) from the inner core close to the rim. The rims of the porphyroblasts show two different garnet zoning types with significantly higher XGrs and can be distinguished into: type-3 with a small jump in XGrs (from Grs10 to Grs25), in XAlm (Alm75 to Alm60) and in XPrp (Prp15 to Prp10) and type-4 with a higher jump in XGrs (from Grs10 to Grs30), in XAlm (from Alm75 to Alm55) and in XPrp (from Prp15 to Prp5). Type-4 comprises a large garnet volume with a continuous decrease in XGrs (Grs30 to Grs20) and a continuous increase in XAlm (Alm55 to Alm65), and in XPrp (Prp5 to Prp10) towards the outermost rims.

To estimate the P-T conditions of pre-Alpine and eo-Alpine garnet growth, grossular-, almandine- and pyrope isopleths were calculated with the program Theriak Domino. The intersections of the isopleths yielded 0.7-0.9 GPa and 550-650°C for the pre-Alpine type-1 and type-2 garnets and also 0.8-0.9 GPa and temperatures from 550 up to 600°C for the eo-Alpine type-3 and type-4 garnets.

First approaches of this study support Variscan followed by an eo-Alpine metamorphic imprint and exclude a Permian HT/LP event.

Strain localization history of the Simplon Fault Zone: How far can we look back?

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Large-scale shear zones localize deformation, where with progressive exhumation old initial deformation fabrics are continuously overprinted under changing physico-chemical conditions. The study of such meso- to micro-scale structures provides the key for unraveling the retrograde geological evolution. When looking at these structures in the high strain parts, the question arises, up to which former stage these features still can be preserved, i.e. how far back in time can we look? To answer this question, we combine quantitative microstructural analyses in mylonitic quartz veins, with Ti in quartz geochemistry and thermochronological modeling on samples collected along vertical profiles across the Simplon Fault Zone(SFZ, SW-Switzerland).The SFZ is a major mid- to upper crustal shear zone accommodating substantial amounts of orogen parallel extension.

With increasing proximity to the fault plane (FP), dynamically recrystallized quartz grain sizes in the footwall decrease from a few mm (2-4 km away from FP) to sizes as small as 10-20 micrometers (a few meters away from FP). Along with this grain size reduction, dynamic recrystallization processes change from grain boundary migration, over subgrain rotation to bulging recrystallization. These variations indicate continuous strain localization, with decreasing temperature conditions and increasing flow stresses. Despite these trends, in close vicinity to the FP recrystallized grain sizes in different quartz veins show a considerable spread and all three recrystallization processes are found in different veins. When measuring Ti contents in these quartz veins, they are always high in the more distant parts but decrease the closer the sample is located to the FP. Similar to the quartz microstructures, the Ti concentration also shows a considerable spread near the FP, covering the entire range from highest to lowest Ti values. Ti in quartz geothermometry yields temperatures from 530°C down to 350°C. How is it possible that ‘high-T’ and ‘low-T’ microstructural and geochemical signatures can occur in samples just a few millimeters apart from each other, but all located in the most intensely deformed parts of the SFZ?

The answer to this question is synkinematic quartz veining combined with selective strain partitioning. All mylonitic quartz represents former, synkinematic quartz veins that formed during different episodes of the long lasting deformation history of the SFZ. At the time of their formation, their Ti uptake is in equilibrium with the fluid, reflecting the geochemical conditions of vein formation. Due to the inefficient resetting of the Ti concentrations under retrograde deformation conditions, the formation temperatures are largely preserved. In terms of the quartz microstructures, the timing and amount of overprinting of initial structures by subsequent deformation stages depends on the amount of strain accommodated in the gneissic matrix and its variation in space and time. In this sense, some of the early-formed quartz veins preserve an old stage of dynamic recrystallization, while others are completely overprinted by younger low temperature deformation (e.g. small grain sizes, bulging recrystallization). Whether the veins are old or young can be inferred from the Ti in quartz signature. It follows that even in the very high strain part of major shear zones, a careful combination of microstructural and geochemical analysis allows us to look far back into the temporal evolution of such a shear zone, with the potential to thereby obtain improved, high-resolution information on the spatial and temporal evolution of retrograde shear zones.

New geochemical data of Badenian volcanic rocks from south Pannonian Basin in Baranja, Eastern Croatia

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Investigated area is situated in the south part of the Pannonian Basin in Baranja province (Eastern Croatia). This abstract presents new geochemical results of volcanic and pyroclastic rocks, collected during the investigations in Baranja through preparing of Basic geological map of Republic Croatia (scale 1:50 000).

Investigated volcanic rocks (lavas) and pyroclastic rocks that include tuffaceous breccias and crystallovitrophyric tuffs are collected from three localities: Popovac, Vračevo and abandoned Batina quarry. Field evidence suggest polyphase magmatism which is evidenced by Badenian sediments that overlie lavas and by dykes cutting Badenian limestones (Begovac quarry). In Batina quarry volcanic and tuffaceous breccia are overlain by sub-horizontal beds of Quaternary loess. K-Ar measurements on volcanic rocks gave 13.8 and 14.5 Ma.

Volcanic rocks and magmatic fragments of volcanic and tuffaceous breccias (Batina quarry) are composed of plagioclase, olivine and clinopyroxene phenocrysts set in the groundmass of glass, microlites of phenocrystic population and accessory apatite, ilmenite and magnetite. Clinopyroxene and olivine microlites may be pseudomorphosed by chlorite and serpentine, respectively. Amygdules are filled by calcite and chlorite.

Volcanic rocks have SiO_2 ranging from 52.58 wt.% to 57.64 wt.% and Na_2O+K_2O content of 4.97-5.83 wt.%. They are dominantly sodium rich (Na_2O/K_2O = 2.1-5.5). In the TAS diagram they show subalkalic affinity and plot in the field of basaltic andesites and andesites. In the diagram K_2O – SiO_2 they show calc-alkaline to high-K calc-alkaline affinity. The lavas are moderately fractioned in the term of Mg# and Cr content (50.1-61.3 and ~ 110 ppm, respectively) but are very depleted by Ni (< 20 ppm) suggesting olivine + spinel fractionation. Rounded fragments of basaltic andesites from the volcanic breccias are characterized by lower K_2O, HFSE and REE, and higher Cr and Ni contect with regard to the basaltic andesite and andesite lavas.

All lavas show moderate enrichment of LREE over HREE [(La/Lu)cn = 5.41-8.38] at ~ 86 times chondrite relative concentrations. Negative Eu anomaly (Eu/Eu* = 0.77–0.95) indicates early feldspar fractionation at low pressure. The spider diagram normalized to N-MORB values shows an inconsistent secondary LILE enrichment. Negative anomaly of Nb-Ta relative to La is well pronounced [(Nb/La)n = 0.41-0.48] as well of other HFSE which is typical of subduction zone magmas.

However, although the chemistry of Badenian calc-alkaline basalt-andesite rocks in Baranja is similar to those of the recent orogenic and subduction related areas, the origin of their primary magma should be linked to post-orogenic geotectonic environment typical for continental margin (back-arc) rift-basin. Thus, the geotectonic setting of Baranja volcanic rocks harmoniously complements initial extension phase of Neogene geodynamic evolution of Pannonian Basin proposed by many authors. The Pannonian Basin is interpreted as post-colision continental back-arc basin which extended during the Miocene due to uplift the upper mantle diapirs that caused strong trancurent faulting. This allows the differentiation of the Basin in several small pull apart rhomboidal depression. Calc-alkaline basaltic to basaltic andesite magmas, which may fractionated to andesitic and/or dacite and rhyolite extrusives, erupted along weakened tectonic zones of the basinal depressions.

Middle and Upper Triassic slope and basin carbonates along the Neo-Tethyan (Meliata) margin (NE Hungary): facies and paleoenvironmental interpretation

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The studied area, the Aggtelek-Rudabánya Hills (NE Hungary) is part of the Silicic nappe system of the Inner Western Carpathians. In the Triassic pre-rift stage (from ?Middle–Late Permian to Middle Anisian) the evolution of the area was uniform, however, during the Neotethyan synrift stage in the Early-Middle Anisian the Steinalm carbonate ramp broke up, creating three different tectonostratigraphic units: the pelagic Bódva Unit, the Szőlősardó Unit representing slope sedimentation and the Aggtelek Unit where the carbonate platform building continued until the Late Norian. During the time period between the Middle Anisian and Rhaetian different types of carbonate rocks were deposited on the slopes and in the basins of these units: 1) greyish pink bedded limestone that suffered multiple phases of brecciation, 2) red, nodular, cherty limestone with purple-red shale intercalations, 3) grey to red bedded limestone with stromatactis structures, 4) the Massiger Hellkalk and Hangendrotkalk Members of the Hallstatt Formation and 5) grey, cherty beds of the Pötschen Formation.

Within the framework of the current study sedimentary and microfacies analyses were conducted regarding the Middle and Upper Triassic slope and basin carbonates of the three units, including resampling and revision of important drilling cores, detailed geological mapping of the surface outcrops and thin-section analysis. The next step in the near future will be the Conodont-biostratigraphical revision of important, yet not dated cores and profiles as well as stable isotope and other instrumental analyses.

The aim of the work is to create a modern and comprehensive facies model for the different rock types thus to gather additional data related to their paleoenvironment and paleogeographical position, clarify the similarities and differences between the different formations and try to correlate the Hungarian examples to the Austrian ones. A future goal is to use these newly acquired data and interpretations to help understand the otherwise very complex structural system and tectonic movements of the Aggtelek-Rudabánya Hills by determining the original relative position of the tectonostratigraphic units.

Inside the Gurktal nappes – A modified tectonic and lithostratigraphic concept

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The Gurktal nappes represent a part of the Austro-Alpine superunit. They extend over the geographic region of the Gurktal Alps, located in the southern part of Austria (Styria, Carinthia) and form an area of around 4000 sqkm. Historically the Gurktal nappes are a key area in understanding of Alpine tectonics where nappe-stacking has been early mentioned (HOLDHAUS, 1921). Studies of several authors followed during the 1920s to 1950´s (e.g. SCHWINNER, THURNER, STOWASSER, TOLLMANN, BECK-MANNAGETTA) giving base-descriptions of rock types and lithological units. During the 1970´s to 1990´s (e.g. PISTOTNIK, VAN GOSEN, NEUBAUER, FRIMMEL, LÖSCHKE, KRAINER) the view on the Gurktal nappes was expanded by works on lithostratigraphy, tectonics (NEUBAUER & PISTOTNIK, 1984), petrology, geochronology and structural geology. Hitherto a synthesis is missing.

Tectonically the Gurktal nappes are part of the Drauzug-Gurktal nappe system (Thesaurus-Redaktionsteam/GBA, 2013) and represent the uppermost/top tectonic unit of the Upper Austro-Alpine nappes, underlain by the Ötztal-Bundschuh nappe system to the W and by the Koralpe-Wölz nappe system to the N, E and SW. The lithologies are composed of Palaeozoic metavulcanites and metasediments as well as mica-schists and gneisses, transgressively overlain by Carbono-Permo-Mesozoic (meta-) sediments. Based on new comments on the Lithostratigraphic Chart of Austria (Volume 1 – Palaeozoic Era (them) – HUBMANN et al., 2013) a lithostratigraphic model for the Gurktal nappes can be shown. In this context we discuss the conceptional idea of a classification in lithodems and complexes (lithodemic units). Comments on the Geological Map of Salzburg 1:200.000 (PESTAL et al., 2009) and the succession of tectonic units in the Gurktal nappes (Thesaurus-Redaktionsteam/GBA, 2013) give evidences for a modified tectonic model. From substratum to top, indicated by metamorphic grade, age and rock characteristics six nappes can be divided: a group of basal mica-schist nappes, the Murau nappe, the Phyllonite zone, the Pfannock nappe, the Stolzalpe nappe and on top the Ackerl nappe. The geologic/tectonic evolution can be divided in two main events: A Variscan event during Carboniferous indicated by white mica Ar/Ar-cooling ages, followed by an Eoalpine event during Cretaceous times. Several data in the Gurktal nappes and surrounding areas show that this part of the Alpine orogen formed the upper plate during nappe-stacking in an orogenic wedge during Eoalpine subduction with a normal metamorphic gradient and maximum conditions at (upper-)greenschist-facies.

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Viscous overthrusting versus folding: 2D numerical modeling and application to the Helvetic and Jura fold-and-thrust belts

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The geometry of the Helvetic and Jura fold-and-thrust belts has been studied in detail since more than 100 years. However, the dynamics of the combined folding and thrusting are still incompletely understood. Two types of nappes have been described in the Alps: fold nappes and thrust nappes. While fold nappes are characterized by continuous sedimentary layers that can be traced back to their root (parautocthonous), thrust nappes exhibit a basal thrust (allochtonous). Detailed mapping in the Alps has shown that the tectonic style can vary laterally from fold to thrust type. Moreover thrust planes in the Helvetic nappe system and in the Jura are often folded and thrust nappes often exhibit considerable internal ductile deformation. It has been proposed that the pre-Alpine stratigraphy, especially the alternation between shales (weak) and limestone (strong), control the tectonic style of the nappes in the Helvetic and Jura fold-and-thrust belts.

We use 2-D numerical simulations of viscous flow to simulate the layer-parallel shortening of a strong viscous layer embedded in a weak viscous matrix, and above a flat detachment plane. A thin weak zone exists initially in the layer representing an initial discontinuity (e.g. thrust plane). We investigate systematically the control of (1) the ratio of the layer thickness to the matrix thickness (between the layer and basal detachment), (2) power-law versus linear viscous rheology and (3) the viscosity ratio between layer and matrix, on the deformation style. When the matrix is linear viscous, only thickening or folding of the layer occurs. When the matrix is power-law viscous (n=5), deformation occurs mainly by folding when the thickness ratio is >~1 and the viscosity ratio is >~10. Overthrusting of the layer occurs when the viscosity ratio is >~100 and the thickness ratio is <~1. Both overthrusting and folding can occur simultaneously for thickness ratios >~1 and viscosity ratios >~50.

Our simulations show that overthrusting is mechanically possible during dominantly viscous flow. The results support the interpretation that many structures in the Helvetic and Jura fold-and-thrust belt resulted from an effectively and dominantly ductile deformation. The results further show that for the same rheology but varying thickness ratio the deformation style can vary from folding-dominated to overthrusting-dominated, which is in agreement with observations in the Helvetic and Jura fold-and-thrust belts.

Orogen-parallel exhumation and topographic gradients east of the Tauern window: a possible clue for shear strength at depth and intra-orogenic raft tectonics

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The interplay of indentation by the Southalpine indenter, surface uplift and exhumation of the Tauern window characterizes the post-collisional Late Oligocene to recent evolution of the central sectors of the Eastern Alps. Strong Miocene E-W extension, basement subsidence in the Pannonian realm and surface uplift in the Tauern window area created an E-W topographic and exhumation gradient allowing the brittle upper crust to move along the mid-crustal ductile decollément level towards the east. The purpose of this study is to estimate the critical topographic angle of the brittle upper crust to move along the basal viscous layer. Subject of research is the area between the viscously behaving Penninic zone of the eastern Tauern Window and the brittle-behaving Austroalpine basement units with its Neogene basins on top. We use published apatite fission track (AFT) and (U-Th)/He data from two sections of the Hohe Tauern to the east to constrain the E-W exhumation gradient. We also consider partitioning of translation of the Austroalpine crust by ca. ENE-trending orogen-parallel Oligocene faults separating the Hohe Tauern from the Northern Calcareous Alps, respectively the combined Hohe Tauern/Niedere Tauern block from the Nock/Gurktal/Murau Mts. domains. For comparison, we include an E-W section along the southern Northern Calcareous Alps and sections along the SEMP and Mur fault zones. Assuming a thermal gradient of 30 ºC/km, we find a similar gradient of ca. 0.04 for both basement sections. This low gradient is close to a gradient typical for viscous material with low shear strength. These relationships imply that gravitational collapse alone might be sufficient to explain the eastward motion of the brittle Austroalpine crust over a thick viscous layer. Flow above a low-friction viscous layer also explains the eastward tilting of blocks like the Saualpe and Koralpe blocks along antithetic high-angle normal faults. Together, the area east of the Tauern window could be explained by intra-orogenic raft tectonics.

Deformation within a subduction channel at eclogite facies conditions and consecutive exhumation: The Eclogite Zone of the Tauern Window, Austria

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Many recent models for the exhumation of subducted oceanic crust assume corner flow in a subduction channel and exhumation of the very dense metabasites, i.e. eclogites, within a buoyant melange of serpentinites or metasediments. The Eclogite Zone of the Tauern Window represents a paleo-subduction channel in the Eastern Alps, which formed during the subduction of the Penninic ocean beneath the Adriatic continent in the Tertiary. It comprises metasediments as well as large metabasite lenses. Since serpentinites are very rare and occur only in small patches in the western Tauern Window, the metasediments are likely to be the buoyant medium for the exhumation of the eclogites. The Eclogite Zone was exposed to P/T-conditions of 20 - 25 kbar and 600±30°C and exhumed in a very short time span of 1 - 2 Ma. Most of the deformation of this rapid exhumation was presumably concentrated in the metasediments almost exclusively displaying the retrograde mylonitization. This is due to the rheological weakness of gneisses, schists, and marbles in comparison to the metabasites. In addition, the large strains required for exhumation caused a penetrative amphibolite to greenschist facies overprinting. Although only weakly deformed, the metabasites show almost the complete deformation history comprising localized eclogite facies shear zones and the whole amphibolite to greenschist facies deformation sequence during exhumation. The foliation consistently dips to the SSE with 70-85° demonstrating the long-standing operation of this shear plane orientation. However, the omphacite stretching lineation plunges SW, while the hornblende stretching lineation is WSW-plunging to sub-horizontally W-trending.

The structural field mapping is completed by microstructural analyses and crystallographic preferred orientation (CPO) measurements. The variable foliation intensity corresponds to a wide range of CPO intensities. In eclogites indicative of dynamic recrystallization of omphacite and garnet, omphacite exhibits a pronounced CPO. Weaker CPOs of other eclogite samples reveal strain gradients and localized deformation. Occasionally, the hornblende CPO mimics the omphacite CPO arguing for a static overprint. In contrast, differing omphacite and hornblende CPOs indicate ongoing deformation during exhumation. The metasedimentary rocks show a strong mica foliation with a pronounced muscovite CPO. The quartz CPO in the metasediments indicates simple shear deformation with top to the NE sense of shear.

From the mineral CPOs and particular elastic moduli and volume fractions, the CPO-related contribution to bulk rock elastic anisotropy was estimated. P-wave velocity distributions of the eclogite samples exhibit rather low anisotropies of 1-2 %, which are mainly caused by the omphacite CPO. The growth of retrogressed mineral assemblages, specifically hornblende, causes a slight anisotropy increase up to 3 %. P-wave anisotropy of the paragneisses approximates 7 %. It is mainly caused by the muscovite CPO, because the minimum velocity parallels the foliation normal. In metasediments containing only very small amounts of muscovite the elastic anisotropy is around 5 % and mainly caused by the quartz CPO.

From the compilation of all these data comprehensive information on the internal architecture, elastic anisotropy, accumulated bulk strain and strain partitioning within the Tauern Window subduction channel is expected. A more detailed model of subduction channel deformation may result, which could be compared to already existing models.

Alpine metamorphism in the continental Etirol-Levaz slice (Western Alps, Italy) – Insights from petrological, thermodynamic and geochronological investigations

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The Etirol-Levaz slice in the western Valtournenche of Italy is a continental fragment trapped between two oceanic units, the eclogite-facies Zermatt-Saas Zone in the footwall and the greenschist-facies Combin Zone in the hanging wall. It has been interpreted as an extensional allochthon derived from the Adriatic continental margin and stranded inside the Piemont-Ligurian oceanic domain during Jurassic rifting. The slice consists of pre-Mesozoic high-grade gneisses, micaschists and metabasics which have been overprinted under eclogite-facies conditions during Early Tertiary Alpine subduction. We analyse metabasic and metasedimentary rocks in terms of their chemical and mineral compositions and focus on mafic eclogites of which two samples are dated with the Lu-Hf geochronometer. Distribution maps of major bivalent cations in garnets are used to identify zonation patterns and to distinguish between different garnet generations.

Eclogites generally consist of the assemblage garnet + omphacite ± epidote ± amphibole ± phengite ± quartz. In one sample, garnets have compositions of Alm52-61 Grs18-41 Prp5-22 Sps0.5-2 and display typical growth zoning. Some garnet grains are brittlely fractured, strongly corroded and overgrown by epidote. Amphibole occurs as a major phase in the matrix and shows a progressive evolution from glaucophane in the core to pargasitic hornblende towards the rim. Amphibole grains are often truncated by epidote veins. Another sample shows a particular Ca-rich bulk composition (18.3 wt% Ca) and displays two distinct garnet generations. Perfectly euhedral cores show compositions of Grs42-45 Alm47-51 Prp3-6 Sps2-7 and typical prograde growth zoning. These cores are overgrown by irregularly shaped rims characterised by an initial rise in Mn and the Fe-Mg ratio. Omphacite in this sample with jadeite-contents of 19-28 mol% apparently has been fractured and annealed by jadeite-poor (7-12 mol%) omphacite suggesting brittle behaviour at eclogite-facies conditions or brittle deformation between two high-pressure stages.

We constrain pressure and temperature conditions for prograde, peak and retrograde mineral assemblages using equilibrium phase diagrams. Preliminary results suggest that high-pressure rocks of the Etirol-Levaz slice record equilibration at different metamorphic stages along a single Alpine metamorphic cycle. We also use thermodynamic modelling of mineral growth during prescribed PT paths to unravel the significance of observed garnet zonation patterns. Application of Lu-Hf geochronometry is used to further constrain the timing of Alpine high-pressure metamorphism in the Etirol-Levaz slice.

New constrains to the Mesozoic structural evolution of the Inner Western Carpathians achieved by metamorphic, structural and age data

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A complex thin-skinned nappe pile of the Inner Western Carpathians was studied in the central part of the Rudabánya Hills, NE Hungary. A new structural model and evolution were suggested on the basis of structural, metamorphic petrological, geochronological and paleontological data.

The investigated nappes derive from the Neotethys Ocean and its attenuated continental margins and built up by Triassic and/or Jurassic sedimentary rocks. The flysch-type, fine to coarse-grained sedimentary sequence of the Telekesoldal nappe (Meliata nappe system) has evidenced for Bajocian-Callovian sedimentary age (~160 – 170 Ma) and low-grade metamorphism (1.5-2.5 kbar and 300-350°C). The Torna nappe system built up by Triassic sedimentary cover rocks of an attenuated continental crust suffered low-grade overprint with 3-4.5 kbar and 300-350°C, corresponding to 10-15 km of burial. This tectonic burial resulted in S0-1 foliation in both tectonic units. Because of their very similar early deformational history (D1 foliation, D2 folding, D3 kink-type folding) and metamorphic degree, it is supposed that their tectonic contact is a pre-metamorphic nappe contact. Newly obtained K-Ar ages put a time constraint of 142 – 113 Ma for D1 phase.

The metamorphosed, deformed and exhumed Meliata and Torna rocks were emplaced onto non-metamorphic Triassic to Jurassic series (D4 phase). Outcrop- and map-scale structures refer to NW-SE shortening and southeast-vergent nappe emplacement.

Later, the metamorphosed over non-metamorphosed tectonic couplet was thrust again onto the metamorphic Meliata nappe system along E-W striking thrusts (D5 phase). Thrusting associated with reworking of the previous nappe contacts and map-scale F5 folding. Fold vergency indicates southward tectonic transport.

Research on the basal cataclastic breccias of the overthrusting units permits to establish a relative chronology of D4 and D5 thrust contacts and the p-T data of the movements. Trapped fluids in synkinematic minerals indicated temperature up to 200-320°C and pressure up to 3.6 kbar during the D4 nappe movements. Fluid inclusions from the D5 contact resulted in significantly lower p-T values (200-260°C, 0.3-1.0 kbar), indicating thrusts in shallower crustal level.

Migrating high temperature fluids along the nappe contacts caused partial or total reset of the K-Ar isotope system, thus the measured 87–94 Ma is suggested to be connected to nappe movements.

Geodynamic implication: 150-160 Ma southern directed subduction of the West Carpathian margin (marked by the blueschist-facies Bôrka nappe slice) continued at 140 Ma, when the uppermost, Mesozoic part of the thinned and already imbricated crust entered the subduction zone, indicated by the medium-pressure metamorphism of the Torna unit. Part of the Jurassic Meliata sediments submerged into the subduction zone, too. This is the time (D1) when the Torna structural unit underplates the tectonically buried Meliata sedimentary melange. Meanwhile, part of the already HP metamorphosed oceanic and continental crustal fragments (Bôrka nappe) exhumed to the foot of the buried Meliata sedimentary melange. Ongoing compression pushed tectonic slices of the HP unit into the Meliata unit as a tectonic matrix. Low-grade prograde metamorphism of the Torna and Meliata tectonic units and retrograde metamorphism of the Bôrka HP nappe were coeval, indicated by K-Ar data (140-120 Ma).

The mid-Cretaceous Eoalpine phase resulted in thick- and thin-skinned nappe movements (southeast- and south-vergent) in the Western Carpathians, dominating the present tectonic scene and being responsible for the former contradictory views on the structural setting.

Plagioclase metastability during HP-metamorphism? Observations and models from the Adula Nappe

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The Adula Nappe in the Central Alps consists of pre-Mesozoic basement with some Mesozoic cover rocks. Its rock assemblage is assumed to be derived from the distal Mesozoic European continental margin towards the North Penninic ocean. In Eocene times, at least parts of the Adula Nappe experienced extensive alpine metamorphic overprint at eclogite-facies conditions and subsequent rapid exhumation to mid-crustal depths. The Adula Nappe displays a stunning lithological heterogeneity and has been referred to as a lithospheric high-pressure/ultra-high-pressure (HP/UHP) mélange though it is not clear whether (1) the heterogeneity results from intense mixing in the alpine subduction channel or (2) is partly inherited from the pre-Mesozoic history while the Adula Nappe remained coherent during alpine history.

Here, we describe the metamorphic record in orthogneisses from the central portion of the nappe (Alp de Ganan). In the study area, thin layers of orthogneiss are intercalated with HP garnet-mica-schists, which enclose eclogite-cored metabasic boudins. In contrast, the orthogneisses display the commonplace assemblage Qtz + Kfs + Pl + Wm + Bt ± Grt ± Czo/Aln ± accessory minerals (Ap, Zrn, ore minerals). Equilibration under eclogite-facies conditions, however, is expected to produce plagioclase-free jadeite-gneisses. Several explanations exist for the absence of high-pressure relicts in the metagranitoids: (1) The orthogneisses never experienced HP conditions, (2) the orthogneisses did experience HP conditions, were transformed to jadeite-gneisses and completely re-equilibrated to plagioclase-gneisses during retrograde metamorphism, and (3) orthogneisses experienced HP conditions but plagioclase remained metastably through the metamorphic history.

We present petrographic descriptions, whole rock chemical data and extensive microprobe data including chemical maps from orthogneisses sampled at Alp de Ganan. The only clear hint to high-pressure conditions is phengitic white mica preserved in cores of matrix grains and as inclusions in K-feldspar porphyroclasts. In the foliated matrix, white mica coexists with biotite. These matrix grains show pronounced chemical zoning with high silica contents up to ca. 3.4 Si p.f.u. in cores. The increase of Al towards the rim is secondary and controlled by diffusion, probably during biotite growth or deformation. Biotite is only weakly zoned and displays phlogopite components between 50 and 54 %. K-feldspar porphyroclasts consistently contain high-Si phengite as inclusions. Equilibrium assemblage diagrams calculated for the bulk compositions of our samples predict the observed matrix evolution during nearly isothermal decompression from 16 kbar at 700 – 750 °C. This trajectory exactly matches the lower pressure part of published P-T data concerning the nearby-located Trescolmen eclogites. Si-contents as high as observed, however, are predicted only at considerably higher pressures in assemblages with clinopyroxen. The entire sequence of assemblages including observed high-Si contents in phengite can be reproduced in equilibrium phase diagrams if clinopyroxen is removed from the database and a PT-Path as recorded in the adjacent eclogites is assumed. We therefore favor a scenario in which plagioclase remained in the rock metastably through the P-T evolution of a coherent basement unit. Similar metastable survival of plagioclase is described from other HP/UHP terranes.

P-T-t estimates in low-grade metamorphic terrains, a key to reconstruct the geodynamic evolution of the Alpine continental subduction (Briançonnais zone, Western Alps)

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The study of the geodynamic evolution involving continental subduction and exhumation processes requires knowledge of detailed Pressure-Temperature-time paths as recorded in different units across mountain belts. Such P-T-t estimates can be obtained from well equilibrated high-grade metamorphic rocks; usually several methods are available. By contrast, in low-grade metapelites P-T-t estimation using such an approach is challenging, especially if no index minerals occur. Metapelites at greenschist facies metamorphic conditions show a poor spectrum of metamorphic minerals, such as quartz, chlorite and K-white mica; commonly detrital metamorphic relics inherited from a prior metamorphic history remain. Therefore, to acquire reliable P-T estimates a multi-method approach is required, involving qualitative and quantitative Raman study of Carbonaceous Material (RSCM), chemical analysis from standardized X-ray maps and multi-equilibrium inverse thermodynamic modelling of chlorite and white mica. This thermobarometry study may be coupled with $^{40}Ar/^{39}Ar$ dating on newly crystallized phengite in order to constrain the age of crystallization.

In the French Western Alps, the Briançonnais zone is a remnant of the continental subduction wedge. Several studies conducted over the last ten years have aimed at constraining the P-T-t conditions and evolution of the internal parts of the continental wedge (e.g. the Vanoise and Ambin massifs) during the Alpine orogeny. By contrast, the metamorphic evolution of the external part of the Briançonnais Zone, (i.e. the Briançonnais cover and the Briançonnais Zone houillère) remains largely unconstrained. The present study focused on these units; P-T and P-T-t paths were estimated using a multi-method approach advertised above. Examples will be shown, notably for a sandstone sample in the Briançonnais Zone houillère. The study allows distinguishing Hercynian peak metamorphic conditions of 371 ± 26°C and 3.5 ± 1.4 kbar (recorded by detrital minerals) and Alpine peak metamorphic conditions of 275 ± 23°C and 5.9 ± 1.7 kbar. Another sample, taken further south, from the Plan-de-Phasy unit, allows to estimate phengite crystallization conditions at 270 ± 50°C and 8.1 ± 2 kbar at an age of 45.9 ± 1.1 Ma. According to these and previous results in more internal parts of the Briançonnais zone, an adjusted geodynamic model is proposed for the evolution of the Alpine continental subduction. The results are consistent with a diachronous evolution of the Briançonnais zone involved in the Alpine continental subduction.

Gabbro olistoliths from the Mts. Kalnik and Ivanščica ophiolite mélanges in the NW Dinaric-Vardar ophiolite zone (Croatia)

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Mts. Kalnik and Ivanščica ophiolite mélanges vestige for the Repno oceanic domain (ROD), a discrete domain of Neo-Tethys that connects Meliata with Dinaric-Vardar oceanic systems. The domain exposes ophiolitic rocks in four mélange sectors: Mts. Ivanščica, Kalnik, Medvednica and Samoborska Gora. The large gabbro blocks are relatively more abundant in the Kalnik and Ivanščica Mts. mélange sectors, mostly exposed as fault-bounded tectonic inclusions incorporated during ophiolite/mélange emplacement. The preliminary results on petrography, mineral chemistry and bulk rock chemical composition of the gabbro olistoliths are presented and interpreted.

Three mineralogical and geochemical gabbro groups could be distinguished (A, B and C). The gabbros of group A and B show isotropic texture whilst those of group C are coarse grained intergranular. The gabbros of group A are bimineral, composed of plagioclase and augite, the gabbros of group B additionally contain significant but variable amount of edenitic amphibole, whilst edenite represents an additional minor phase in group C. The clinopyroxene from the gabbros is augite (Wo36.5-44.7En29.8-47.7Fs11.0-29.7). Magmatic plagioclase preserved in the rocks of groups B and C shows continuous normal zoning patterns with maximum core to rim compositional range of An41.5-33.7. Edenite textural position and the high content of TiO_2, Al_2O_3 and Na_2O (up to 2.5, 8.3 and 2.7wt.%, respectively) suggest its igneous origin (cotectic with augite). Ilmenite and apatite occur as accessory minerals in all three groups. The C group gabbros contain discrete domains of parallel oriented ilmenite plates (up to 35μm wide) exsolved from a completely decomposed ferromagnesian mineral. A significant chemical difference with respect to the Mn-content of ilmenite was measured between rocks of group B and C (7.82-7.96wt.% vs. 3.28-4.67wt.% MnO). The representative gabbro from group A contains low-Mn ilmenite (< 1.5wt.% MnO) typical of ocean ridge gabbros.

All gabbros are in part altered. The most prominent alteration is transformation of plagioclase to albite and/or peristerite. Less intensive are alterations of augite and edenite to ferro-anthophyllite and/or magnesiohornblende, ferrohornblende, ferroactinolite, actinolite. Other secondary minerals are sericite, calcite, prehnite, diabantite-brunsvigitic chlorite, epidote, leucoxene, high-Al and -Fe titanite, low-Mg stilpnomelane (Mg#=0.20-0.22; K=0.21-0.72 a.p.f.u.) and high-Al pumpellyite, typical of greenschist facies hydrothermal alteration.
Analysed gabbros discriminated into three geochemical groups: (A) N-MORB-type gabbros with slight subduction signatures [(Th/Nb)n=1.80-2.07; (Nb/La)n=0.85-0.90], (B) IAT-type edenite gabbros with clear supra-subduction characteristics [(Th/Nb)n=4.41-5.10; (Nb/La)n=0.41-0.53], and (C) BABB-type gabbros [(Th/Nb)n=2.86-4.04; (Nb/La)n=0.57-0.75]. The representative rocks of the groups A, B and C dated to Early Jurassic, Late Jurassic and to the Cretaceous era, respectively. Early Jurassic gabbros reflect a peculiar stage of Palaeo-Tethyan slab break-off, Late Jurassic gabbros vestige a nascent intra-oceanic arc, and Cretaceous gabbros indicate the existence of magmatism in the back-arc marginal basin. The analyzed gabbroic rocks enable a refinement and completion of the geodynamic evolution of the ROD.

Biostratigraphy, isotope stratigraphy (δ18O, δ13C) and geochemical characteristics (XRF) of Upper Tithonian to Lower Cretaceous deeper-water sedimentary rocks (Northern Calcareous Alps, Salzburg) as a tool to prospect raw material for the cement industry

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We investigated the Uppermost Jurassic to Lower Cretaceous deeper-water calcareous to siliciclastic and siliceous sedimentary rocks (Oberalm, Schrambach and Rossfeld formations) of the Leube quarry in the central Northern Calcareous Alps of Salzburg. Based on an already existing detailed biostratigraphy supported by Calpionellids and Ammonoids, we measured the geochemical characteristics (XRF) and the isotope stratigraphy (δ18O, δ13C) of the more than 450m thick sedimentary succession. Aim is to establish besides the existing classical prospecting methods a new method based on geochemical data to recognise similar successions in the partly deeply weathered and highly deformed Late Jurassic to Early Cretaceous successions of the Northern Calcareous Alps. Beside the limestones of the Oberalm Formation, characteristic sedimentary rocks in the Upper Tithonian to Lowermost Cretaceous are reef slope breccias of the Barmstein Limestone and the oligomictic breccias of the late Upper Tithonian so called “Tonflatschenbreccia”. This succession is characterized by a general deepening- and fining-upward trend getting upsection more and more homogeneous. Generally the content of clay increases and the amount of carbonate decreases. Reason is the back-stepping of the Plassen Carbonate Platform in the Late Tithonian to Middle Berriasian. This trend also becomes apparent in the analysis of major elements with XRF showing a more and more homogeneous chemical composition of the samples. The δ18O and δ13C curves constitute more or less a similar trend.

The drowning of the Plassen Carbonate Platform around the Middle/Late Berriasian boundary resulted in the deposition of a condensed section with red and green limestones and marls of the Gutratberg beds in the uppermost part of the Oberalm Formation. This event can also be seen in the geochemical data and the isotope curves and represents the upper boundary of the Oberalm Formation. The Late Berriasian to Valanginian Schrambach Formation is characterized by the deposition of a relatively homogenous marly and well-bedded limestone marl sequence followed by the Rossfeld Formation (Late Valanginian to Early Aptian). The deposited rocks change to coarse grained siliciclastic breccias and conglomerates followed by a fining upward trend with finegrained arenites, siliceous limestones and marls. The abrupt change at the Schrambach/Rossfeld boundary is also clearly visible in the geochemical data.

We present the first correlation of isotope and geochemical data in connection with high resolution biostratigraphy. Using a standard profile of a more or less complete sedimentary succession of the considered period in the deeper part of the basin, these resulting data can provide the basis to correlate sections from different outcrops. It will be also able to distinguish different depositional areas within the basin. This combination of different methods should help to recognise the completeness of successions occurring usually in weathered outcrop conditions. Besides classical prospecting methods this approach can act as a new tool in the prospection of raw materials for the cement industry.

Alternative models to explain the evolution of Alpine-type collisional orogens: the importance of rift inheritance

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Many plate kinematic and tectonic models proposed for the evolution of the Alps in Western Europe are deeply inspired by present-day SW Pacific-type subduction systems. However, key features characterizing the upper plate of Pacific-type margins, such as high temperature-low pressure metamorphic overprint associated with volcanic arcs and back arc basins are not found in the Alpine domain, despite the fact that the upper plate (Adriatic plate) is very well exposed. This significant difference questions the validity of the supposed similarity between the Alpine Tethys and Pacific-type systems, especially with respect to the nature of the subducted lithosphere and the original basin width.

In our presentation we will first explore the most recent insights on rifted margins architecture and dynamics from the southern North Atlantic, Pyrenean and Alpine domains and discuss how these results may impact the plate kinematic reconstruction and geodynamic evolution of the Alpine system. Based on these observations we will propose an alternative scenario for the pre-Alpine rift evolution. Furthermore, we will show that the rift architecture exerted a major control on the structural and sedimentary evolution of the Alpine system during plate convergence (tectono-sedimentary evolution of Flysch and Molasse sequences) as well as on the final architecture of the orogen (evolution of the external massifs and along strike variations of the Alpine orogenic structure). A key result of our studies is that rift inheritance strongly controlled the final architecture of the interal parts of the orogen. The intimate link between ophiolites and remnants of thinned continental crust and the strong segmentation and diachronous evolution of the mountain belt are largely a result of rift-related tectonics and do not need to be explained by “ad hoc” models. The observation that the Alps in Western Europe developed from a complex paleogeographic domain and represent a collage of different orogenic belts and accretionary prisms that were formed diachronously along different parts of the convergent African-European system questions the comparison with classical steady-state Pacific-type subduction systems.

The structure and P-T evolution of the Dent Blanche Tectonic System (Austroalpine Domain, Western Alps): from the Permian lithospheric thinning to the Alpine subduction and collision

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The Dent Blanche Tectonic System (DBTS) is a composite thrust sheet consisting of superimposed units of polycyclic basement, i.e. Arolla and Valpelline Series, both derived from the Adriatic continental margin. These units preserve a polyphase structural and metamorphic history, comprising both pre-Alpine and Alpine cycles.

The Pre-Alpine history is characterised by a polyphased Permian (from 290 to 265 Ma) granulite-facies event (peak at 860°C, 8 kbar) in the Valpelline Series, and by Permian (~290 Ma) granitoids that intruded at 750°C, 4-5 kbar in the Arolla Series. It is therefore concluded that the Valpelline and Arolla Series are representatives of the lower and upper crust, respectively, of the Adriatic continent.

The Alpine history is heterogeneously preserved in both the Valpelline and the Arolla Series. In the Valpelline Series, previous authors described rare relics of chloritoid-mica in cordierite pseudomorphs and kyanite replacing silllimanite. The lack of extensive blueschist-facies overprint could be due to the low a(H_2O) activity and/or the lack of Alpine ductile deformation. In the Arolla Series, highly strained granitoids display glaucophane-phengite (10-14 kbar, 400-500°C) overprinted by actinolite-chlorite (2-4 kbar, 220-330°C). This transition from blueschist-facies to greenschist-facies parageneses is also seen in some metacherts.

Two main tectonic boundaries are observed within the DBTS. Firstly, the contact between the Arolla and Valpelline Series is marked by a thick (10 m) zone of mylonites that locally display blueschist-facies minerals (blue amphibole, garnet, phengite, aegirine-augite), overprinted by greenschist-facies assemblages. The dominant foliation in the Arolla-Valpelline mylonites shows a prominent NW-SE stretching lineation, and both these structures are overprinted by NE-SW trending folds.

Secondly, the Roisan-Cignana-Shear-Zone (RCSZ) is a NW-dipping shear zone, which cuts through the Arolla-Valpelline contact and separates the DBTS in two subunits, the Dent Blanche nappe to the NW and the Mont Mary nappe to the SW. It results from several deformation phases developed at blueschist (13±2 kbar, 480±50°C) then greenschist (2-4 kbar, 200-300°C) facies conditions. Within this shear zone, tectonic slices of Mesozoic and pre-Alpine metasediments are amalgamated with continental basement rocks. The occurrence of blueschist-facies assemblages along the contact between these tectonic slices indicates that the amalgamation occurred prior to or during the subduction process, at an early stage of the Alpine orogenic cycle.

The structural, petrological and geochronological data provided in this study and those available in the previous works enable us to propose a possible kinematic evolution for the current geometry of the Austroalpine domain. We will discuss the contributions of (i) the Permian lithospheric thinning, (ii) the Jurassic rifting and (iii) the subduction-collision processes in controlling the final geometry of the Austroalpine domain.

Tectonic models for Adria and the External Dinarides in the context of Jurassic-Cretaceous paleomagnetic results

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Adria is a crustal block playing an important role in the geodynamic history of the Central Mediterranean s.l. Recently, a reliable Late Jurassic – Eocene APW path was obtained for its "autochthonous" core. This can serve as a reference frame for describing displacements in its more tectonized margins, like the External Dinarides, where we also carried out systematic paleomagnetic investigation, involving Gorski Kotar and the Velebit Mts from the mainland, several islands of the Northern Adriatic basin, and further in the south, Dugi otok and Vis islands.

The External Dinarides have a complicated internal structure. That is why the tectonic models published for the area are diverse. When the different models are inspected in the context of the above mentioned paleomagnetic data, we can conclude that. 1. the Adriatic islands from the Northern Adriatic basin down to Vis island must have moved in close coordination from the Albian on, although some tectonic models place them to different tectonic units. 2. coeval paleomagnetic directions for the Adriatic islands and for "autochthonous" Adria are co-incident from the late Albian on, thus the paleomagnetic results support the models which regard the former as the imbricated margin of the latter. 3. the Northern Adriatic mainland rotated about 30° CW with respect to Adria, which may be regarded as "inherited" (two carbonate platforms) or may signify relative rotation during Late Eocene between the thrust sheets of the mainland and Adria.

Acknowledgements: This work was supported by a joint project of the Academies of Sciences of Croatia and Hungary, by Croatian Ministry of Science Education and Sport project no 119-1191152-1167 and by OTKA (Hungarian Scientific Research Fund) project no. 049616.

Identification of tectonically active areas in the Panonnain basin: a combination of DEM based morphotectonic and structural analysis of Bilogora Mt. area (NE Croatia)

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Bilogora Mt., which is predominantly composed of highly deformed Pliocene-Quaternary clastic sediments, represents more than 90 km long and 10 km wide young transpressional structure related to the NW-striking Drava basin boundary fault (DBBF). DBBF was reactivated from originally normal into dextral fault accommodating c. 10 km displacement during Pliocene-Quaternary transpression in the southern part of the Pannonian Basin. On-going tectonic activity is documented by historical seismicity reporting several moderate earthquakes of intensity VI°-VIII° MCS in vicinity of larger towns. It is characterized by NE-SW orientation of the greatest horizontal stress direction determined from fault plane solutions of instrumentally recorded earthquakes ($3,5 \leq ML \leq 5,6$), indicating steeply NE-dipping, and S-SW dipping seismogenic structures with predominantly strike-slip and reverse motions.

Landscape features has been analyzed by DEM raster with 10 m cell resolution. It was modeled and analyzed using ESRI ArcMap 9.x.x. software package with CalHypso, Spatial Analyst, ArcHydro 1.1 and StPro extensions as well as Matlab software. Study area was divided into 130 drainage units. For each unit relative elevation and slope distribution values, drainage unit area-altitude relations (hypsometric integral values) as well as unit absolute asymmetry ratios were calculated. In addition, we analyzed main drainage longitudinal trunk channel statistical values extrapolating parameters of maximum concavity (Cmax), position of maximum concavity (ΔI/L), concavity factor (Cf), steepness index (ksn) and concavity index (θ). All calculated geomorphic parameters have been combined and overlayed as rasters, which enable a separation of drainage units characterized by geomorphic parameters that could possibly indicate an on-going tectonic deformation. These units are located between towns of Koprivnica and Pitomača on northeastern slopes and in the vicinity of Daruvar on southwestern slopes, in the northwestern and southeastern part of Bilogora Mt., respectively.

To verify about a possible relationship between geomorphic indices and tectonic deformation a set of 72 reflection seismic sections was analyzed using Schlumberger Petrel Seismic to Simulation software. This software enabled construction of structural depth model comprising 6 stratigraphic horizons and more than 50 faults active during the Neogene-

Quaternary times. Spatial correlation between geomorphic and structural data proved that calculated geomorphic indices in the northwestern part of Bilogora Mt. correlate well with subsurface fault-related folds of Late Pontian-Quaternary age. These folds are formed in hangingwalls of either normal-inverted or younger reverse faults that cut across the base Pliocene-Quaternary horizon and propagate towards the surface. Vertical offset along these faults is in range between 20-480 m, thus indicating a slip rate of ≤ 0.1mm/year during the Pliocene-Quaternary times. Using the published empirical geometrical fault-scaling relationships, we estimate that at least some of these faults are capable to generate earthquakes with magnitudes up to 6.86 which are significantly greater than historically reported in Croatian Earthquake Catalogue.

Acknowledgements: This research was financially supported by the Ministry of Science, Education and Sports of the Republic of Croatia (Project CROTEC, grant no. 195-1951293-3155).

Single event time-series analysis in a karst catchment evaluated using a groundwater model

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The Lurbach-Tanneben karst system (Styria, Austria) is drained by two major springs and replenished by both autogenic recharge from the karst massive itself and a sinking stream that originates in low permeable schists (allogenic recharge). Detailed data from two events recorded during a tracer experiment in 2008 demonstrates that an overflow from one of the sub-catchment to the other is activated if the discharge of the main spring exceeds a certain threshold. This data was used to examine how far the time-series analysis (auto-correlation, cross-correlation) supports the identification of the transient inter-catchment flow observed in this karst system. As inter-catchment flow is found to be intermittent, the analysis was focused on single events. In order to support the interpretation of the results from the time-series analysis a simplified conceptual model of the karst system was implemented in the numerical groundwater flow model MODFLOW. In particular, the overflow inferred from the tracer experiment was represented using the wetting capability package of MODFLOW. Thus, the groundwater model represents a synthetic karst aquifer for which all aquifer properties are known in detail. Different types of recharge events were employed to generate synthetic discharge data, which was then used for the time-series analysis. In addition, the geometric and hydraulic properties of the karst system were varied in several model scenarios to distinguish in the results from the time-series analysis the effects of recharge from those of aquifer properties. Comparing the results from the time-series analysis of the observed data with those of the synthetic data a good general agreement was found. For instance, the cross-correlograms show similar patterns with respect to time lags and maximum cross-correlation coefficients if appropriate hydraulic parameters are assigned to the groundwater model. Thus, the heterogeneity of aquifer parameters appears to be a controlling factor. Moreover, the location of the overflow connecting the sub-catchments of the two springs is found to be of primary importance, regarding the occurrence of inter-catchment flow, and further support our current understanding of an overflow zone located near the sinkhole. Thus, time-series analysis of single events can potentially be used to characterize transient inter-catchment flow behaviour of karst systems.

Acknowledgements: This work was supported by the Austrian Academy of Sciences ÖAW (Project: Global models of spring catchments) and the Austrian Science Fund FWF: L 576-N21. The authors would like to thank R. Benischke and G. Winkler for their comments. The Lurgrotte cave staff is thanked for the access to the cave.

Rockfall occurrence at the southern border of the Tauern Window – structural, lithological and geomorphologic aspects

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The southern part of the central Tauern Window with the main tectonic units Sub-Penninic and Penninic nappes are overthrusted by Austroalpine nappes (SCHMID et al., 2004; PESTAL et al., 2009). Therefore the tectonic and lithological heterogeneity in this region results in a variety of areas with different lithological and structural anisotropies and consequently geotechnical-lithological properties (MELZNER et al., 2012). This fact has fundamentally influenced the landscape evolution: The area is characterized by two main strike slip fault systems. These tectonically predefined weak zones have been subject to glacial and glacio-fluvial erosion processes. Nowadays the valleys follow the main faults in NW–SE- or WSW–ENE-striking directions, and also related syn- und antithetic faults, respectively (LINNER et al., 2009).

The varying anisotropy affects the spatial distribution and extent of potential rockfall source areas within the study region (MELZNER et al., 2012):

Due to the young landscape evolution an almost preserved, oversteepened glacial and post-glacial relief can be recognized. Hence, nearly all of the lithological units form cliffs starting from 48 or 50 degree of slope inclination. However, more competent rock has greater proportions of steeper terrain than less competent rock.

Typically, steep cliffs occur within the Upper Austroalpine Prijakt-Polinik complex (LINNER & FUCHS, 2005; PESTAL et al., 2009). The lithological properties of this complex and the orientation of its rock mass structure (gently dipping from the NW to NE) favour the development of significant rockfall source areas. Field investigations demonstrated that these cliffs are generally very susceptible to rockfalls due to the heterogeneous anisotropy of this lithological unit. The heterogeneous anisotropy results in a range of failure mechanisms as well as considerable diversity in block size and shape:

- Small-scaled transitions between competent and less competent rock together with the ongoing process of detachment along a few widely spaced discontinuities sets are likely to cause selective weathering and subsequent susceptibility to comparatively large volume rockfalls.
- The number of brittle faults increases from the Prijakt-Polinik complex towards the Melenkopf complex. This results in rockfall source areas that are very small but highly fractured and loosened.
- Some cliffs have been constructed from a sequence of scarps generated by several large volume rockfall events. It is striking that the scarps follow the same orientation as some of the dominant fault planes, which occur with a high degree of separation.

Several rockfall areas are associated with deep-seated slope deformations. These mass movement types shape the landscape in the Tauern Window and have their origin (in regard to mechanism, location etc.) in the varying anisotropy of rock as mentioned above. Depending on the mass movement type (e.g. rock slides, rock creep, rock spreads, etc.) and its stage of development rockfall either occurs within the scarp area, along/ within the body or along the oversteepened front parts of the slope deformations.

Due to the glacial and postglacial landscape evolution, most of the slopes are covered by moraine deposits or scree. The (re-)mobilization of boulders caused by erosion processes, mass movements or wind throw, are common processes. Such „secondary“ rockfalls can be triggered nearly everywhere throughout the whole study area.

Acknowledgements: The presented work was part of the INTERREG IVA Project MassMove initiated by the Austrian Federal State Government of Carinthia, Austria.

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Deformation and metamorphism of blueschists within the Phyllite-Quartzite Unit of the External Hellenides, Greece: a comparative study on fluid inclusions

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The Phyllite-Quartzite Unit, exposed in the southernmost part of the Mani peninsula, occurs between the medium-grade metamorphosed Plattenkalk Unit and the low-grade metamorphosed Tripolitsa Unit. The unit contains blueschists arranged as boudins which are surrounded by chloritoid-bearing micaschists. HP/LT metamorphism resulted from subduction of the Adriatic plate beneath the Eurasian plate during Eocene time. Structural mapping indicates three phases of folding. Stage F1 is rarely preserved and results from uniaxial stretching by holding steep SW-plunging fold axes. Superposition of folding events F2 and F3 form a large km-scale fold interference pattern with tight S- to SE and shallow W-E plunging fold axes, respectively.

On microscale, blueschists contain glaucophane+chloritoid+phengite+quartz. The surrounding rocks consist of chloritoid+phengite+paragonite+chlorite+quartz. Mineral chemical analysis of chloritoid indicates a prograde growth. Chloritoide porphyroblasts reflect an earlier foliation S1 (D1) and show locally pseudomorphic transformations to phengite and chlorite that are accompanied with SSW-directed shearing (D2). D2 is responsible for the penetrative foliation S2.

Constraints for the post-peak P-T evolution of the Phyllite-Quartzite Unit have been performed by fluid inclusion studies on late-stage boudin necks close to the blueschists. Necks consist of coarse grained quartz aggregates. Fluid inclusions (FIs) show a frequent occurrence of aqueous saline inclusions predominantly with halite daughter crystals. FIs occur up to 3-phase (S,L,V) and indicate the chemical system H_2O-NaCl-$CaCl_2$. The system is established by eutectic temperatures Te and Raman spectroscopy. Te shows always very low temperatures in the range of -72°C which is interpreted as metastable phase behaviour or crystallization stage. Last ice melting of about -49°C occurs earlier than hydrohalite melting (~-35°C) which coincides well with respective Raman spectra. This indicates a fluid composition around 47 mass% H_2O, 36 mass% NaCl and 17 mass% $CaCl_2$. Densities lie between 1.24 and 1.17 g/cm3. Assuming proposed maximum peak temperatures from blueschists from this area of about 550°C, conditions for extension of boudin necks can be established due to fluid density isochore calculations between 7 and 9 kbar. This fluid inclusion study will now be compared with fluid inclusions in concordant quartz veins which act as host rocks of the blueschist boudin structures.

Middle Triassic eclogite in the Rila Mountains (Rhodope Upper Allochthon, Bulgaria): A vestige of Palaeotethys subduction?

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The Alpine nappe pile of the Rhodope Metamorphic Complex in Bulgaria and Greece was assembled during a protracted history of subduction and collision along the southern margin of Europe. It is subdivided into four thrust systems or tectonic superunits, the Lower, Middle, Upper and Uppermost Allochthon. Previous Lu-Hf dating (KIRCHENBAUR et al., 2012) yielded Eocene ages for eclogite at the base of the Middle Allochthon in the central Rhodopes, and Cretaceous ages for eclogite in the Upper Allochthon in the eastern Rhodopes. In addition, Jurassic HP and UHP metamorphism is suggested by zircon and monazite dating. The overall situation, with older eclogite in higher allochthons and younger eclogite in deeper ones, is analogous to the Caledonides and European Alps. Here we report new data from eclogite of the Upper Allochthon exposed in the Rila Mountains, in the northwestern part of the Rhodope Metamorphic Complex.

The eclogite crops out near Metoch Pchelino, about 3 km SW of the famous Rila Monastery. It is part of a lithologically heterogeneous and strongly sheared, N-S striking zone containing metabasic and –ultrabasic rocks as well as garnet-kyanite metapelites. Most of the eclogite is retrogressed but relics of omphacite are still present. Mn and Lu contents in garnet show typical bell-shaped profiles which are evidence of prograde garnet growth during P and T increase. Lu-Hf chronometry using the whole rock and three garnet separates yielded a well-defined isochrone with an age of ca. 238 Ma (Ladinian). As most of the Lu is in the garnet cores, this age is interpreted as the age of pressure increase during subduction.

Triassic eclogite has so far not been found in Europe but only from Turkey towards east. The distribution of Triassic eclogite and arc magmatites in Turkey (e.g. AKAL et al., 2011) suggests southward subduction of Palaeotethys during the Triassic, contemporaneous with opening of Neotethys to the South, and finally leading to collision of the resulting continental ribbon with Europe between Late Triassic and Middle Jurassic. The Rila eclogite fits in such a scenario, possibly representing the suture between the European margin to the north and a Gondwana-derived fragment to the south, the Ograzhden-Vertiskos terrane. When the Rhodope allochthons later formed, during subduction and closure of Neotethys and the Vardar ocean, the Rila eclogite and Vertiskos-Ograzhden terrane became part of the Upper Allochthon.

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Carnian-Norian tectonics and seawater from Silicka Brezova, Western Carpathians

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After the Middle Triassic extension and the break-up of the Neotethys Ocean intense tectonic characterize the Late Triassic distal carbonate shelf, expressed in facies changes and breccia formation. A first tectonic pulse in the Late Carnian (Tuvalian 1) results in the flooding of the formerly emerged Wetterstein carbonate platform by forming a pelagic plateau, which lasts until the Late Norian (compare Muerzalpen facies of the Northern Calcareous Alps). The overlying Late Triassic sequence is exposed in a system of several quarries and trenches all west of the village Silicka Brezova in the Western Carpathians (Silica nappes). In the Tuvalian 1 and 2 deeper slope deposits of hemipelagic filament limestones with intercalated resediments from the nearby Waxeneck carbonate platform are relatively high in their Li and Br palaeo-seawater ionisation. A higher Li concentration in the Tuvalian 2 may correspond to volcanic activity; as known e.g., in the Buekk Mts. The next tectonic pulse is reflected in a rapid deepening around the Tuvalian 2/3 boundary: On top of an unconformity hemipelagic reddish Hallstatt-like limestones were deposited; they show a rapid decrease in Li and Br concentration. The Late Carnian to Middle Norian time span is characterized by deposition of grey and reddish hemipelagic limestones, still low in Li and Br. Intense tectonic in the Late Norian result in a sedimentary sequence with a general fining upward trend. The Hallstatt Limestones components of Late Carnian to Middle Norian age differ in their litho- and microfacies from the underlying sequence. The provenance area of the clasts might be the outer shelf in the Hallstatt Zone indicating Late Triassic strike-slip induced basin formation as evidenced e.g., in the Karavank Mts. A low NO_3 concentration and a higher F concentration reflect a typical palaeo-seawater of this palaeogeographic realm. The Dachstein carbonate platform progradation is evidenced by shallow-water resediments in the latest Norian hemipelagic limestones, again with an increase in the Li concentration. The tectonic and the known Late Triassic crisis events are reflected in the palaeo-seawater composition.

Petrographic features of chloritoid schist from southeastern slopes of Mt. Medvednica, (Zagorje-Mid-Transdanubian zone, Croatia)

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In the frame of detail mapping of parametamorphic rocks on the southeastern slopes of Mt. Medvednica (Zagorje-Mid-Transdanubian zone, Croatia), samples of the chloritoid schists were analyzed in more detail.
This study is a part of preliminary research that included XRD, XRF, ICP-MS, SEM, electron microprobe and microstructural characterization of chloritoid schists in order to determine their petrography, microstructural features, mineral assemblages, phase composition, whole-rock and mineral chemical composition and morphology of accessory minerals (zircon typology).

The samples can be categorized as chlorite-muscovite-quartz schist, chloritoid-chlorite-quartz-muscovite schist, chlorite-muscovite-quartz-chloritoid schist and interbeds of marble. Accessory minerals in chloritoid schist are tourmaline, zircon and rutil. Microstructural features show two deformational events, the sinmetamorphic and postmetamorphic events. The latter deformational event is recorded in the development of flazer structure, where the mineral grains in cleavages are translated, fractured and rotated.

The whole-rock chemical analyses show high concentrations of SiO_2 (74.79 wt. %), K_2O (2.5 wt. %), Al_2O_3 (13.22 wt. %), and low values of MgO (0.99 wt. %) and CaO (0.08 wt. %).These results indicate that acid rocks could be a possible protolith. The REE distribution normalized to chondrite shows higher LREE to HREE concentrations ((La/Yb)N=5.68, (La/Sm)N=3.05, (Gd/Yb)N=1.21), while the Eu anomaly has a low value (Eu/Eu*=0.7).

Such metamorphic mineral assemblage is characteristic for low-grade metamorphism. The chlorite-chloritoid geothermometer gives metamorphic temperature values of approximately 450°C.

The source rocks of the chloritoid schist are argillaceous sandstones, derived from acid magmatic rocks, interbeded with carbonates. Carbonate interbeds indicate deposition in a marine environment. The morphology of zircons shows that the source for protolith is of granitoid composition, while their weak roundness indicates a short transport.

The role of rift-inherited hyper-extension in Alpine-type orogens

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The Alpine orogen is commonly interpreted as the imbrication of rifted margins and intervening “oceanic” domains. Notably, the understanding of the architecture and evolution of rifted margins underwent a paradigm shift thanks to new high-resolution refraction and reflection seismic imaging method developments combined with the Ocean Drilling Program. Indeed most continental rifted margins show evidence for hyper-extension prior to lithospheric breakup. Hyper-extended domains are characterized by: 1) extremely thin continental crust and exhumed subcontinental mantle extending over hundreds of kilometers, 2) necking zones marking sharp boundaries between little extended crust and hyper-extended < 10km thick crust.

The discovery of hyper-extended domains and necking zones in rifted margins still awaits to be fully integrated in conceptual and numerical models of collisional orogen evolution. This study aims to constrain the extent to which rift-inherited hyper-extension may control the architecture and evolution of Alpine-type orogens.

Based on the available geological and geophysical datasets, the Alpine orogen can be subdivided into external and internal domains. Notably, the external domains formed at the expense of the former proximal rifted margin associated with a poorly extended crust. In contrast, diagnostic elements for hyper-extended domains are being increasingly recognized in the internal domain of the Alpine orogen while the identification of former necking zone remains more problematic. However, based on the available data, we suggest that the transition between the external and the internal domains still preserves the evidence of a former necking zone.

As a result, we propose that the evolution of the Alpine orogen is strongly controlled by rift inheritance. We suggest that subduction is initiated within the hyper-extended domain rather than the oceanic crust. Subduction processes are enhanced by partial serpentinization due to rifting processes. The continental collision is then triggered by the arrival of necking zones at convergent plate margins. Since they mark the boundary between little extended proximal and hyper-extended domains, necking zones act as buttresses initiating the transition from a subduction to a collisional stage. The continental collision, controlled by the necking zone, will create a major boundary in the orogen delimiting (1) the highly deformed and overthickened internal domain preserving the relics of rift related hyper-extension from (2) the weakly deformed external domain which neither suffered significant rift-related crustal thinning nor orogeny-related thickening.

Eventually, adopting a more realistic pre-orogenic margin architecture may significantly modify our view on mountain building formation of Alpine type orogens. Besides, results of this work should be seen in the light of recent discoveries from present-day deep-water rifted margins questioning the nature of the Alpine Tethys as either related to a true Atlantic-type ocean or to hyper-extended rift basins showing hyper-extended continental crust and local mantle exhumation but failing to create a stable plate boundary.

Tectonics in the Swiss Molasse Basin

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The Swiss Molasse Basin is located to the North of the Subalpine Molasse and the Prealpes Klippen belt, and is forming along its northern edge an erosive limit with the first fault-related folds of the Jura fold-and-thrust belt (JFTB). Originally the Molasse Basin extended farther north into the JFTB as documented by the numerous Molasse occurrences in the box-shaped synclines. Towards the W-SW the Molasse Basin grades into the fault-related fold structures of the Subalpine Chains in France. In its wester portion the Molasse Basin forms a wedge-top foreland basin, whereas in its oriental part, east of the eastern tip of the JFTB, it forms a classic flexural foreland basin. This transition – where the alpine orogenic front jumps from the frontal Jura thrust (including the Mandach thrust) to the Alpine front s.str. – occurs along a series of major NW-SE trending faults such as the Neuhausen and Randen faults and the Hegau-Bodensee graben faults, as well as the St. Gallen fault system farther SE. The transition between the tip of the JFTB belt and these faults is formed by the Permo-Carboniferous Graben of N Switzerland.

Strain partitioning inside the Swiss Molasse Basin develops a complex pattern of evaporite-cored structures (folds and grabens, fault-related folds laterally terminated by steep oblique ramps, extensional structures (grabens), inversion features above Permo-Carboniferous basins, triangular structures (mostly at the transition with the Subalpine Molasse thrust zone), and strike-slip fault systems. The latter such as the Vuache fault system or the La Lance Fault and the Pontarlier Fault in the JFTB regionally form a conjugate fault system with left-lateral faults striking N-S and dextral faults striking NW-SE. They cut from the JFTB into the Molasse basin. Locally former normal faults are reactivated in a strike-slip mode such as in the N-S trending Fribourg Zone.

Strain partitioning also occurs in a vertical profile; thus the whole area, including the JFTB, is detached above a layer of Triassic evaporites. In the southern part of the Molasse Basin the Tertiary Molasse series s.str. are detached from the Mesozoic substratum. The basement also bears major tectonic faults that form a series of Permo-Carboniferous grabens, the extent and direction of which remains elusive, except in a few rare cases such as the graben of N Switzerland. The thrust faults and strike-slip faults are restrained to the cover series and root in the basal Triassic detachment and do not extend into the basement.

The structural development of the foreland basin is classically associated with the formation of the JFTB. Recent sedimentology studies from Molasse series in the Jura synclines show distinct facies pointing to syndepositional topographic barriers which we interpret to be embryonic folds. Combined with other information such as onlaps (from seismic studies) we suggest that the onset of folding in the Molasse Basin and the JFTB is much earlier as hitherto suggested – probably as early as Oligocene.

Recent studies have combined surface field data, subsurface data from seismic surveys, earthquake analysis (especially distribution of clusters) with 3D modeling. The objective is to construct a kinematically consistant 3D-model that will help orient and constrain hydrocarbon and deep geothermal energy exploration as well as seismic hazard analysis.

Aspects of the pre-Alpine and Alpine tectonic evolution of the Gurktal Extensional Allochthon, Eastern Alps: Constraints from structural studies and ^{40}Ar/^{39}Ar white mica ages

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The nature and extent of Alpine thrusting of the Gurktal nappe complex represents one of the most controversial topics of Austrian geology. New structural and white mica ^{40}Ar/^{39}Ar ages from the Gurktal nappe complex, Eastern Alps, indicate ESE-directed distributed shear mainly leading to the present-day juxtaposition of the deeper Murau nappe overprinted in higher greenschist metamorphic conditions during the Cretaceous, to the higher, nearly unmetamorphic Stolzalpe nappe. The boundary in between represents, therefore, a ductile low-angle normal fault and the unmetamorphic Stolzalpe nappe the main body of a Late Cretaceous extensional allochthon. The distributed extensional shear system along the western margin of the Gurktal nappe complex overprinted nappe stacking structures and operated from initial ductile via semi-ductile and finally to brittle conditions within the same kinematic framework. A plateau age of 89.0 ± 0.6 Ma was found for newly grown white mica in the basal Lower Triassic Stangalm Quartzite exposed at the base of the Mesozoic cover succession on the Bundschuh basement. For the first time, a plateau age of 85.78 ± 0.33 Ma demonstrates the pervasive Late Cretaceous metamorphic overprint on the Murau nappe in the footwall of the regional, ESE-directed ductile detachment fault. This age is interpreted to date cooling after the throughout recrystallization of rocks composing the Murau nappe.

Furthermore, a post-Variscan angular unconformity below the Lower Triassic Stangalm Quartzites (PISTOTNIK, 1976) proves the preservation of style and orientation of Variscan structures in the Bundschuh basement unit. Essentially, an open N-trending fold is unconformably overlain by the above mentioned Lower Triassic Stangalm Quartzite. The basement micaschist displays three stages of deformation. Deformation stage D1 relates to the formation of a penetrative foliation within amphibolite facies conditions as pseudomorphs after staurolite testify. The second deformation stage D2 is represented by formation of E-W-trending isoclinal folds similar as in the wider surroundings. The isoclinal folds are again refolded in open, N-trending folds, representing deformation stage D3. This fold is discordantly cut and overlain by the Stangalm Quartzite. These relationships argue for a Variscan age of the dominant metamorphism within amphibolite facies conditions.

The pre-Alpine deformational structures at this angular unconformity indicate Variscan N–S shortening as the most dominant structure. This is in line with reports suggesting Variscan ca. SSW-directed SSW–NNE shortening at the famous angular unconformity between Devonian limestones and the Permian Prebichl Fm. at the structural base of the Northern Calcareous Alps (NEUBAUER, 1989). Together, these structures indicate ca. N–S resp. NNE–SSW Variscan shortening within present-day coordinates. However, this must be confirmed by further regional investigations.

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Emplacement mechanisms of evaporite mélanges: conceptual models and application to Northern Calcareous Alps

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Because of the very low shear resistance, evaporite mélanges often form decollément surfaces of extensional and contractional allochthons. Evaporites are commonly deposited in an early stage of passive continental margin formation and are overlain by thick successions deposited during the subsequent thermal subsidence stage. These latter rocks are resistant against penetrative internal deformation. Evaporite mélanges are common (1) at passive continental margins, where they are deformed during gravity-driven raft tectonics in an extensional geodynamic setting, and (2) in external foreland fold-thrust belts within a convergent geodynamic setting. In the following, we first review the most important features of both settings and then we apply these to the Northern Calcareous Alps (NCA). In gravity-driven raft tectonics at passive continental margins, an upper extensional domain is separated from a lower compressional domain at its toe. Ocean-directed rafting at low temperatures is mainly driven by thickness variations of the overburden, occurs during intermediate stages of the depositional history of the passive margin succession and may last as long as a topographic gradient is in existence. The resulting structure of the extensional domain is characterized by pronounced thickness variations of the syn-tectonic overburden within halfgrabens. In contrast, external foreland fold-thrust belts are generally transported continent-wards during episodic stages of shortening after the termination of the sediment deposition, and no pronounced thickness variations occur in the overburden except in wedge-top basins. In nature, earlier extensional deformation may have been overprinted by subsequent contraction causing complications in the structure of the thin-skinned fold-thrust belt. The central and eastern NCA are called to have formed by gravity-driven sliding of thick masses of mainly Middle-Upper Triassic carbonate platform and basin sediments on the uppermost Permian-Lower Triassic evaporite mélange (Haselgebirge Fm.) during Mid–Late Jurassic times. Main arguments for this interpretation are the presence of major Haselgebirge bodies within mainly Upper Jurassic formations and the presence of up to hill-sized blocks (mainly limestones of the Hallstatt facies realm) in a Haselgebirge matrix. This interpretation also assumes a continent-ward motion, considered as sliding into local basins, e.g. the Lammer basin. We challenge the interpretation of gravity-driven emplacement of the present structural edifice and present the following arguments for an essentially Early–early Late Cretaceous age of emplacement of cover nappes with evaporitic mélange at the base. Based on cross-sections between Hall/Tyrol and the eastern margin of NCA distributed over ca. 450 km, we distinguish three architectural modes of Haselgebirge occurrences: (1) sulphate-dominated N-vergent thrust sheets; (2) double-vergent halite-rich diapiric bodies soling in N-vergent thrust faults; these bodies are sometimes overprinted virtually by mixed thrust-strike-slip faults; and (3) sulphate-dominated post-metamorphic normal faults (e.g., Rettenstein). Type (1) N-vergent nappes were transported continent-wards against gravity on ductile evaporite mylonite zones partly over the Lower Cretaceous siliciclastic Rossfeld Fm. Ductile mylonite zones are well preserved mainly in sulphates (anhydrite, polyhalite) and partly dated at ca. 110 Ma. Such mylonitic ductile shear zones were mapped in several areas from the southern margin (Werfen Imbricate zone) to close to the northern margin of the NCA (Berchtesgaden – Dürrnberg). Except differences between Hallstatt and Dachstein facies realms, no significant local thickness variations and wedge-shaped strata are known in neither Middle–Upper Triassic nor Jurassic stratigraphic units. Exclusive Jurassic raft tectonics as mechanism for evaporitic mélange emplacement seems therefore unlikely. Of course, the new interpretation does not exclude earlier stages of local gravity sliding, e.g. during Jurassic/Cretaceous, likely in front of convergent allochthons. However, the main body (Juvavic tectonic units) emplaced along a “high”-temperature sulphatic ductile shear zone (Haselgebirge evaporite mélange) in a Cretaceous fold-thrust belt.

Acknowledgements: Work is supported by FWF grant no. P22,728 Polyhalite.

Source rock investigations and organic geochemistry of a Cretaceous succession of the Outer Dinarides (Mokra Gora, Tara Mountain, SW Serbia)

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A Cretaceous (Albian to Turonian) succession containing organic-rich sediments is exposed in the area of Mokra Gora and Tara Mountain (SW Serbia). Four sections representing different positions of the basin were investigated regarding source rock potential and organic geochemical characteristics. The Cretaceous geodynamic history and the depositional settings of organic-rich sediments in the Alpine-Dinaric realm is still not completely understood and controversially discussed. After an orogenetic process with decreasing tectonic activity during the Late Jurassic to Early Cretaceous a new depositional cycle started around the Early/Late Cretaceous boundary. In the Outer Dinarides of SW Serbia a Cretaceous sedimentary succession on top of the former nappe stack is preserved. The investigated succession is characterized by a basal transgressive part (Albian) followed by a series of alternating layers of siliceous to marly limestones and thin bedded black marls rich in organics (Cenomanian). This series represents a deepening upward. The black marls contain pithonellas, rarely heterohelicides, hedbergellas, ammonites, echinoderms and molluscs. On top of the investigated succession light limestones with rudists, shell fragments and gastropods represent a shallow water development of Upper Cenomanian to Turonian age.

The stratigraphic age of the organic-rich interval is proven as Cenomanian by means of *Aeolisacus inconstans, Ovalveolina maccagnae, Rhapidionina laurinensis* and *Cisalveolina fraasi.*

All samples were investigated by means of Leco- and Rock Eval analyses regarding their source rock characteristics. For selected samples organic-geochemical analyses were performed to determine the origin and composition of the organic matter.

The black marl development in the investigated area can be divided into two parts due to the gained results. The samples of the stratigraphic lower part reach peak values of more than 18 % total organic carbon (TOC) and hydrogen indices (HI) of greater than 700 mg HC/g TOC. Based on a modified van-Krevelen-diagram the kerogen of the samples can be classified as type I and II. Lamalginite is by far the most abundant maceral in these samples and indicates algae to be the primary source of the organic matter. In the stratigraphic higher part values for TOC and HI are below 2.5 % and 400 mg HC/g TOC, respectively. The samples plot in the field of type II and III kerogen. The frequent abundance of vitrinite also indicates a stronger terrestrial influx for these samples. Tmax-values between 400 and 426 °C indicate low maturity of 0.3 to 0.5 % Ro for all investigated samples of the succession. This is confirmed by organic geochemical results (sterane-ratio, MPI). Results of organic geochemistry analyses further argue for open marine to transitional depositional environments with anoxic to partly euxinic conditions poor in oxygen. The organic matter is mainly of marine origin, terrestrial input is more important for the upper units of the succession. This argues for differing water depths. The presence of arylisoprenoids is an indicator for photic zone anoxia. Cadalene, which is typical for terrestrial input, could be detected in the higher parts of the succession displaying the transition to more shallow water environments.

Due to these results the investigated black sediments can be seen as excellent potential source rocks featuring high potential to generate hydrocarbons in the nappe stack of the Dinarides.

In-sequence and out-of-sequence thrusts: nappe structure of the western Northern Calcareous Alps revisited

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In fold-and-thrust belts, syntectonic sediments provide a means to date deformation. The youngest sediments below a thrust sheet give the maximum age of thrusting, and growth strata record growth of individual structures. Applying this concept shows that the Northern Calcareous Alps (NCA) thrust sheets were emplaced from the Barremian onwards. Thrust activity propagated from the SE to the NW and reached the South Penninic units in the Turonian or Coniacian. Shortening did not cease after thrust sheet emplacement, while the NCA were carried piggy-back over Penninic units. Growth strata in the various Cretaceous syntectonic clastics (Branderfleck Fm., Gosau Group) document significant contraction after thrust sheet emplacement well into the Maastrichtian.

As defined by previous authors, the major thrust sheets of the western NCA are from base to top: The Allgäu thrust sheet, the Lechtal thrust sheet and the Inntal thrust sheet. The first two are part of the Bajuvaric nappe complex, whereas the last belongs to the Tirolic nappe complex. This model of the NCA thrust sheets assumes far-travelled nappes that are entirely separated and have a continuous thrust at their base. If the NCA thrust sheets would adhere to such a simple model the thrusts should display ramp-flat geometry and form a hinterland dipping duplex, which they do not.

Using the information from syntectonic sediments following problems with the traditional nappe subdivision emerge:

(1) The Inntal thrust sheet was emplaced out-of-sequence after thrusting of the Lechtal thrust sheet in its footwall. In the Karwendel mountains, it is connected to the Lechtal thrust sheet in a north-facing anticline dissected by out-of-sequence thrusts. These were originally interpreted to be the base of the Inntal thrust sheet.

(2) The Albian Lechtal thrust ends in a tight anticline in the Arlberg area and is replaced by the Coniacian to Santonian Mohnenfluh thrust.

(3) The Tirolic basal thrust has an Eocene age, where it was drilled (well Vordersee1 east of Salzburg); At the surface, the sinistral Inntal shear zone separates the Bajuvaric Lechtal thrust sheet from the Tirolic nappe complex, and not a flat-lying thrust.

In fact the western NCA are one single tectonic unit. All thrusts end laterally. However, individual thrusts do have offsets in the range reported previously, but thrusts loose offset laterally. In many cases, thrusts do display to out-of-sequence geometries: The Inntal out-of-sequence thrust truncates folds in its footwall and hanging wall, as it should. However, also the Lechtal thrust dissects pre-existing anticlines and synclines. We speculate that only a model of thrust propagation involving significant footwall deformation can describe these thrusts correctly.

Relict rock glaciers- complex aquifer systems in alpine catchments, Niedere Tauern Range, Austria

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In the 1990s water resources investigations in the Niederen Tauern Range, Austria demonstrated that springs draining relict rock glaciers are of importance for water supply and human consumption as well as for the alpine ecosystem. Recent studies show that in the easternmost subunit of this mountain range, the Seckauer Tauern Range, up to 20% of the area above 1500 m a.s.l. and more than 40% of the area above 2000 m a.s.l. drain through relict rock glaciers. Thus, the hydraulic properties of these alpine aquifers are considered to have an important impact on the hydrology of the region. Their storage capacity affects and regulates strongly the risk of natural hazards such as floods and debris flows and the possibility for economic use of the water resources. However, the hydraulic properties of relict rock glaciers and their inner structure are still poorly understood.

The investigation area is the Schöneben Rock Glacier (SRG) located in the central part of the Seckauer Tauern Range. The SRG cover consists predominantly of coarse-grained, blocky gneissic sediments and extends from 1720 to 1905 m a.s.l.. It covers an area of 0.11 km² and drains a total catchment of 0.76 km² with its maximum elevation of 2282 m a.s.l.. Discharge of the rock glacier spring is recorded since 2002. Natural tracers, electrical conductivity and water temperature are continuously monitored since 2008. Furthermore, a tracer test with simultaneous injection of the fluorescent dyes naphthionate and uranine at two injection points (one close to the front and one close to the rooting zone of the rock glacier) was performed. The analysis of the spring hydrograph on the one hand shows a slow base flow recession indicating a high storage capacity and on the other hand sharp discharge peaks immediately after rainfall events referring to a high hydraulic conductivity. The spring hydrograph therefore reveals similarities to the flow dynamics of karst springs. Results from analytical recession models are consistent with the conceptual model of a heterogeneous aquifer that is composed of multiple overlapping exponential segments with recession coefficients ranging from 0.06 to 0.002 d-1. The peak of the uranine breakthrough curve was recorded after approximately 100 days. This agrees well with the reciprocal of the intermediate recession coefficient, which may be interpreted as the mean residence time of the corresponding flow component. In addition to this intermediate flow component, the rapid spring responses to recharge events with sharp discharge peaks and negative electric conductivity and temperature peaks within a few hours suggest the existence of a fast flow component. Using electrical conductivity to separate the discharge components of the hydrograph yields up to 20% event water with residence times in the order of hours whereas 80% of the discharge is found to be pre-event water with longer residence times. The highest percentage of event water coincides with the highest discharge rates. The natural and artificial tracers thus support the conceptual model of a heterogeneous aquifer with at least two different storage components. While a coarse grained, blocky upper zone is believed to provide the fast run off component, a fine grained (sandy, poorly silty although with larger embedded blocks) inner zone provides the base flow component.

Acknowledgments: This project is co-funded by the European Regional Development Fund (ERDF) and the Federal Province of Styria, funding program "Investionen in Ihre Zukunft". Project homepage: http://www.uni-graz.at/hydro-blogle.

Pre-Alpine and Alpine evolution of the Seckau crystalline basement (Seckau mountains, Eastern Alps)

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The massif of the Seckau mountains (Seckauer Tauern) is mainly built up of granitoids, overprinted by Eoalpine (Cretaceous) deformation during nappe stacking and subsequent extension, and greenschist facies metamorphism. Whole rock Rb-Sr age data of ca. 432 Ma and 350 Ma were assumed to indicate the protolith ages (SCHARBERT, 1981). In this study, a suite of granitoids was geochemically analysed by X-ray fluorescence (Bruker Pioneer S4) in order to derive the processes of magmatic evolution and differentiation. In general, three types of magmatites can be distinguished: granites, granodiorites and quartz-monzodiorites. The first two form the majority, whereas the intermediate quartz-monzodiorites are only locally exposed.

Following the A/CNK discrimination diagram a clear distinction between S- and I-Type granitoids can be established. The S- type granites are mainly part of the structurally uppermost sections and are covered by Permian to Lower Triassic metasedimentary sequences of the Rannach Formation.

Within the AFM diagram all granitodis are characterized by a calcalkaline trend. This suggests formation of the melts during a subduction process. Within the R1-R2 digram, the granitoids are related to both pre-plate collision, syn-collision and post-collision uplift settings. We therefore suggest that the granitoids of the eastern Seckau massif are part of an intrusion sequence during distinct stages of a plate tectonic cycle, i.e. from pre- to post collision, and that the related magmas differentiated from intermediate (quartz-monzodiorites) I-type to acidic (granites, granodiorites) S-type.

Biotites separated from the granitoides yield Rb-Sr age data between 83 and 87 Ma, and 80 to 76 Ma. These ages are assumed to represent cooling ages related to the exhumation of the Seckau massif subsequent to Eo-Alpine greenschist facies metamorphism.

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Jurassic and Lower Cretaceous tectonics of the Western Carpathians: coupled vs. uncoupled hinterland shortening and foreland stretching

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During Jurassic and Early Cretaceous, tectonic evolution of the Western Carpathians was governed by two competing, but mutually related processes – hinterland collision and prograding nappe stacking after closure of the Neotethys-related Meliatic oceanic domain, while the external zones underwent lithospheric stretching that graded into opening of the Atlantic-related Penninic oceanic zones. This contribution attempts at interpretation of these processes from the point of view of crust dynamics as revealed by deep-seated structural-metamorphic and surface sedimentary records.

Opening and ensuing spreading of the Meliatic branch of Neotethys was initiated in early Middle Triassic and lasted until Late Triassic (245–210 Ma) while overall distensional tectonic regime acted on its broad northern European passive margin. The geodynamic situation changed by the earliest Jurassic, when this shelf underwent wide rifting during Lias to Middle Dogger with formation of extensional, gradually pelagic basins (200–170 Ma). Contemporaneously, subduction of the Meliatic oceanic lithosphere commenced. These processes were likely triggered by a change in large plate kinematics – SE-ward drift of Africa and Adria with respect to Europe during opening of Central Atlantic. The Western Carpathian orogenic wedge nucleated by accretion of material scraped off the subducted Meliatic crust, accompanied by formation of early melanges rich in ophiolite material. In the Middle Jurassic time, the continuing rifting in distal European foreland resulted in breakup of the South Penninic-Vahic Ocean (ca 170–165 Ma). During the next periods, the Western Carpathian orogen behaved as an autonomous converging system driven by the downgoing Meliatic slab.

The Late Jurassic epoch started with incipient collision after closure of the Meliatic basin and by subsequent overriding of the Carpathian Austroalpine passive margin by the Meliatic accretionary complex, including a blueschist nappe (originally a distal passive margin element). In the peripheral foreland, compressional basins developed sequentially in front of thin-skinned thrust sheets of the later Hronic and Silicic nappe systems, which were filled with synorogenic, partly mass-flow deposits with decreasing amount of ophiolitic material (165–155 Ma). Activity of the pro-wedge slowed down during the latest Jurassic – earliest Cretaceous, while the retro-wedge grew at this time (155–140 Ma). After all the Meliata-related oceanic zones were consumed, thrusting relocated to the pro-wedge again, where the Gemeric basement sheets were stacked above the Veporic basement/cover superunit (140–125 Ma). In a coupled system, the collisional crust thickened considerably, as registered by structural-metamorphic and thermochronological data from the Veporic basement.

Throughout the late Lower Cretaceous, the wedge remained in a contractional regime. After foundation of an intracontinental underthrusting zone between the Fatric and North Veporic zones at ca 110 Ma, the pro-wedge began to grow rapidly by incorporation of the entire Fatric-Tatric crust. This was enabled by thermal softening of the Veporic basement and resulting decoupling of the Neotethyan collisional stack from the lower Fatric-Tatric plate. Subsequently the uplifted plug in the wedge centre – supra-Veporic mountainous area, which supplied the mid-Cretaceous peripheral flysch basins with clastic material (110–95 Ma), collapsed by orogen-parallel extension during the Late Cretaceous (90–70 Ma).

Acknowledgements: The author is thankful to the VEGA Scientific Grant Agency (project 1/0193/13) and to the Slovak Research and Development Agency (SK-AT-0002-12) for the financial support.

Possible amounts of tectonic overpressure in the Adula nappe (Central Alps) derived from a new restoration of the NFP-20 East cross section

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Within the NFP20-East cross section through the Eastern Swiss Alps, the Adula nappe is remarkable for eclogite and garnet peridotite lenses testifying to Late Eocene high- to ultrahigh-pressure metamorphism. The pressure values established for these rocks by petrological methods exceed those of the over- and underlying units and define a gradient spanning from c. 17.5 kbar in the north to c. 30 kbar in the south. The oldest pervasive structures postdating high-pressure metamorphism are related to strong top-to-the-north-northwest shearing ceasing under amphibolite- to higher greenschist-facies conditions. Paradoxically, but similar to other ultrahigh-pressure units in the Alps, these movements were top-to-the-foreland, i.e. thrusting movements associated with decompression. Conventional kinematic reconstructions for the exhumation of the Adula nappe assume that peak pressures recorded in different parts of the nappe were lithostatic and combine the depths thus obtained with radiometric ages. In all published kinematic restorations, the Adula nappe is therefore restored to a depth from which it could only be exhumed to mid-crustal levels by a major to-to-the-south normal fault for which there is no evidence in the structural record. As an alternative to such models accepting that large part of the structural history during exhumation may have been completely erased by later shearing, we propose a purely structural restoration of the central part of the NFP20-East cross section. Benefitting from a probably unmatched wealth of structural and geochronological studies performed along this cross section, the new three-step restoration not only takes into account folding and relative movements between individual units but also nappe-internal thinning resulting from shearing which significantly contributed to the exhumation of the Adula nappe. The restoration results in maximum burial depths of the Adula nappe reaching from c. 47 km in the north to c. 62 km in the south. Assuming a density of 2700 kg/m^3 for the overburden, these depths would correspond to pressures between c. 12.4 and 16.6 kbar while the pressures actually observed are c. 40% (north) to 80% (south) higher. Various numerical and analytical studies have shown that tectonic overpressure, i.e. the isotropic part of the stress tensor exceeding lithostatic pressure, can be up to about the same amount as lithostatic pressure for realistic rheological properties and strain rates of rocks. Admitting such an amount of tectonic overpressure would therefore reconcile the petrological and structural records of the Adula nappe. Hence, we suggest to consider the possibility that tectonic overpressure rather than excessive deepening caused the high- to ultrahigh-pressure metamorphism in the Adula nappe.

The central Alps - eastern Alps boundary in western Austria: a crustal-scale cross section

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A N-S oriented crustal-scale cross-section was constructed east of the Rhine valley in Vorarlberg, western Austria, addressing the central Alps - eastern Alps boundary. The general architecture of the examined area can be described as a typical foreland fold-and-thrust belt, comprising, from bottom to top, the Subalpine Molasse, (Ultra-)Helvetic, Penninic, and Austroalpine nappes. These units overthrusted the autochthonous Molasse along a south-dipping listric basal thrust. The European basement together with its autochthonous Mesozoic/Cenozoic cover is found below this basal thrust.

In the northern part of the section seismic data allow to place the top of the autochthonous Mesozoic at a depth of 3500 m BSL with a moderate dip to the south along the cross section. Several seismic sections show normal faults offsetting the top of the European basement as well as the autochthonous cover and the overlying autochthonous Lower Marine Molasse. In the wider area of Lake Constance and the Rhine Valley (SW Germany, NE Switzerland, SE France) the European Basement is characterised by a mostly ENE – WSW striking Palaeozoic trough system. The observed faults are interpreted as fault structures originally belonging to this Palaeozoic trough system and reactivated during the flexure of the lower plate, due to the N-S convergence of the European and the African plates.

This flexure resulted also in the formation of the North-Alpine foreland basin, filled first with Flysch deposits followed by Molasse sedimentation. Due to the ongoing shortening the Subalpine Molasse was multiply stacked, forming a triangle-zone. The shortening within the Subalpine Molasse in the cross section has been calculated using the Lower Marine Molasse as a reference and amounts to approx. 46 km, (~70%).

During top to the N thrusting of the Austroalpine and Penninic nappes the Mesozoic – Cenozoic sediments of the European continental margin were detached from its basement, stacked and thrusted to the N, until reaching their actual position on top of the Subalpine Molasse. This stack is known as the Helvetic nappe stack. The internal structure of the Helvetic nappe stack differs east and west of the Rhine Valley; e.g. the Swiss Säntis nappe contains only Cretaceous sediments, whereas the Vorarlberg Säntis nappe, holding the same tectonic position in the nappe stack, is build up by Jurassic and Cretaceous strata. Former studies supposed the presence of a major fault structure parallel to the Rhine Valley to decouple the tectonic evolution. Based on our data we alternatively trace these differences back to lateral level changes of the detachment horizons, caused by the reactivation of the lateral ramps and the differences in the original thickness of incompetent lower Jurassic basement strata in pre-existing Jurassic basins.

Plio-Quaternary deformation of the Jura mountain belt: a quantitative geomorphology approach

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The Jura mountain belt is the westernmost and one of the most recent expressions of the Alpine orogeny. The Jura has been well studied from a structural point of view, but still remains the source of scientific debates, especially regarding its current and recent tectonic activity. It is deemed to be always in a shortening state, according to old leveling data and neotectonic observations on paleo-meanders of the Doubs river. However, the few GPS data available on the Jura don't show evidence of shortening, but a small extension parallel to the arc. Moreover, the traditionally accepted assumption of a collisional activity of the Jura raises the question of its geodynamic origin. The Western Alps are themselves in a post-collisional regime and characterized by a noticeable isostatic-related extension, due to the interaction between buoyancy forces and external dynamics.

The quantitative morphotectonic approach coupled with neotectonic study applied to Quaternary deposits and speleothems aims to characterize the current tectonic regime of the Jura. In particular, the analysis of watersheds and associated rivers profiles allow quantifying the degree and the nature of the equilibrium between the tectonic forcing and the fluvial erosional agent. Slope profiles of rivers are controlled by climatic and tectonic forcing through the expression:

$$S = (U / K)^{1/n} A^{m/n}$$

(with U: uplift rate, K: erodibility, function of hydrological and geological settings; A: drained area, m, n: empirical parameters).

We present here a systematic study of these profiles coupled with a morphological study of oxbows, which help to identify and characterize the morphological evolution of rivers in response to vertical movements, hence potential tectonic forcing. Associated to this morphotectonic approach, the tectonic analysis of karst cavities located in the vicinity of the main faults of the belt, allowed to characterize tectonically active zones, both in terms of age and displacement's quantification.

Progress in integrated Late Triassic stratigraphy of the Northern Calcareous Alps

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During the Late Triassic, despite new important originations a general decline in biodiversity was marked by a series of steps between the Carnian and the Rhaetian, with the T-J boundary event as final strike. The Reingraben Event and the Julian-Tuvalian boundary are two first massive turnovers; the Carnian-Norian boundary records a major vertebrate turnover, the early to middle Norian boundary comes up with a turnover in both the reefal and pelagic fauna and the most dramatic loss (70%) in biodiversity among Late Triassic molluscs. Around the Norian-Rhaetian boundary, the pelagic fauna of higher trophic level starts declining, whereas the reefs show a blooming time. A refined stratigraphy and a construction of a well-calibrated carbon isotope reference curve are necessary to decipher between gradual environmental changes and abrupt or even catastrophic events during the Late Triassic.

A first step was the formalization of the Late Triassic stages. The base of the Carnian and Hettangian are now formally defined, the base of Norian is still under discussion and the Rhaetian's base is proposed at Steinbergkogel, Austria. Its newly accepted definition is based on the FO of the conodont species Misikella posthernsteini, close to the FO of the ammonoid Paracochloceras suessi, of a radiolarian turnover and of the extinction of most species of the bivalve Monotis. The oldest stratigraphic record of reliably identified coccolithophores lies just below the FO of M. posthernsteini, whereas the FO of the coccolith Crucirhabdus minutus is recorded slightly above. This first appearance takes place along with a discernible increase in abundance of the nannolith Prinsiosphaera triassica, the most important Rhaetian pelagic carbonate producer. These bio-events represent the initiation of the pelagic carbonate production. It is interesting to notice that they occur together with a major turnover in the pelagic fauna of higher trophic level (ammonoids, conodonts, bivalve Monotis) and the beginning of a flourishing time for the reefs.

Improvement in the Upper Triassic delta13Ccarb curve shows that after a gentle increase until the base of the Carnian, the early Carnian records three negative excursions of 2 to 3‰ amplitude. The two first excursions rebound to previous values, whereas the third negative excursion, at the Julian-Tuvalian boundary, is followed by a positive excursion up to +5‰. The remaining upper Carnian displays stabile values around 2‰. The Carnian-Norian boundary interval is marked by a minor increase of less than 1‰. The early to middle Norian crisis is marked by a turning point from lower Norian slowly increasing carbon isotope values to gradually decreasing ones. In the late Norian the isotopic values are relatively stable around 2.5‰, before increasing again in the early Rhaetian and reaching a maximum around the lower-upper Rhaetian boundary. The isotopic record remains constant until the top of the Rhaetian with its significant negative shift identified in a number of marine sections in close proximity to the extinction event.

From an isotopic point of view, only the two lower Carnian excursions, the early-late Carnian boundary and the Triassic-Jurassic boundary can be interpreted as events, whereas other biotic crises of the Late Triassic seem to have occurred during periods of gradual changes in the carbon isotopic composition of seawater.

Base level changes and landscape response in the Eastern Alps: Tectonics versus Climate

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The landscape of the Eastern Alps is strongly bimodal with two observed landscape types that differ in their morphological appearance. At low elevations, in vicinity to the active valley floors, the landscape is characterized by steep topographic gradients, incised gullies and disequilibrium landforms. In contrast, the second landscape type occurs at high elevations relative to the actual base levels and is characterized by low slopes and gentle channel gradients. The transient state of the landscape between the two described landscape types is characterized by planation surfaces located at distinct levels (relict landscape) dissected by deeply incised gorges (modern landscape).

The bimodality and the transient state of the landscape is commonly interpreted in terms of glacial erosion driven by the climate change during the Pleistocene where large parts of the Eastern Alps (e.g. Salzach catchment) were coined by several glaciation cycles, scouring deep alpine valleys and establishing new erosional base levels. However, it is striking that landscapes in the Eastern Alps with minor glacial impact during the LGM (e.g. Mur catchment), are also in a transient state indicated by similar geomorphic features (non-equilibrium channels, migrating knick points and active hill-slopes) suggesting different tectonic or climatic regimes at different time slices. Recently, these observations were interpreted as reaction of the drainage system on new base levels caused by a large scale pulse of uplift since around 5 my.

To understand the evolution of the landscape during the last 5 my we pose the following questions: a) What is the spatial distribution of old versus young landscapes in the Eastern Alps? b) When did the transition from "old" to "young" landscapes start and what are the process rates? c) What are the driving forces for the formation of the young landscape?

In this study we present first results of a detailed and systematic morphometric analysis of drainage systems covering large parts of the Eastern Alps. We compare catchments covering different lithological units with different glacial impact to understand the modes of alpine landscape evolution due to uplift driven topography and erosion driven relief formation.

The catchment wide analysis of digital elevation models shows several eye-catching anomalies in the hyposmetric curves, in the relationship between surface elevation and topographic gradient, in the stream power pattern of the drainage system and in longitudinal channel profiles. First order anomalies detected by these numerical analyses are consistent with numerous field observations on planation surfaces, incised gullies and knick points and can be identified in catchments with and without glacial impact. Therefore we suggest that recent uplift of the Eastern Alps and subsequent incision is NOT only controlled by glacial scouring but shows also a tectonic signal beyond isotactic rebound due to glacial erosion and unloading.

Late Oligocene to Miocene exhumation and cooling history of the Tauern Window (Eastern Alps) – new age constraints

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The Tauern Window exposes a nappe stack of Subpenninic (European lower plate) and ophiolite-bearing Penninic units. It is surrounded by overthrusted Austroalpine nappes (Adriatic upper plate). After nappe stacking and metamorphic overprinting the units within the Tauern Window were refolded and exhumed in Miocene time in response to Adriatic indentation. The western and eastern margins of the window are characterized by two ductile extensional fault zones, the Brenner- and Katschberg shear zone systems (BSZS, KSZS), respectively. Amount of exhumation is greatest in the footwalls of these Neogene shear zone systems.

Rapid exhumation (≥ 1mm/a) in the footwall of the BSZS lasted from 20-15 Ma and was triggered by sinistral transpression along the Guidicarie Belt beginning at 23-21 Ma. Rapid cooling (≥ 25° C/Ma) from 550-270° C lasted from 18-12 Ma (VON BLANCKENBURG et al., 1989; FÜGENSCHUH et al., 1997). In contrast, the exhumation and cooling history of units in the footwall of the KSZS was still poorly constrained. New 40Ar/39Ar laser ablation ages on white micas from the KSZS indicate that mylonitic shearing started at an unknown time before 20 Ma and ended before 17 Ma, as supported by the following arguments: (1) post-kinematic white mica located at the base of the KSZS overgrow the main Katschberg foliation and yields similar ages as found in white mica oriented parallel to the foliation (20.05 ± 0.19 Ma and 19.5 ± 0.17 Ma, respectively) and hence, is interpreted as a cooling age; (2) a sample from the top of the KSZS yields almost identical ages for re-folded and foliation-parallel white mica (17.34 ± 0.16 Ma and 16.48 ± 0.25 Ma, respectively) and are interpreted to date cooling below 400° C. Hence, mylonitic shearing that exhumed the footwall of the KSZS must have ended before 17 Ma. Rb/Sr cooling ages of white mica indicate that cooling from c. 550° C began at c. 22.5 Ma or earlier (Favaro & Schuster et al., in prep.). The end of rapid cooling is poorly constrained owing to the large range of the zircon fission track ages (16-11 Ma; DUNKL et al., 2003; BERTRAND et al. in prep.), which most likely reflects the long time spent within the partial annealing zone of zircon (BERTRAND et al., in prep.).

The age data suggest that Adriatic indentation (23-21 Ma, according to stratigraphical constraints) rather than extension in the Pannonian Basin (starting after 20 Ma) triggered the onset of rapid exhumation in the Tauern Window. The data also suggest that there was a delay in time between the onset of rapid exhumation and rapid cooling in the west, in contrast to the east. The later onset of rapid cooling in the west (BSZS) is probably due to the greater contribution of upright folding and hence, erosional exhumation to total exhumation. In the east the contribution of normal faulting predominates, allowing for a shorter delay time between the onset of rapid exhumation and cooling.

However, an onset of rapid exhumation before 23-21 Ma cannot be excluded in the case of the eastern Tauern Window. An onset of exhumation before Adria indentation would necessitate an alternative trigger for exhumation, e.g., the counterclockwise rotation of the northwards subducting Adriatic slab beneath the Eastern Alps, as inferred from the obliquity of the trace of the slab tip at 150 km depth to the Tauern Window (LIPPITSCH et al., 2003).

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Crystalline nappes in the Cental Alps: case study Suretta nappe and Bernhard nappe complex

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The Suretta nappe in the Grisons (eastern Switzerland) and the Bernard nappe complex in the Valais (western Switzerland) are both part of a major basement-bearing nappe stack attributed to the Middle Penninic nappe system of the Swiss Alps which is derived from the Briançon swell. They formed in the course of Alpine southward subduction of the Briançon swell beneath the Piemont-Ligurian ocean and the Adriatic continental margin and subsequent collision with the European continental margin. Their present-day shape intrigued Emile Argand who reconized much of their structure and kinematics.

The *Suretta nappe* is exposed on the eastern flank of the Lepontine dome in eastern Switzerland. The general axial plunge of about 30° towards the ENE of all units in this area together with the Alpine topography provides an oblique section through the entire Suretta nappe. The Suretta nappe was detached by a basal thrust within the crystalline basement. Its internal structure is governed by a major thrust fault and several folds in the upper part of the nappe. A Permian shallow intrusion (Rofna Porphyry complex) occupies the frontal part of the nappe.

The *Bernard nappe complex* is exposed on the western flank of the Lepontine dome in western Switzerland. It consists of an imbricate stack of basement slices and Permian-Triassic clastics. A large-scale fold is associated with an inverted Permian basin.

The structure of both nappes is controlled by pre-existing structures, leading to regional complexities and differences between and within the study areas, which are difficult to predict in any general model. In the case of the Suretta nappe, Jurassic normal faults probably served as a trigger for the localization of early folds and thrusts, and the occurrence and shape of the Rofna Porphyry complex influenced the level of basal detachment of the Suretta nappe. In the case of the Bernard nappe complex, a Permian graben structure largely controlled the deformation style, i.e. fold versus thrust relationships.

The structural architecture of both the Suretta nappe and the Bernard nappe complex can be interpreted as being basically the result of three main deformation phases:

(1) The Avers phase and the Evolène phase respectively are responsible for the northward detachment of Briançon cover units (e.g. Schams nappes, Klippen nappe) and for the contemporaneous emplacement of Piemont-Liguria rocks (e.g. Avers nappe, Tsaté nappe) onto Briançon basement and its adhered cover. This is a typical example for cover substitution. Relics of brittle deformation features at thrust contacts point to an early brittle thrusting stage, marking the onset of a continuous thrusting history during the Paleocene and Eocene.

(2) The Ferrera phase of the Penninic system of the eastern Swiss Alps equals the Anniviers phase of the Penninic system of the western Swiss Alps. These phases represent the main stage of ductile deformation during nappe formation. Mainly nappe imbrication, associated with isoclinal folding affected the Briançon continental crust. The transport direction is inferred to be NNW and deformation probably took place during the Eocene.
(3) Eocene-Oligocene backfolding and backshearing severely modified the geometry of the Middle Penninic nappes: the Niemet-Beverin phase (in the Grisons) and the Mischabel phase (in the Valais). While thrusting continued at the base of the nappes, large-scale folding affected parts of the nappes. The upper levels of the nappes were strongly affected by top-to-the-S(E) shearing in this process, resulting in the formation of mélange zones. Fold axes associated with this phase constantly trend ENE-WSW in both study areas.

The Tauern Window (Eastern Alps. Austria): a new tectonic map, with cross-sections and a tectonometamorphic synthesis

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We present a tectonic map of the Tauern Window and surrounding units (Eastern Alps, Austria), combined with a series of crustal-scale cross-sections parallel and perpendicular to the Alpine orogen (Swiss Journal of Geosciences in press). This compilation, largely based on literature data and completed by own investigations, reveals that the present-day structure of the Tauern Window is primarily characterized by a crustal-scale duplex, the Venediger Duplex (Venediger Nappe System), formed during the Oligocene, and overprinted by doming and lateral extrusion during the Miocene. This severe Miocene overprint was most probably triggered by the indentation of the Southalpine Units east of the Giudicarie Belt, initiating at around 20 Ma and linked to a lithosphere-scale reorganization of the geometry of mantle slabs. A kinematic reconstruction shows that accretion of European lithosphere and oceanic domains to the Adriatic (Austroalpine) upper plate, accompanied by high-pressure overprint of some of the units of the Tauern Window, has a long history, starting in Turonian time (around 90 Ma) and culminating in Lutetian to Bartonian time (45-37 Ma).

The Tauern Window exposes a Cenozoic nappe pile consisting of crustal slices derived from the distal continental margin of Europe (Subpenninic Units) and the Valais Ocean (Glockner Nappe System). These were accreted to an upper plate already formed during the Cretaceous and consisting of the Austroalpine Nappe pile and previously accreted ophiolites derived from the Piemont-Liguria Ocean. The present-day structure of the Tauern Window is characterized primarily by a crustal scale Late Alpine duplex, the Venediger Duplex, which formed during the Oligocene. This duplex was severely overprinted by doming and lateral extrusion, most probably triggered by the indentation of the Southalpine Units east of the Giudicarie Belt, which offset the Periadriatic Line by some 80 km, beginning at around 20 Ma ago and linked to a lithosphere-scale reorganization of the geometry of the mantle slabs.

While this work hopefully contributes to a better understanding of the three-dimensional structure of the Tauern Window, two important problems remain. Firstly, what was the relative contribution of orogen-parallel extension by normal faulting, escape-type strike-slip faulting and orogen-normal compression, all of which acted contemporaneously during the Miocene? The answer to this question has a strong bearing on the relative importance of tectonic vs. erosional denudation. Secondly, there remains the unsolved problem of the quantification of kinematic and dynamic interactions between crustal (Adria-indentation, Carpathian roll-back and Pannonian extension) and mantle structures (reorganization of the mantle slabs underneath the Eastern Alps) that fundamentally and abruptly changed the lithosphere-scale geometry of the Alps-Carpathians-Dinarides system during a very severe Miocene overprint, initiating at around 20 Ma ago.

Acknowledgements: We greatly benefitted from advice and scientific interaction with R. Schuster, M. Rockenschaub and G. Pestal from the Geologische Bundesanstalt in Vienna, as well as with R. Brandner, A. Töchterle and B. Fügenschuh from Innsbruck University, B. Lammerer from Munich University, W. Kurz from Graz University and E. Kissling from ETH Zürich. We were supported in part by grants from the German Science Foundation (DFG grants Ha 2403/10 and RO 2177/5) and the Alexander-von-Humboldt Stiftung (to SM).

The structure of the Hallstatt evaporite body (Northern Calcareous Alps, Austria): a compressive diapir superposed by strike-slip shear?

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Based on previous detailed mining- and surface geological maps and on own structural observations in the Hallstatt salt mine, we reinterpret the structure of the Hallstatt evaporite body of the uppermost Permian Haselgebirge Fm. within the Northern Calcareous Alps (NCA). The Haselgebirge Fm. is now a rock salt mylonite, which contains, at all scales, abundant lenses of protocataclasite composed of sulphates, mudstones, clay and host limestones. In comparison with results of analogue modeling we interpret the present shape of the Hallstatt body as a WNW-ESE elongated compressive diapir. This diapir is overprinted by N-S shortening and dominantly sinistral shearing along a W-trending shear zone, resulting in elongation and thinning of the evaporite body along the shear zone. The internal structure shows steeply dipping rock units and a steep foliation and the structures are formed by either pure shear flattening or simple shear under mainly subhorizontal maximum principal stresses. Earlier ductile fabrics of likely Early Cretaceous age are preserved in sulphate rocks like anhydrite and polyhalite and are subsequently overprinted by mylonitic fabrics in rock salt and cataclastic fabrics in other rocks. These processes caused cataclastic disintegration of mechanically strong lithologies and the foliation of rock salt wraps around these lenses mainly as a result of shearing.

Because of the low strength of halite, the Hallstatt evaporite body is now subject of recent subvertical shortening and the strain rate of this process could be quantified by deformed subhorizontal boreholes. We quantified the strain rate at 8 x 10-10 [s-1]. This value is similar to such strain rates (10-10 to 10-9 s-1) estimated by the grain size of halite from other salt mines in the NCA (LEITNER et al., 2011). The coincidence of both values argues, therefore, for a sub-recent formation of the halite microfabrics.

Acknowledgements: The work is supported by FWF grant no. P22,728 Polyhalite.

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Chemostratigraphic constraints of marbles from the medium-grade, partly polymetamorphic Austroalpine Basement (Eastern Alps)

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Calcitic marbles of different tectonic units from the Austroalpine Crystalline Basement (Eastern Alps) were studied regarding their geochemical and isotope characteristics. The investigated units, the Greim, Wölz, Rappold, Koralpe-Saualpe, Pohorje, Millstatt, Plankogel and Radenthein Complexes are part of the polymetamorphic Koralpe-Wölz nappe pile, composed of garnet-bearing micaschists and paragneisses, quartzites, amphibolites, eclogite relics and different types of metacarbonate rocks.

For stratigraphic purposes samples were selected by geochemical screening using Mn/Sr- and Rb/Sr-ratios as well as Sr-, C, and O-isotope signals to control their primary compositions. Limiting factors for Mn/Sr are proposed by ≤2 and for Rb/Sr by ≤0.02. Limits for primary isotope ratios are given by the spread of well-established secular Phanerozoic seawater curves. Marbles reflecting primary signals do not exceed 0.70925 for 87Sr/86Sr and O- and C-values scatter between -8 to 0 and -1 to 6‰ respectively (V-PDB).

Although high-P/T metamorphic conditions within the nappe pile may facilitate a high level of post-depositional changes of the signals, a sufficient quantity of samples falls within the primary fields. Mn/Sr-ratios vary between 0.036 and 2.814 and Rb/Sr-ratios between 0 and 0.132. Delta18O- and delta13C-values range from -12.95 to 0.10‰ and -1.58 to 4.78‰ respectively.

The evaluation of the geochemical and isotope signals allows distinguishing two distinct groups of marbles within the Koralpe-Wölz nappe pile. The Rappold, Plankogel and Koralpe-Saualpe Complexes are summarized within group I which is characterized by relatively low and less variable Sr-values (between 0.707997 and 0.708465). In contrast O- and C-data are strongly scattering with ratios between -11.08 and 0.10‰ and -1.58 and 4.78‰ respectively. Just a few samples of this group show altered values not in equilibrium with the primary seawater. Group II, including the Wölz, Greim, Millstatt and Radenthein Complexes, shows variable and relatively high Sr-ratios from 0.708556 and 0.711090, most of them exceeding the possible values provided by the seawater curve. The oxygen-isotope signature fluctuates within -12.95 and -4.01‰ and carbon-ratios scatter from -0.9 and 2.02‰.

For each group a complex showing the best fitting dataset was used for chemostratigraphy by comparing the obtained isotope ratios with the seawater curves. For group I, represented by the Rappold Complex, a deposition age in the late Early to Middle Devonian is likely. Marble-chemistries from the Millstatt Complex as a representative of group II point to sedimentation ages from the late Silurian to the earliest Devonian.

The obtained deposition ages as well as lithologic successions allow comparing both groups with un- or weakly metamorphosed Paleozoic counterparts from the Austroalpine and Southalpine. The lack of an Ordovician magmatic event and a minor influence of the Variscan tectonometamorphic evolution are characteristic for the complexes of group I, lying in the south-eastern parts of the Koralpe-Wölz nappe pile. These facts as well as isotope signatures and ages are similar to the Paleozoic of Graz. Group II, mainly within northern and western areas, however shows similarities with the other Austro- and Southalpine Paleozoic units including the Greywacke Zone, Gurktal nappes, Carnic Alps and the Karawanken.

Lithostratigraphy and internal structure of the Austroalpine units in the Niedere Tauern and northern Gurktal Alps (Eastern Alps, Austria)

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South of Schladming, between the Enns and Liesing valley in in the North and the Mur valley in the South the Niedere Tauern form an about 100 km long West-East orientated mountain chain with a rough morphology. Its peaks reach up to 2800 m in the West and drop down to about 2400 in the East. South of the Mur valley the Gurktal Alps are characterized by a smoother landscape and a lower altitude. The whole area is built up by nappes of the Austroalpine unit. Crystalline basement rocks are dominating, whereas metamorphosed Permomesozoic sedimentary sequences occur in some places. As indicated by fission track ages the break in morphology is due to Neogene south dipping normal faults including the Prebersee and Seetal fault (EDER & NEUBAUER, 2000). However, the position of the normal fault system and the internal structure and lithostratigraphy of the Austroalpine nappes was only locally known until now.

The tectonic lowermost Upper Austroalpine nappes in the area belong to the Silvretta Seckau nappe system. These nappes consist of Neoproterozoic to Ordovizian paragneisses (partly magmatic), micaschists and amphibolites. Orthogneisses of presumably Ordovizian and/or Carboniferous intrusion age occur and partly a post-Variscan cover including Permian metaconglomerates and metapelits and Lower Triassic quartzites is preserved. The medium to high grade imprint in the basement rocks occurred during the Variscan tectonometamorphic event, whereas only greenschist facies metamorphic conditions were reached during the Alpine event in the Cretaceous. Nappes of the Silvretta-Seckau nappe system built up antiformal structures in the West (Schladminger Tauern) and East (Seckauer Tauern) of the Niedere Tauern.

On top of the Silvretta Seckau nappe system several nappes of the Koralpe-Wölz nappe system occur. They consist of Neoproterozoic to Devonian sequences dominated by micaschists and paragneisses with intercalations of marbles, quartzites and amphibolites. From bottom to top the Ennstal phyllite, Wölz (including Gensgitsch Complex), Greim, Rappold and Radenthein Complex can be distinguished. A Permian upper greenschist facies imprint is proofed for the southern parts of the Wölz Complex, whereas amphibolite facies and the intrusion of pegmatites can be recognised in the Greim and Rappold Complexes. The Alpine metamorphic grade increases from lower greenschist facies at the base to amphibolite facies in the Rappold Complex, whereas the overlying Radenthein Complex shows again a greenschist facies imprint.

Good outcrops of the south dipping Neogene normal faults are scarce, but they can be localised by mapping the boundaries of the crystalline complexes. Between the southern slopes of the Niedere Tauern and the Mur valley they dissect the Cretaceous nappe pile and create a complex pattern in map view. One major fault continues from the “Lessach phyllonit lamella” along the northern boundary of the Rappold Complex until Schöder. Further to the East some of the faults are turning to Southeast and most probably continue into the Görschitztal fault at the western margin of the Seetaler Alpen and Saualpe.

Rb-Sr biotite ages covering large parts of the area range from 60 to 87 Ma. They are interpreted to reflect cooling of the rocks below 300 °C. Their distribution is complex and can’t be explained by the Neogene fragmentation alone.

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Listvenite from Serbia as Gemstone Resource

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Listvenite occurrences in Serbia are mostly related to Jurassic ophiolites of Vardar zone, but also to the Palaeozoic ophiolites in Eastern Serbia, as hostrocks which were altered by hydrothermal fluids genetically related to Late Oligocene-Early Miocene volcanic activity. In the last decades listvenite exploration was mainly focused on potential ore mineralisation, while minor attention was related to study the gemstone within listvenite. Therefore, this paper focuses on the study of mineralogical and petrologic characteristics of listvenite in terms of utilisation as a gemstone and, in addition, to estimate preliminary the overall potential of listvenite as a resource of gemstone and decorative stone.

Samples of listvenite were obtained from trenches and outcrops. Optical and scanning electron microscopy methods were used to study gemstone minerals, which were also subjected to trial lapidary processing.

In the Fruska gora listvenitized serpentinites the Kozje Brdo deposit and numerous smaller deposits and minor occurrences of silica gemstones were explored. Relatively small masses of Late Oligocene – Early Miocene volcanic rocks had enough heat source which enabled formation and circulation of hydrothermal fluids which altered serpentinite along the tectonised zones and led to formation of listvenite. The gem raw materials of the Fruska Gora mountain are represented by chalcedony and carbonate-silica breccia with agate. Magnesite is the oldest mineralisation phase of hydrothermal activity, highly tectonically shattered, and subsequently pervaded and cemented by dolomite, ankerite and calcite with admixed silica.

The Vuckovica deposit of carbonate-silica breccia and greyish-blue agate is located around 15 km southwest of Kragujevac in a small listvenite/serpentinite mass in tectonic contact with Cretaceous sediments. Numerous magnesite-dolomite-silica veins 0.1 - 3 m thick occur in this serpentinite, among which the most decorative is serpentinite breccia cemented by carbonate and silica minerals. In the veins magnesite is tectonically broken and subsequently cemented by dolomite and silica (opal-chalcedony) of green, greenish-dark or yellow colour.

The Sirca occurrence is located around 5 km ENE of the Kraljevo town. Gemstones occur within small lens of hydrothermally altered serpentinite, which is in tectonic contact with surrounding Early Cretaceous sandstone and marlstone. During Late Oligocene – Early Miocene volcanic activity, listvenite was formed and later on partly covered by labradorite andesite and pyroclastics of the third volcanic phase. Post volcanic hydrothermal fluids reacted with serpentine minerals forming carbonate-silica onyx, colourless chalcedony, opal, silicified magnesite and quartz crystals.

Palaeozoic listvenite in Eastern Serbia is hosted in structures within an obducted ophiolite sequence of mainly gabbroic rocks with associated serpentinite. Listvenite as gemstone resource was studied at the Antina cuka deposit, around 15 km SSW of the Kucevo town. The Antina cuka listvenite appears as small lenses formed at the contact of andesite and serpentinite. According to mineralogy and petrography, they are subdivided into serpentine-rich, silica-rich and silica-carbonate-rich varieties, all of which can be used as an attractive gemstone.

The potential of listvenite deposits and occurrences in Serbia as a resource of dimension stone is restricted due to the small volume of deposits. On the other hand, favourable aesthetic and polishing properties of the listvenite make them a very potential resource of gemstone and decorative stone.

Acknowlegments: This research was partly financed by the Ministry of Education and Science of the Republic of Serbia (Projects number 176006, 176016 and 176019).

Towards a quantitative evaluation of the degree of coincidence between the orientation of a magnetic fabric of deformational origin and the stress tensor calculated from microtectonic measurements

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In the geophysical and geological literature both the magnetic susceptibility tensor (k) used for the evaluation of magnetic susceptibility anisotropy (AMS) measurements and the stress tensor (T) of fault tectonics determined by inversion methods are associated with the deformation of the material in some extent. Although the relation of these tensors to the strain tensor is widely debated, results of AMS and tectonic measurements on identical or close localities from the Transdanubian Range demonstrated fairly good agreement between the directions of the extension calculated from the results of the two independent approaches. Beyond the graphical similarity of the stereograms (especially the directions of the principal axes associated with the ellipsoids of the tensors) we aim to establish a statistical framework to provide a quantitative comparison.

The main difficulty in the quantitative comparison is that the number of computed parameters is typically different for the two tensors: while it is 6 for the AMS tensor, it is less or equal to 6 for the stress tensor (the exact value depends on the specific inversion method used to determine the stress). This fact permits to apply such transformations, when one, ore more (maybe all the three) tensor invariants of T and k coincide. By this transformation in hand we accommodate Hotelling's T-squared distribution to establish a multivariate test to investigate our null hypothesis stating T=k. As long as the computed significance level exceeds the conventional 5%, the null hypothesis is accepted. This approach can be extended to provide a quantitative comparison between a vector and one of the principal directions of a tensor. For example, in case of extensional deformation, which is the dominant mode of tectonic deformation during Cenozoic in the Transdanubian Range, it is possible to investigate the degree of coincidence between the principal axis of the minimal compressive stress (i.e. the direction of the tension) and the direction of the magnetic lineation (i.e. the principal axis with the largest eigenvalue of k). Several examples for such applications will be presented for Eocene and Oligocene clay rich localities with well-developed magnetic fabric from the Transdanubian Range.

Acknowledgements: This work was supported by OTKA (Hungarian Scientific Research Fund) project no. 105245.

New constraints on kinematics and timing of the Periadriatic Fault System from the petrology and Lu-Hf apatite geochronology of Giudicarian magmatic lamellae and the Presanella intrusion (Southern Alps, Italy)

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The Periadriatic Fault System (PFS) extends from west to east over 700 km through the Alps. Along this prominent Tertiary corridor of strike-slip faulting all the major Alpine intrusions are emplaced. The Adamello batholith is the largest of these intrusions consisting of five major intrusive units with a progressive younging towards the NE from mid-Eocene to mid-Oligocene times. The Presanella tonalite is the youngest of these intrusive units. It is located where the W-E to WSW-ENE trending dextral transpressive Tonale fault segment of the PFS is truncated by the SSW-NNE trending Giudicarie fault. Along the northern Giudicarie fault (NGF) a sequence of magmatic lamellae is aligned. To constrain the intrusive relationships and the age of these magmatic lamellae with respect to the Adamello batholith, we analyzed major and trace element compositions of the igneous units and dated representative samples by Lu-Hf apatite geochronology. Five samples were taken from the NW Presanella, the NE Presanella, and the southern Rumo, northern Rumo and Meran lamellae. Petrologically, the Presanella samples represent tonalites, while the Rumo and Meran lamellae have quartz-dioritic compositions, but differences in modal composition are small. All five samples define a metaluminous, sub-alkaline trend. The most significant feature is the decreasing SiO_2-content from SW to NE with the exception of the northernmost sample from the Meran lamella displaying a slightly higher SiO_2-content than the northern Rumo lamella sample. Trace element characteristics indicate a syn- to post-collisional setting. Epsilon Hafnium-values of all bulk rock samples are negative and very similar ranging from -3.5 to -4.2, except for the sample from the NW Presanella with a slightly lower radiogenic composition (ε_{Hf} = -5.1). As expected, apatite separates from the NE Presanella and the Meran lamella exhibit high Lu/Hf-ratios and radiogenic Hf isotope compositions. Calculated whole rock-apatite Lu/Hf-ages of the two samples range from 30-32 Ma, with errors of less than 1 Ma, and overlap within error. Since the closing temperature of apatite is very high (>650°C; BARFOD et al., 2005), these ages can be assumed to represent intrusion ages. The small variations in petrology and geochemistry of the Presanella intrusion and the magmatic lamellae as well as the corresponding apatite Lu-Hf ages suggest that both originate from the same magma source. Variations within the Adamello batholith and even within the Presanella intrusion are larger than the variations between NE Presanella and the three investigated magmatic lamellae samples from the NGF. This observation together with the field record of a tectonic rather than an intrusive emplacement with intense brittle deformation (POMELLA et al., 2011) imply that the magmatic lamellae have been tectonically dissected from the NE Presanella intrusion and transported up to 50 km northwards by sinistral transpressive displacement along the NGF.

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What Happened 5 Million Years Ago in the Alps?

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There is rising evidence that some 5 million years ago a surface uplift event started in the Alps that caused a renewed and ongoing phase of tectonic activity. This uplift event appears to encompass not only the Alps, but also the surrounding regions including the foreland basins (in particular the northern Molasse basin), the Styrian and Vienna basins in the east and parts of the Bohemian Massif. The event is particularly visible in the eastern half of the orogen where topography is lower, convergence is more active and pervasive Miocene strike slip tectonics provides a backdrop against which the Post-Miocene events may be evaluated more clearly than in the west. The evidence includes (i) young karst-cave formation ages at elevations high above current ground water tables, (ii) the indirect evidence of ancient fissions track ages at surface elevations above 2000 m, (iii) bimodal landscapes with substantial planation surfaces about 500 meters above current valley floors (iv) coalification and compaction studies in the sedimentary basins surrounding the eastern Alps, (v) current geodetic surface uplift rates, as well as: (vi) numerical modeling evidence that appears to indicate that the Alps are geomorphologically premature. Overall, it appears that some 1000 m of surface uplift occurred within the last 5 million years. Along the eastern margin of the Alps, the event has been described as an inversion event in the sedimentary basin and has been brought in connection with the cessation of a subduction zone underneath the Carpathian arc. However, the event appears to be associated with little horizontal tectonics and it is regionally widespread, so that we suspect that more deep-seated drivers are responsible. The implications of the event for the discussion around tectonic versus climatic drivers as causes or consequences of young erosion and tectonics in the Alps are profound: Modern consensus holds that the global deterioration of climate some two million years ago is the principal driver for the youngest phase of uplift and erosion in the Alps. We argue here that the glaciation of the Alps was only possible because the 5 million year tectonic event uplifted the range enough so that an icecap could form. As such, we diplace the "chicken or egg debate" (currently in the vogue of climatic drivers) one step back: We argue for a deep seated uplift event as the cause for glaciation in the Alps.

Statistical analysis of a huge fault database around the bend of the Western/Eastern Alps

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The internal arc of the Western and Central Alps underwent an important brittle deformation stage, expressed on the field by meso-scale to kilometric scale brittle structures. Regional paleostress studies achieved all around the arc highlights two distinct extensional phases.

The first is an orogen-parallel extension phase, dated of about 10 Ma using pseudotachylites in the Lepontine Dome (ALLANIC & GUMIAUX, 2013). The strike of the extensional axes turns with the alpine arc, from the Lepontine Dome to the back of the Argentera massif. This major signal increases to the NE of the belt, and could be compatible with the roughly E-W extension observed in the Eastern Alps, particularly within the Tauern

Window, where the maximum age of the brittle deformation at 20 +/-1 Ma is given by the ZFT ages, whose closure temperature is ~240°C±10°C (BERTRAND et al., in prep.).

The second brittle deformation phase corresponds to an orogen-perpendicular extension. This last one becomes more important toward the South of the belt, especially in the Briançonnais zone, from the Vanoise massif to the North of the Argentera massif. This phase appears to be linked to the current activity of the belt, as shown by seismotectonics, especially in the Briançon area (review in SUE et al., 2007).

This paper focus on a new global statistical approach of the sub-databases available, that we compile in a huge database of more than 12.000 individual measurements all-around the bend of the Western/Eastern Alps. Beyond the paleostress mapping, we propose to statistically characterize both extensional phases. Assuming that the second one (perpendicular) is linked to the current activity of the belt, itself ruled out by isostatic processes, we concentrate on the first orogen-parallel extension, which origin remains a matter of debate. “Unfolding” the alpine arc, using a simple geometrical modeling of the belt, allowed unraveling the surprising stability of the orogen-parallel extension in the Whole Western, Central, and Eastern Alps. This approach rises up the issues of (i) the geodynamic origin of this extension developed during Miocene times within an active collisional belt; (ii) the precise timing of its development; and (iii) its continuity between Western and Eastern Alps in terms of both kinematics and time.

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The abandoned Remshnig mine, occurrence of rare minerals; Palaeozoic or Tertiary ore mineralization?

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Parallel with the Pohorje mountainous chain and north of the Drava River, a hilly area of Kobansko extends in northern Slovenia. In the central part of the region, polymetallic Remshnig mine is situated in the thrust zone of weakly metamorphosed old Palaeozoic rocks of the Magdalensberg formation, the Remshnig nappe in the hanging wall, and the retrogressed schists of the Pohorje formation in the footwall. Though the Remshnig ore deposit is known more than 250 years, its origin and mineral association is still not known completely. Some new findings are presented in this contribution. The results are based on field observations and SEM investigations.

Macro- and microstructures of the rocks reveal several phases of tectonic activity, including twice reactivated subhorizontal shear movements, due to which dynamometamorphic imprint can be followed in all rocks. The first one reflects as ductile deformations, yielding mylonitization and foliation. The second shear produced slaty cleavage, which broadly follows foliation. The origin of these two structures is associated with upper Cretaceous nappe stacking and Tertiary Austroalpine eastward escape (e.g. FODOR et al., 1998, 2002, 2008). Own unpublished model of the Pohorje tectonic block origin suggests that Pohorje and Kobansko/Kozjak were still one common block at the time of the Pohorje granodiorite magma emplacement in Lower Miocene and were separated later.

Hydrothermal ore mineralization and silicification follow slaty cleavage in partly brecciated marmorized dolomite lenses and subordinately in metatuffites and phyllites. Younger oblique fractures cut foliation and slaty cleavage, developed as a consequence of renewed shearing. Secondary cleavage plains were formed indicating dextral sense of shear. All structures are cut by younger subvertical faults of prevailingly southwest-northeast trend, and subordinately transversely to this direction. These fractures are not silicified and contain no primary (sulphide) ore mineralization.

The present state of investigations does not allow strict definition of the Remshnig ore deposit genesis. Nevertheless, some important relations can be drown, which neglect its Palaeozoic origin: ore mineralization occurs within the thrust zone; sulphide mineralization and strong silicification followed cleavage, which is of Tertiary (probably of Miocene) origin; the Kobansko block separated from the Pohorje block in middle to upper Miocene and Kobansko was until then, within the impact area of the granodiorite intrusion; mineral composition and sulphur isotope composition of the Remshnig and Okoska gora (Pohorje) ore deposits are closely related (DROVENIK et al., 1976, 1980). Consequently, there is a great probability that the Remšnik ore mineralization is connected to the Miocene Pohorje magmatism, as has already been proposed by some authors. The question is, whether the mineralization could be related to remobilization of pre-existing ore minerals.

Characteristic Remshnig mine ore veins are composed mostly of quartz and carbonates, of which the most frequent is dolomite. Paragenesis of predominant Pb, Cu and Zn silver-bearing sulphide ore minerals is represented mostly by chalcopyrite, galenite, sphalerite and pyrite. They are associated with numerous secondary minerals. Among them, coatings of two rare hydrous sulphates of Cu and Zn occur, found for the first time in Slovenia. The emerald green, tabular monoclinic crystals of slightly rounded shape and only some tenth of millimetre in size were determined as ramsbeckite. Platy, hexagonal crystals most probably belong to namuwite. Its submicroscopic structure and small quantity have not permitted reliable determination, yet.

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The tectonometamorphic evolution of the Austroalpine Complexes in the Vinschgau (Ötztal Complex, Campo-Ortler Complex, Texel Complex) in the course of the mapping project CARG 012 (sheet Schlanders)

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The Austroalpine nappe stack in the investigated area, located in the Vinschgau area (Southern Tyrol), comprises from bottom to top the Campo-Ortler (COC), the Texel (TC), the Ötztal (ÖC) complexes and the Matsch (M) nappe. All these units have been known for a long time and were essentially defined based on the degree and age of their metamorphic overprint. Their delimiting faults are only partly well known (e.g. Vischgau shear zone (VSZ), Schneeberg Fault Zone (SFZ) while in other areas they are hard to pin down. This is partly due to the lack of obvious fault rocks such as mylonites or cataclasites as well as to missing petrological/geochronological data (e.g. the contact between TC and ÖC).

The currently mapped sheet Schlanders (CARG 012) offers the chance to carefully investigate the above mentioned units and their tectonic contacts and to implement them into a tectonic model based on new petrological, geochronological and structural data.

Based on our current observations the tectonic contact beween the ÖC and the overlying M nappe is characterized by a two-stage evolution. A subhorizontal mylonite layer can locally be mapped, revealing a top-to-the-west sense of shear. Unfortunately these mylonites can not be continuously traced and therefore the exact position of the contact between ÖC and M still stays enigmatic. Especially in places where the inferred Permian dykes are missing within the M nappe the paragneiss and micaschist lithologies can hardly be attributed to either of the two nappes. The younger overprinting contact is fully brittle and marks the southern contact of the ÖC and M nappes near the Vinschgau valley. There several meters thick cataclasites and gouge layers offset and obliterate the original mylonitic contact. The nature of this E-W trending contact is not yet fully understood since arguments in favour of a south-directed thrust as well as a top-north normal fault could be found. Most likely the mylonitic contact has be folded prior to brittel faulting.

The VSZ, marked by mylonites and ultramylonites in the northern flank of the Vinschgau valley can be traced along a steeply west-dipping synform/antiform pair towards north(east) and finally into the SFZ. The exact location of the triple point between ÖC, TC and Schneeberg complex has still to be mapped. Yet another and more southerly located segment of the VSZ remains to be looked for at the contact between the Texel complex and the Meran Mauls basement.

In conclusion the Schlanders map sheet is a key area for deciphering the pre-Eoalpine (ÖC-M contact) as well as the Tertiary (post-nappe folding/faulting) evolution of the Eastern Alps.

How good do simple experiments using natural rocks reproduce natural observations and theoretical calculations: selected examples ranging from high-P to high-T settings

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The metamorphic evolution of a rock can be deciphered using three approaches: 1.) the practical geothermobarometric approach, 2.) the theoretical pseudosection approach and 3.) the experimental approach. Whereas with the first two approaches it is possible to constrain several stages of the P-T-X evolution, the experimental approach allows mostly only the investigation of a distinct P-T condition of a rock. On the other hand, experimental investigations allow to put additional constraints on the evolution of a rock under defined P and T conditions. These constraints consider additional variables such as textures, aH_2O, nH_2O, fO_2 etc. In order to obtain results as close as possible to the natural rocks it is best to use natural rocks as starting materials. The disadvantage of this method being the complex chemical compositions of the rocks and therefore the deviation from chemical end-member systems. Therefore these experiments need to be evaluated not only 1.) in terms of their ability to reproduce the natural observations but also 2.) in their ability to reproduce theoretical calculations. In this study, a brief summary of three experimental investigations from a variety of P-T settings will be given with respect to the points discussed above.

The first example are the high-T low-P experiments concerning contact metamorphism of metapelites at the rim of the Permian Brixen Granite. In order to put experimental constraints on the temperature of contact metamorphism, experiments were performed in a hydrothermal apparatus at 0.3 GPa and temperatures of 580°C and 650°C using two natural quartzphyllite samples from the area as starting materials. The agreement between the observed textures and mineral compositions therefore allows putting additional constraints on the T conditions of this contact metamorphic event. On the other hand it was not possible to reproduce the variation of Na contents in cordierite throughout the contact aureole.

The second study deals with the experimental investigation of high-P/high-T granulites from the Bohemian Massif. Large bodies of felsic high-P/high-T granulites with the assemblage quartz + ternary feldspar (mesoperthite) + garnet + rutile ± kyanite occur in the Southern Bohemian Massif. They are thought to have formed during the Variscan orogeny in a Carboniferous subduction setting, at 950-1050°C and 1.5-1.9 GPa, from granitic protoliths. We used granitic gneiss as starting material whose chemical composition almost perfectly matches the main granulite type of the Southern Bohemian Massif. Although the natural phase assemblages were well reproduced, the presence of F in the starting material lead to severe inconsistent results concerning theoretical calculations.

The third study is concerned with the gabbro-eclogite transformation. The aim of this study was to provide experimental constraints on the gabbro-eclogite transition and compare the results to the locality Bärofen in the Koralpe (Styria, Austria) where a well-described gabbro-eclogite transformation has been observed. The experimental investigations using natural starting materials used drilled cores of fine-grained gabbros from the Odenwald. Recalculation of the mineral assemblages assuming relevant buffer assemblages was only partly successful. The experiments have shown that it was possible to reproduce 1.) microtextures, present in the Bärofen locality and 2.) mineralogical changes as a function of P, T, $a(H_2O)$ and fO_2.

Overall there is a surprisingly good agreement between the experiments and the natural observations, theoretical calculations are still hampered by minor elements (e.g. F) not considered in the claculations so far.

From orogenic buildup to extensional unroofing: the evolution of the Adria - Europe collisional zone in the Medvenica Mountains of Croatia

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Quantifying the kinematics of the Miocene extension in the Pannonian Basin is of critical importance for understanding the evolution of Adria-Europe collision in particular in the transitional zone from the Alps to the Dinarides. Recent studies have demonstrated that large-scale extensional unroofing along low-angle detachments have affected the Europe-Adria contact in the Dinarides during Miocene times. The relationship between this extensional exhumation of Adriatic units in the Medvednica Mountains (Croatia), the roughly coeval Miocene extension affecting the Alpine-derived units during E-ward extrusion and the formation of the Pannonian Basin is still unknown and the focus of this study.

The Medvednica Mountains, a NE-SW striking mountain range within the internal Dinarides, has been the focus of a field kinematic study, complementary low-temperature thermochronology (apatite fission track), metamorphic petrology, isotope dating (Rb-Sr measurements) and microstructural analysis. The observations indicate that the mountains consist of two units, reflecting distinct Adriatic paleogeographical positions. The upper unit contains Paleozoic mostly fine-grained clastic sequence metamorphosed in sub-greenschist facies, overlain by a proximal Adriatic facies consisting of Triassic shallow water carbonates. The lower unit is made up by a volcanic sequence overlain by Triassic carbonates metamorphosed in greenschists facies that bears a strong resemblance to the Triassic break-up volcanism and subsequent sedimentation affecting the distal Adriatic units observed elsewhere in the Jadar-Kopaonik unit of the Dinarides. The strong contrast between the Middle-Upper Triassic facies of the Medvednica Mountains suggests large scale thrusting during Cretaceous nappe stacking.

Subsequently, the studied area has been affected by significant extensional deformation creating the present-day turtleback geometry. This resulted in the formation of brittle normal faults in both units, locally tilted by the uplift of the mountain core, which indicate mostly NE-SW extension. The lower unit is affected by a pervasive deformation characterized by a wide mylonitic shear zone with stretching lineations indicating consistently top-NE to E sense of shear. Low-temperature thermochronology and absolute age dating (in progress) will clarify the exact ages of nappe-stacking and subsequent extensional exhumation.

The present-day geometry of the mountains was established during the Pliocene-Quaternary inversion.

Furthermore, the results demonstrate that the extensional geometry and sense of shear is typical for the Miocene extensional exhumation and basin formation that affected the Adria-Europe contact elsewhere in the Dinarids, e.g. Kozara-Prosara-Motajica and Fruska Gora extensional structures. By comparing similar extensional features observed in for instance the Rechnitz and Pohorje extensional structures, the combined study potentially demonstrates that the Miocene mechanism of extension and sense of shear is structurally coherent at the scale of the entire Dinaridic and Alpine margins.

The influence of the rotation of Adria and extension in the Pannonian Basin on lateral extrusion in the Alps: insights from crustal-scale models

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The influence of slab-pull induced extension in the Pannonian Basin and rotation of the Adriatic indenter on lateral extrusion processes in the Eastern Alps has been studied through analogue crustal scale modeling. Extension at high angle to the shortening direction has been implemented in the models; these are analogues for the northward convergence of the Adriatic plate and the coeval back-arc type extension in the Pannonian Basin.

Cross-sections and top-view images of the models have been analyzed in detail using particle tracing techniques (DPIV) which enables to calculate surface vector fields and visualize strain localization and block rotations. In the models the amount, timing and direction of extension have been the main variables together with a 20 degrees counter clockwise rotation of Adria. Additionally, a rigid buttress simulating the Bohemian Massif has been implemented, thereby decreasing the width of the area that can accommodate deformation.

The modeling results demonstrated that all models feature a compressional, strike-slip and tensional domain from west to east, respectively. The strike-slip (extruding) domain shows ‘en-bloc’ rotations in response to displacement velocity variations. The crustal blocks are bounded by conjugate strike-slip faults, which is indicative for lateral extrusion processes. When extension is present the amount of rotation increases, the extruding domains propagate further to the west and the direction of extrusion is parallel to the direction of extension. When extension was ceased whilst convergence continued the extruding domain decreased in size but remained active.

The models which included rotation of Adria, are characterized by the absence of conjugate strike-slip faults and the area that accommodated extrusion is decreased. Thus, it is probable that an indenter rotation has a negative effect on the lateral extrusion tectonics and amount of extension. However, when a Bohemian Massif type boundary was present, along with rotation of Adria, the amount of extension and development of conjugate sets of strike-slip faults are similar to models without rotation. Due to the increase in wrenching, in response to a narrow domain that could accommodate deformation, the models actually featured an increase in the amount of conjugate faults.

The results of this study imply that slab-pull driven extension in the Pannonian domain facilitates the lateral extrusion processes in the Eastern Alps and determines the direction of lateral displacements. A 20 degrees counter-clockwise rotation of Adria does not enhance lateral extrusion whereas the presence of the Bohemian Massif type boundary in the north does, as it fosters the formation of extrusion type fault systems. Furthermore, ongoing lateral extrusion despite stagnation of back-arc extension is in line with recent GPS data.

The Alps/Apennines boundary: structures and kinematics of interfering orogens and comparison with other modern analogues

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Although debated for more than one century, the relationship between the Alps and Apennines remains a puzzling geologic question.

The Alps and the Apennines presently form two independent and adjacent segments of the Alpine orogen. They have opposite tectonic vergence, W/NW for the Alps, and E/NE for the Apennines, both oriented roughly perpendicular to their arcuate trends. The junction area of the two chains is characterised by tectonic domains (MOLLI et al., 2010) resulting from the kinematically complex interaction between the opposite dipping subductions active in the last 30 Myr, i.e. east-southeast "alpine" and west-northwest "apennine". At the junction deformation is represented by extensional fault system and basins development overprinting distributed, crustal-scale contractional structures and widespread block rotation.

Our understanding of the tectonic evolution of this junction can take advantage of comparisons with modern convergence systems such as the Ryukyu-Taiwan, Southern Chile-South Sandwich, Colombia-Lesser Antilles, Hikurangi-Puysegur, Manila-Philippine, New Guinea-Solomon-New Hebrides. In these other modern systems we can identify tectonic architectures controlled by both the structural association and the relative evolution of single structures and basins.

Here we analyse the differences of structural/tectonic evolution of junction areas as a function of the ways that plates kinematically interact. We also present the Alpine-Apennine junction as a key area to understand the dynamics of crustal evolution of interfering convergence systems.

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Low thermal evolution of the Southern Veporic Unit crystalline basement (Central Western Carpathians) constrained by new fission track data

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New thermochronological data, combined with a previous one and geological knowledge enable to constrain the Late Cretaceous to Neogene tectono-thermal evolution of the southern zone of Veporic crystalline basement. Presented zircon and apatite fission track (FT) data can be correlated with sixth principal tectono-thermal stages. During the late Early Cretaceous period (TS1; ~120–90 Ma), the Veporic crystalline basement was buried below the palaeo-Alpine nappe stack in the depths of ~20–30 km and suffered a greenschist- to amphibolite-facies metamorphic overprint (~350–600°C and ~500–800 MPa). The Alpine metamorphism culminated with maximum temperatures at ca. 120–90 Ma and cooled below the 40Ar/39Ar blocking temperature on mica mostly between 90 to 80 Ma ago. After burial an orogen-parallel extensional exhumation and unroofing of the Veporic domain occurred during the Late Cretaceous to Palaeogene (TS2; ~90–35 Ma). The exhumation of the Veporic domain is documented by zircon FT ages of 75–71 Ma and apatite FT ages of 63–55 Ma, indicating a "rapid" cooling phase during the Late Cretaceous to Palaeocene followed by moderate cooling phase from the Palaeocene to Early Eocene. The exhumation of the Veporic domain continued till the Late Eocene–Bartonian, as it was revealed by preservation of its erosion level due to transgression of the Late Eocene sediments. The Late Eocene to Early Miocene period (TS3; ~35–20 Ma) is related to burial beneath the Upper Eocene to Oligocene strata. The Oligocene sedimentary sequences with thickness less than ~1.5–2.0 km were deposited on uncovered Veporic crystalline basement with only minor indication of reheating. The Early to Middle Miocene period (TS4; ~20–13 Ma) is characterized by uncovering of the Veporic domain after the deposition of the Late Palaeogene to Early Neogene sedimentary sequences. The Early to Middle Miocene denudation of the Veporic domain almost completely removed the Palaeogene sedimentary sequence before the creation of the Sarmatian Veporic volcano-plutonic complex. The obtained apatite FT data of Palaeogene cooling ages from the Slávča and Hrdzavá valleys near the Tisovec intrusive complex revealed that the wider area was not regionally reheated by the mid-Miocene thermal event. The volcanic activity at the centre of the Veporic volcano-plutonic complex occurred during the Middle Miocene (TS5; ~13–11 Ma), according to $^{40}Ar/^{39}Ar$ dating results. The mid-Miocene thermal event was revealed also by zircon FT age of 13 Ma. However, the extent of contact aureole did not exceed more than 1 km, according to maintain of low-thermal Palaeogene record in its neighbourhood. The final exhumation of the Veporic domain occurred in the Neogene to Quaternary times (TS6; ~11–0 Ma). An intensive denudation processes were documented by removing of at least the 1500 m of volcano-sedimentary rocks of upper stratovolcanic structure (cone) during the last 10 Ma. In addition, preservation of the planation surfaces suggests a relatively young (Pliocene and Quaternary) but most probably not so intensive exhumation of the mountains.

Acknowledgement: This work was supported by the Slovak Research and Development Agency under the contracts Nos. APVV–0625–11 and by the VEGA No. 1/0193/13.

Permian metamorphism and magmatism in the internal Western Alps: Constraints from high spatial resolution U-Th-Pb geochronology

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Evidence of the late Paleozoic HT-evolution in the Western Alps remains a controversial issue. As in other parts of the Alps, magmatic and metamorphic effects in the basement reflecting the Variscan HT-orogeny are well known, but the situation is not so clear for the subsequent Permian evolution. Permian extension in the Adriatic lithosphere has been linked to asthenosphere upwelling, causing high temperature metamorphism at medium pressure and widespread partial melting, which led to upper crustal magmatic activity (e.g. Marotta & Spalla, 2007). However, the relation of the magmatism to the associated metamorphism is well documented in a few areas only, and age control is generally poor. This is particularly true for the Western Alps, where Permian metamorphism has long been proposed, but so far radiometric age data are lacking.

In this study, the use of high spatial resolution geochronology (SHRIMP and LA-ICP-MS U/Th-Pb dating) in combination with structural and petrological methods has proved successful to fill some of the gaps in the current knowledge on the pre-Alpine metamorphic evolution of several Austroalpine units of the Western Alps.

In the SW part of the Sesia Zone, in the II DK unit, upper amphibolite to granulite facies metamorphism was dated at ~277 Ma and at ~270 Ma in metapelites. A leucosome dates at ~290 Ma.

In the eclogitic micaschist complex (EMC), the Corio-Monastero metagabbro contains zircon with rims that crystallized at HT metamorphic conditions and date at ~277 Ma. Local recrystallized rims yield ages at ~230 and ~190 Ma, indicating two (fluid-induced?) episodes. During exhumation this gabbro was intruded by dikes. In one of these zircon shows two age populations at ~270 and ~235 Ma. Two intermediate to felsic intrusions in the EMC yield ~277 and ~266 Ma.

In the Valpelline Series of the Dent Blanche unit, three stages of amphibolite to granulite facies metamorphism are evident: The age data show ~287 Ma, ~274 Ma, and ~263 Ma. These metamorphic stages clearly postdate the Variscan metamorphic cycle, which occurred around 350 Ma, as confirmed by this study.

In the Emilius Klippe preliminary results indicate a Permain HT evolution as well: Basic intrusives have been dated at ~290 Ma (compare BUSSY et al., 1998) and a granitic intrusive at ~283 Ma. Zircon and allanite, both interpreted to be of metamorphic origin, cover an age range clustering at ~276 Ma.

These ages, together with petrological data, evidence that the middle and lower crust in several Austroalpine units in the internal Western Alps experienced a regime of high temperature in Permian times. The time span recorded in zircon ranges between ~290 and ~260 Ma. Age relics of the Variscan orogeny are sparse, and so far no evidence has been found of the regional HT metamorphism at ~310 Ma, known in the Ivrea Zone (e.g. EWING et al., 2013). It remains to be explored whether the differences among age data are due to differences in the Permian metamorphic history of these units or whether they merely reflect chemical differences (e.g. in the growth of zircon) due to local compositional differences or the structural position of the samples analyzed.

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3D FEM modeling of fold nappe formation in the Western Swiss Alps

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Many three-dimensional (3D) structures in rock, which formed during the deformation of the Earth’s crust and lithosphere, are controlled by a difference in mechanical strength between rock units and are often the result of a geometrical instability. Such structures are, for example, folds, pinch-and-swell structures (due to necking) or cuspate-lobate structures (mullions). These structures occur from the centimeter to the kilometer scale and the related deformation processes control the formation of, for example, fold-and-thrust belts and extensional sedimentary basins or the deformation of the basement-cover interface. The 2D deformation processes causing these structures are relatively well studied, however, several processes during large-strain 3D deformation are still incompletely understood. One of these 3D processes is the lateral propagation of these structures, such as fold and cusp propagation in a direction orthogonal to the shortening direction or neck propagation in direction orthogonal to the extension direction. Especially, we are interested in fold nappes which are recumbent folds with amplitudes usually exceeding 10 km and they have been presumably formed by ductile shearing. They often exhibit a constant sense of shearing and a non-linear increase of shear strain towards their overturned limb. The fold axes of the

Morcles fold nappe in western Switzerland plunges to the ENE whereas the fold axes in the more eastern Doldenhorn nappe plunges to the WSW. These opposite plunge directions characterize the Wildstrubel depression (Rawil depression). The Morcles nappe is mainly the result of layer parallel contraction and shearing. During the compression the massive limestones were more competent than the surrounding marls and shales, which led to the buckling characteristics of the Morcles nappe, especially in the north-dipping normal limb. The Doldenhorn nappe exhibits only a minor overturned fold limb. There are still no 3D numerical studies which investigate the fundamental dynamics of the formation of the large-scale 3D structure including the Morcles and Doldenhorn nappes and the related Wildstrubel depression. We study the 3D evolution of geometrical instabilities and fold nappe formation with numerical simulations based on the finite element method (FEM). Simulating geometrical instabilities caused by sharp variations of mechanical strength between rock units requires a numerical algorithm that can accurately resolve material interfaces for large differences in material properties (e.g. between limestone and shale) and for large deformations. Therefore, our FEM code combines a numerical contour-line technique and a deformable Lagrangian mesh with re-meshing. With this combined method it is possible to accurately follow the initial material contours with the FEM mesh and to accurately resolve the geometrical instabilities. The algorithm can simulate 3D deformation for a visco-elasto-plastic rheology. Stresses are limited by a yield stress using a visco-plastic formulation and the viscous rheology is described by a power-law flow law. The code is used to study the 3D fold nappe formation, the lateral propagation of folding and viscoplastic necking from an initially localized perturbation and also the lateral propagation of cusps due to initial half graben geometry. Thereby, the small initial geometrical perturbations for folding and necking are exactly followed by the FEM mesh, whereas the initial large perturbation describing a half graben is defined by a contour line intersecting the finite elements, where more numerical integration points are applied.

Micro-seismic characterization of the Fribourg Lineament - Switzerland

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This analysis investigates low-magnitude seismicity generated within the Fribourg area (Western Molasse Basin (WMB) - Switzerland). It focuses on the Fribourg Lineament (FL), an alignment of weak seismicity that showed recent signs of increased activity (KASTRUP et al., 2007). The FL runs in a North-South direction east of the city Fribourg and is parallel to the Fribourg syncline. Orientation of these two features differs strongly from the surrounding tectonic structures that show a general SW-NE trend.

The FL has been monitored since 2010 by two sparse mini-arrays (seismic navigating systems - SNS). Each SNS consists of one central 3D short-period (1Hz) sensor surrounded by three 1D short-period (1Hz) sensors. They are deployed in a tripartite geometry with an aperture of 100 m, which is best suited for azimuth and apparent velocities determination of incoming signal (JOSWIG, 2008). The recordings of the two SNS are complemented by records of three permanent stations of the Swiss Seismological Service (SED).

Event detection is done by visual event screening of continuous data sonograms (SICK et al., 2012). Sonograms are spectrograms based on power spectral density (PSD) matrix, noise adapted, muted and pre-whitened. Special features of sonograms allow for the extraction and recognition of earthquake signals by visual pattern recognition near to 0 dB signal to noise ratio. Detected events are then located using HypoLine, a software especially designed for SNS. Event location is done interactively whereby simulation results are immediately updated after every single parameter change. This enables to optimal use of prior information, such as geological knowledge, when determining hypocenter location in the multiple probable solutions (JOSWIG, 2008). Both the densification of the seismic sensors around the FL and the increased detection power of sonogram analysis permits lowering the detection threshold of the Earthquake Catalog of Switzerland (ECOS) by about one order of magnitude in the FL area. Our comprehensive catalog of earthquakes detected within the FL after 2010 comprises more than 200 events.

A set of seismic lines interpreted by InterOil was used to build a 3D structural model of the WMB. Fault planes have been extrapolated to the surface across five horizons from top basement to base of the Tertiary cover. An initial analysis of our seismic catalog shows that most of the local micro-seismicity is located in the sedimentary cover. Some events are collocated with interpreted structures; however, an important part of the seismicity is located in areas without known substructures (due to the lack of seismic lines). Since many earthquakes have similar origins over time, signal cross-correlation is used for collocation purposes and in order to identify possible fault zones.

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Provenance analysis and paleogeography of the Gosau Group (Upper Cretaceous - Paleogene) in eastern Austria and western Slovakia

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The Upper Cretaceous to Paleogene sediments of the Gosau Group of the Northern Calcareous Alps (NCA) are unconformably and diachronously overlying folded and faulted Permian to Cretaceous units. Various Gosau Group deposits representing different basins are exposed at the eastern part of the Eastern Alps (Austria) at the south-western margin of the Vienna Basin, and at the western part of the Western Carpathians (Slovakia). In between, NE-SW-striking Gosau sediments are drilled in several wells below the Neogene fill of the Vienna Basin. The Gosau deposits were folded during the Alpine orogeny, and today form structurally complex synclines. From north to south several synclines on different tectonic units of the NCA and on Carpathian units are present: the northernmost Gießhübl Syncline, the Prottes Gosau Group, its Slovakian equivalents of Studienka and Brezová, the Glinzendorf Syncline and the southernmost Grünbach Syncline.

About 250 fine-clastic samples from outcrops, drill cores and cuttings of various Gosau locations and formations have been geochemically analyzed (bulk rock). Additionally, heavy mineral contents of coarse-clastic sediments (523 samples) have been evaluated and more than 600 grains of garnet, chromian spinel and tourmaline have been analyzed by electron micro probe with the aim to reconstruct the hinterland of the Gosau sediments and to distinguish different Gosau basins and to decipher the paleogeographic evolution in this area.

A general trend from chromian spinel dominated heavy mineral spectra of the Coniacian to the Campanian/Maastrichtian to a garnet dominated up to the Paleogene (plus relatively high amounts of tourmaline within the Slovakian Studienka area) can be observed for all Gosau deposits. Almandine is generally the dominant garnet component. Only Coniacian to

Campanian samples from the paleogeographically more southern Glinzendorf and Grünbach basins have significantly lower almandine and higher pyrope and grossular contents. These garnets are partly derived from a metamorphic sole remnant of Neotethys ophiolites to the south and this hinterland supplied only southern Gosau basins until Campanian age in contrast to the ordinary granitic to metasedimentary hinterland which is present for both northern and southern basins. In addition, these structurally high ophiolitic nappes, later on completely eroded, supplied mainly the paleogeographically southern Grünbach and Glinzendorf Gosau basins with ultramafic detritus represented by chrome spinels of a mixed harzburgite/lherzolite composition and high Cr and Ni as well as high Cr/V ratios in relation to low Y/Ni in associated shales. No direct indications for a northern ophiolitic source, the Penninic or Alpine Tethys accretionary wedge to the north of the Gosau basins, could be found. In the younger part of the Gosau basins fill, from the Maastrichtian to the Eocene, only almandine-rich garnets could be observed suggesting a southern provenance from low-grade metamorphic metapelites of exhuming Austroalpine metamorphic complexes. Ophiolite detritus is reduced in the Maastrichtian and disappears in the Paleogene. Major and trace elements generally indicate a mixture of different hinterland compositions and tectonic settings as source of the Gosau basins.

The St. Veit Klippenzone in Vienna - missing piece in the Alpine-Carpathian klippen puzzle

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The St. Veit Klippenzone (SVK) comprises a succession of mainly Mesozoic rocks in western Vienna and the Wienerwald area. Outcrop situation is generally extremely bad in this area, and thus a modern analysis of these disputed klippen strata was completely missing. In recent years unique exposures of the SVK and adjacent flysch formations were available due to a large railroad tunnel (Lainz Tunnel). This contributes significantly to the correlation of the SVK to other klippen zones and it's geotectonic position (Helvetic vs. Penninic vs. Austroalpine).

Geochemistry, heavy mineral data, isotope geochemistry and microfacies studies were used to describe and interpret the strata. Biostratigraphic results include data by macrofossils (rare ammonites) radiolaria, calpionellids and nannofossils.

The SVK and its overlying flysch units build a major tectonic unit within the nappe pile of the Eastern Alps in the Wienerwald area west of Vienna. Coming from the Vienna valley (Auhof), going SE, the tunnel hit first rocks of the Kahlenberg Nappe, up to 2165.5 m, then followed by rocks of the SVK. The SVK was found in a 1097 m long section within the Lainz tunnel. It comprises largely a block in matrix structure, partly tectonically mixed with flysch units (Hütteldorf Formation, Kahlenberg Formation). Tectonic blocks of hard klippencore rocks show sizes from cm to several tens of meters. The matrix consists of strongly deformed fine-grained rocks such as Jurassic and Lower Cretaceous shales and marls. No primary sedimentary contact of the flysch formations onto the SVK could be detected which precludes the interpretation that the SVK constitutes a primary basement for the Rhenodanubian Flysch.

The composite Klippenzone succession recorded within the tunnel and reported from additional outcrops in the area of the Lainzer Tiergarten (Vienna) includes the following stratigraphy: (1) coarse quartz sandstones (Norian/Keuper), (2) fossiliferous grey limestones (Rhaetian), (3) sandy-silty grey marls and limestones with crinoids (Lower/Middle Jurassic), (4) red chert and red shale (Bajocian-Oxfordian), (5) grey marl to argillaceous limestone (Tithonian-Valanginian), (6) aptychus limestones (Neocomian), (7) white silicified limestone (Berriasian), (8) green chert (Valanginian).

The geotectonic position of the St. Veit Klippenzone can be discussed based on our results and comparison samples from the Pieniny Klippen Belt (PKB). Neither the Gresten Klippenzone (Helvetic/Ultrahelvetic units of the European continental margin) nor the Ybbsitz Zone (Penninic units including Ophiolite remnants) provide similar successions. In contrast to former interpretations, a more reasonable correlation can be done with Austroalpine units, i.e. facies successions of the Lower Austroalpine Units (e.g. Mesozoic of Semmering and Radstädter Tauern), and the northernmost marginal units of the Northern Calcareous Alps, based on the occurrences of Keuper sandstones and Rhaetian limestones, and Jurassic strata. Thus, a "northern" Austroalpine derivation seems to be reasonable for the SVK. Comparing with the Western Carpathians we find strong similarities with the Drietoma unit, a unit which has affinities to Lower Austroalpine-Fatric elements such as the Krizna Nappe (i.e. Keuper strata), but was lateron affected by Klippen-style tectonism and incorporated into the PKB. Thus, the St. Veit Klippenzone can be seen as the westernmost extension of the Pieniny Klippen Belt (in a tectonic sense) in Austria and neither belongs to the Helvetic nor to the oecanic Penninic paleogeographic realms.

Composition of the Bohemian spur in the subsurface of the Eastern Alps: indications from exotic blocks

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The Bohemian Massif continues below the Eastern Alps as a basement promontory often referred as Bohemian spur (Tari, 2008). According to surface geology and wells in the Alpine foreland it consists of Variscan basement rocks of the Moldanubian and Moravian unit overlain on both sides by transgressive post-Variscan sediments (Wessely, 1987). However, the continuation of the Bohemian spur below the Alps can be inferred from exotic blocks embedded in the Allochthone Molasse representing the northernmost and youngest tectonic units of the Alps. The exotic material allows an insight in the geology of a hidden segment of the former southern margin of Europe towards the Penninic Ocean.

The Allochthone Molasse consists of sediments deposited in the Alpine foreland basin, incorporated as tectonic slices into the orogenic wedge after 17.5 Ma. Its main part (Schuppenmolasse) is composed of Eggenburgian to early Ottnangian claystones, sandstones and conglomerates. North of the Danube an overlying slice (Waschbergzone) containing additional Paleogene sediments and tectonic slices of the Jurassic and Cretaceous cover of the underlying basement is present. Layers with exotic blocks of crystalline basement appear in early Ottnangian sediments. Such blocks from several outcrops in Lower Austria have been investigated by geochemical and geochronological methods to get information on their source area.

At Waschberg exotic material shows a polymict composition dominated by granites, often with amphibole and pinkish K-feldspar, and granitic gneisses. Further granite-porphyries, migmatic paragneisses and minor amphibolite and marble occur. The blocks are mostly well rounded, badly sorted and reach up to more than 1 m in size. Most probably this material represents debris flows generated from preexisting local gravel accumulations. At Heuberg blocks of monomict biotite-granite are exposed. They are not rounded or sorted and the largest ones are more than 10 m in length. This debris flows originated from a fault scarp (Gebhardt et al., 2008).

Granite and granitic gneiss blocks and pebbles show an overall peraluminous composition. Additionally higher SiO_2-contents connected with increased Rb/Sr-ratios indicate considerable magmatic fractionation of largely S-type granites. Nevertheless granites with pinkish K-feldspar exhibit low $^{87}Sr/^{86}Sr$-initial ratios (0.705 – 0.707, 300 Ma) pointing to a significant I-type component in the magmatic source. Rb/Sr cooling ages of biotite from 12 samples (granites, granitic gneiss, migmatic paragneiss) range from 300 to 230 Ma, arguing for a prolonged cooling history of the hidden Bohemian spur.

By comparing the hidden part of the Bohemian spur which is indicated by the exotic blocks with the adjacent Variscan basement shows obvious differences. The granites of the Moravian unit, which are closest, are clearly different, with I-type composition (FINGER et al., 1989) and Neoproterozoic magmatic ages (FRIEDL et al., 2004). The Moldanubian unit contains a wide range of I- and S-type granites (VELLMER & WEDEPOHL, 1994). They are characterized by magmatic ages of 340–310 Ma (FINGER et al., 2009) but their cooling ages (320–310 Ma, SCHARBERT et al., 1997) are different from the granites of the exotic blocks. Younger cooling ages (around 290 Ma) are known only in the southwestern part of the Moldanubian unit in Upper Austria. The granitic gneisses of the Subpenninic unit in the Eastern Alps are predominantly early Permian in age (VESELÁ et al., 2011) and show mainly I-type composition. At least in the surrounding Variscan basement is no magmatic suite with granites comparable to the investigated exotic blocks.

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Analogue modelling of continental subduction with laterally changing subduction polarity

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Tomographic images from the Alps reveal southeasterly-directed subduction of the European mantle lithosphere in the central Alps and a north-easterly dipping subduction of the Adriatic mantle lithosphere underneath the Eastern Alps. We studied the deformation and surface expression of this lateral change in subduction polarity by using lithospheric-scale physical models. The main parameters investigated for uni-polar and bi-polar subduction systems of the continental lithosphere are: (a) the weakness of the plate interface, (b) the presence of weak lower crust (c) the width of the transition zone between the oppositely dipping slabs.

The results of the analogue experiments show that upper crustal deformation initiated at the plate interface by the formation of a pop-up structure. Along the inclined plate boundary lithosphere-scale underthrusting and a significant amount of Moho displacement occurred. The downgoing plate experienced upper crustal thrusting and a foredeep basin developed. The thickness of the weak-zone interface plays a key role in the amount of continental subduction, and consequently on the onset of intraplate deformation, which occurs only after the weak interface is consumed or sufficiently thinned. However, continental collision and coinciding mantle lithosphere subduction beneath an orogenic wedge takes place only if the lower crust is weak enough to allow crust-mantle decoupling. During collision weak lower crust partly subducts, while the detached part thickens below the orogen affecting the upper crustal deformation pattern and topography.

From the bi-polar subduction models it can be observed that the first pop-up structure is laterally continuous pointing out its independence on the vergence and obliquity of subduction. Ongoing deformation causes the formation of a second pop-up structure on the downgoing plates resulting in lateral asymmetry and the development of a narrow transition zone. Cross sections of the model illustrate an asymmetry in the upper crustal wedge with a clear pro- and retro- side. On the contrary, a wide and symmetrical orogen overlying a vertical slab of mantle lithosphere is characterizing the zone of subduction polarity change, which is also the region of relative low topography. These lateral variations in crustal architecture are expected to be a direct response of lateral input variations of lower crust and mantle lithosphere. However, the width of the zone where interaction of crustal structures related to the different subduction domains occurs exceeds the initial with of the transition zone considerably. In additions, cross-sections reveal the underlying importance of lateral coupling between the mantle lithospheres of opposing dipping slabs resulting in subduction resistance forces on one hand, but in down bending of the neighbouring overriding plate on the other hand.

Our modelling results can be compared with the crustal and lithosphere-scale structure of the Alps, where the orogenic wedge in the Western Alps is asymmetric and a relatively large pro-wedge overlays the downgoing European plate. Eastwards, the upper crustal deformation is more symmetrically distributed above the colliding plates, and the orogen widens reaching maximum values along the TRANSALP profile. Hence, lateral variations of the crustal architecture (symmetry of mountain belts) may be indicative for changes in the subduction polarity of the lower lithosphere.

Pre-Alpine and Alpine Tectonic evolution of the western and northern parts of the Gurktal and Bundschuh nappe system

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The western and northern margin the Gurktal Nappe is classically defined as a structure of Alpine nappe emplacement with Permomesozoic sediments (nappe separators) decorating the thrust. The tectonic boundary stretches from Radenthein northwards and bends sharply to the east heading towards the Turrach sattle. Structural studies along that boundary display a complex tectonic history. (1) The contact between the Pfannock Gneiss and the Königstuhl Conglomerate is interpreted as late-Carboniferous cataclastic fault zone that formed in the course of exhumation of the crystalline and coeval deposition of Carboniferous sediments. Cataclastic pebbles are present within the Carboniferous sediments and suggest exhumation prior to deposition of rocks. The pre-Carboniferous fault can be traced all along the eastern and southern margin oft he Pfannock Gneiss. (2) The Pfannock Schuppe includes an inverted suite of Permian to Mesozoic sediments. It is interpreted as a tectonic sliver with the Pfannock Gneiss in the core of a northwest vergent fold. Shearing and folding is correlated with Cretaceous northwestward nappe stacking. (3) The actual geometry of the boundary is result of bulk extension during the late Cretaceous. Extensional structures with E- to SE displacement dominate N-S trending segments, dextral strike-slip zone the W-E trending segments. The overall geometry can be described as eastward spreading units with normal faults forming extensional bridges between strike-slip domains.

3D thermo-kinematic modelling of a crustal-scale low-angle normal fault: the Katschberg detachment, Eastern Alps.

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In this study we investigate a low-angle normal fault of the Eastern Alps, the Katschberg detachment. This major structure developed during Miocene lateral extrusion and is largely responsible for the exhumation of the eastern Tauern Window. We investigate two E-W profiles that extend 25 km in the footwall and 20 km into the hanging wall. An extensive set of already published and new thermochronological data provides the basis for 2- and 3-D thermokinmatic models. We use a finite-element code (Pecube) to solve the heat equation in 3D and predict the thermal evolution around the Katschberg detachment under given spatially and temporally variable boundary conditions. An inversion routine is used to find the best-fitting parameter combination, which reduces the misfit between modelled and measured thermochronological ages.

According to our preliminary inversion the Katschberg normal fault was active from 21.4±2.2 Ma until 8.3±1.7 Ma with a mean slip-rate of 2.6±0.5 km/Ma, integrating to an offset along the fault of 33.8±4.1 km. This agrees with previous studies, that suggest that the Katschberg detachment was active between ~23 and 12 Ma.

Middle- to Late Miocene exhumation of the central Eastern Alps: new structural-, fission track and apatite (U-Th)He data.

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New structural-, fission track and apatite (U-Th)/He data refine the Eocene/Oligocene to Late Miocene exhumation history of the Seckauer- and Niedere Tauern in the Eastern Alps. Both areas belong to the Austroalpine basement units but experienced different temporal and spatial exhumation. The Seckauer Tauern already cooled to upper crustal levels (2-3 km) during Eocene times, followed by stagnation and very low erosion rates. In contrast, the Niedere Tauern cooled to upper crustal levels during the Middle- and Late Miocene, contemporaneously to the Penninic units within the Tauern Window. Structural investigations suggest that the displacement between these two Austroalpine units occurred along the northern section of the Pöls-Laventtal fault system. We suggest that extrusion became not only lateral in terms of parallel to the trend of the Eastern Alps, but was characterized by a displacement vector at a high angle to the strike of the orogen. This resulted in exhumation of the Niedere Tauern and Pohorje Block that were exhumed within extensional bridges at the northern and southern termination of the Pöls-Lavanttal fault system, respectively.

Thermal modeling of an external Unit of the Eastern Alps - the Helvetic zone of western Austria and Upper Allgäu

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The Helvetic zone of the Eastern Alps is a thin-skinned fold-and-thrust belt comprising Jurassic to Cenozoic shelf deposits. They were detached from their substratum during Cenozoic nappe formation. From the Oligocene onward, they were transported to the north and thrust onto the Alpine Foreland Basin, carrying the Penninic and Austroalpine units piggy-back.

To study the thermal evolution of this external part of the Eastern Alps, maturation of organic matter was measured using vitrinite reflectance. Organic rich dark-colored shales and carbonates build a large part of the Helvetic stratigraphic succession. Fission track dating was done to obtain some time related temperature information on the thermal evolution of the Helvetic nappes. In order to get a more complete image, samples from the Subalpine Molasse in the footwall and from the overlying Penninic Rhenodanubian Flysch were included. Apart from surface outcrops deep wells (Dornbirn 1, Hohenems, V-Au1, Kierwang 1 and Maderhalm 1) were sampled as well. Modeling was done using the PetroMod 2001.1 software by Schlumberger Ltd.

Vitrinite reflectance measurements from the Helvetic zone yielded three different trends: first of all a stratigraphic trend is given – the mean reflectivity (%Rr) decreases for about 0.4% from the Malmian Quinten Limestone to the Late Cretaceous sandstones of the Garschella Fm. Secondly, coalification rises with increasing depth (ca. 0.3%Rr per km). Finally, coalification in general increases from north to south, starting at the high volatile bituminous coal stage and reaching the low volatile bituminous coal- to semi-anthracite stage along the Penninic thrust contact. Measurements deep well samples show a coalification trend that is offset along numerous faults which are known from the drill record. Therefore, a pre- to syntectonic coalification of the Helvetic units has to be claimed.

Preliminary apatite fission track data show that all investigated units were subjected to post-depositional temperatures above the APAZ (i.e. >120°C) since all grains are fully reset. Partially reset zircon samples from few analyzed samples from Helvetic and Rhenodanubian Flysch units argue for maximum temperatures between 180 and 300°C.

By combining results from coalification and fission track analyses a maximum overburden of more than 8 km could be modeled for the Early to Late Oligocene.

INTERNATIONAL FOSSIL ALGAE ASSOCIATION

Abstract volume

9th - 11th September 2013
Schladming, Austria

Editorial:

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Mesozoic dasycladalean algae from Romanian Carpathians: diversity, environment and palaeogeographic context

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Dasycladalean algae are important constituents of the shallow-water carbonate sediments of the Mesozoic. The Romanian Carpathians contain such deposits with an extensive development during the Triassic, Late Jurassic and Early Cretaceous.
From the Middle Triassic (Anisian-Ladinian) carbonate platform deposits are known in the Eastern Carpathians (Rarau and Persani Mountains), Southern Carpathians (Sasca zone) and Apuseni Mountains (Padurea Craiului massif). During Anisian the dasycladalean assemblages are dominated by species of the genera *Oligoporella* and *Physoporella*, and in Ladinian by *Diplopora* si *Teutloporella*. These assemblages developed most frequently in internal platform environments (lagoons) and comprise species with limited stratigraphical range, important for biostratigraphy. It is worth mentioning the global uniformity of these associations.

During the Upper Jurassic the dasycladalean assemblages of the Romanian Carpathians are related to the development of the carbonate platforms that generated to so-called Stramberk-type limestones (e.g., Haghimas, Piatra Craiului and Vanturarita Mountains in the Eastern and Southern Carpathians; Trascau massif in Apuseni Mountains). The dasycladalean assemblages developed either in inner platform environments, with dominance of the genus *Salpingoporella*, or in platform margin environments, where large species of the genera *Petrascula*, *Steinmanniporella* or *Triploporella* are dominant. The late Jurassic carbonate platforms extended also in the Neocomian.

A new stage of the shallow-water carbonate sedimentation developed during the Barremian-Aptian giving rise to the Urgonian carbonate platforms. In the Romanian Carpathians such platforms are known from Rarau, Haghimas and Persani Mountains (Eastern Carpathians), Dambovicioara and Resita-Moldova Noua zones (Southern Carpathians) and Apuseni Mountains (e.g., Bihor-Padurea Craiului unit). During the Early Cretaceous the dasycladalean algae reached their maximum of diversity, and beside *Triploporellaceae* (mostly *Salpingoporella* species) frequent *Dasycladaceae* are known (e.g., *Neomeris* and *Montiella*), present in both internal and external parts of the platforms. The Early Cretaceous seems to represent also a time interval with more dasycladalean provincialism. It is well known the southern-Tethyan affinity of *Salpingoporella dinarica* (a species which is not known from the Romanian Carpathians) as well as the existence of some species with limited palaeogeographic range to the Carpatho-Pontic area (e.g., *Kopetdagaria sphaerica* or *Conradella bakalovae*).

Aknowledgemets: this is a contribution to the research project PN-II-ID-PCE-2011-3-0025

Calcareous algae from the olistoliths at Poiana Zanoaga, northern part of Piatra Craiului Syncline (Southern Carpathians, Romania)

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The Piatra Craiului Massif is a major syncline structure in the Southern Carpathians. Its flanks consist of Middle and Upper Jurassic-Neocomian carbonate deposits, while the filling is represented by conglomerates assigned either to the Upper Aptian, or to the terminal

Albian (Vraconian)-Cenomanian (SANDULESCU et al. 1972, BUCUR et al. 2009). In the northern area of the syncline (Poiana Zanoaga) these conglomerates include large limestone olistoliths. The olistoliths were assigned by POPESCU (1967) and SANDULESCU et al. (1972, map 1:50.000, sheet 110b Zarnesti) partly to the Tithonian and partly to the Barremian. Most of blocks consist of peritidal deposits with frequent fenestral limestones. They contain relatively rare microfossils, including cuneolinid foraminifers documenting the Barremian age. Nevertheless, some of the olistoliths proved to be very rich in fossils, with the dominance of large dasycladaleans easily noticeable on alteration surfaces (eg., the olistolith from the peak known as 'Silha lui Caita').

The following microfacies types dominate the fossil-rich olistoliths from Poiana Zanoaga: coarse bioclastic grainstone, ooidic grainstone, fine peloidal bioclastic fenestral grainstone, intraclastic grainstone/packstone, bindstone with bacinellid structures and various bioclasts, coral-microbial boundstone, intraclastic wackestone (microbreccia).

The microfacies types indicate various sectors of the carbonate platform: from the platform margin (bioconstructions), to the external platform/open internal platform with high hydrodynamics (coarse bioclastic shoals), and to peritidal environments (microbial mats and fenestral structures).

The foraminifers we have identified: *Pseudocyclammina lituus*, *Charentia evoluta*, *Coscinophragma cribrosa*, *Mohlerina basiliensis*, *Protopeneroplis ultragranulata*, *Nautiloculina bronnimanni*, *Andersenolina alpina*, *Andesenolina* cf. *sagittaria* and *Andesenolina perconigi* document an Upper Tithonian-Berriasian age (eg., ARNAUD-VANNEAU et al. 1988, BUCUR & SASARAN 2005) for these limestones.

The calcareous algae are represented by *Petrascula bursiformis* (Etallon) (very frequent), *Petrascula* sp., *Pseudocymopolia* cf. *jurassica* Dragastan), *Salpingoporella pygmaea* (Guembel), *Suppiluliumaella* sp., *Terquemella* sp., and rare specimens of *Clypeina sulcata* (Alth), *Nipponophycus* sp. *Diversicallis dianae* Dragastan & Bucur as well as rivulariacean-type cyanobacteria. Among the problematic microorganisms, we have notices *Lithocodium aggregatum*, sometimes associated with the foraminifer *Troglotella incrustans*.

The above-mentioned calcareous algae are also typical for the Upper Tithonian-Berriasian interval (eg., BUCUR 1999).

Acknowledgements: This study is a contribution to the CNCS project financed through the PN-II-ID-PCE-2011-3-0025 grant.

Lower Cretaceous calcareous algae form the Khur area, Central Iran

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Cretaceous strata are very thickly developed, widely distributed and superbly exposed in the Khur area of Central Iran. They are part of the sedimentary succession of the so-called Yazd Block, the western structural element of the Central-East Iranian Microcontinent (CEIM), an independent microplate within the complex Mesozoic plate tectonic mosaic of the Middle East. During the Cretaceous, the CEIM was detached from Eurasia and surrounded by small oceanic basins which opened and closed in response to (inferred) counter-clockwise rotational movements of the microplate.

The Cretaceous succession starts with conglomerates and sandstones of the up to 1000-m-thick Chah Palang Formation (Upper Jurassic?-lowermost Cretaceous) covering Palaeozoic-Triassic basement rocks or weakly metamorphic rocks of the Shemshak Group (Upper Triassic-Liassic). The levelling of the palaeo-relief continued with the following, up to 500-m-thick Noqreh Formation (interbedded terrestrial to marginal marine sediments) and the carbonate platform deposits of the Shah Kuh Formation (WILMSEN et al. 2013).

The calcareous algae discussed herein have been found in sample from the Noqreh and the Shah Kuh formations. The age of the two formations range between Barremian and Late Aptian, as indicated by the foraminiferal association: *Balkhania balkhanica* Mamontova, *Dictyoconus pachymarginalis* Schroeder and *Mesorbitolina texana* (Roemer).

The calcareous algae association comprise several species of Dasycladales [?*Clypeina* sp., *Deloffrella quercifoliipora* Granier & Michaud, *Montiella*? *elitzae* (Bakalova), *Morelletpora turgida* (Radoicic), *Neomeris* cf. *cretacea* Steinmann, *Neomeris* cf. *srivastavai* Granier, Dias-Brito & Bucur, *Pseudoactinoporella*? *iranica* Bucur, Rashidi & Senowbari-Daryan, *Terquemella* spp., ?*Triploporella* sp.] and Bryopsidales (*Boueina* cf. *hochstetteri* Toula, *Boueina* cf. *pygmaea* Pia, *Permocalculus minutus* Bucur, *Permocalculus* sp.).

This algal assemblage is generally similar to the one identified in the central-western part of the Yazd block (Aliabad area) by BUCUR et al. (2012) except for *Morelletpora turgida*. It is noteworthy that *Pseudoactinoporella*? *iranica* has now been identified for the first time ouside Aliabad, its type locality.

The algae from Khur area provide new data for comparisons between different regions of Central Iran (Ardekan, Aliabad, Khur) as well as additional data concerning the paleogeographic position of the Yazd Block and geodynamic history of the CEIM during Barremian and Aptian times.

Zeapora - an endemic Devonian 'praecodiacean' of Graz or a common tropical cosmopolitan?

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In his 1894 monograph on Devonian fossils of the Graz Palaeozoic Karl A. PENECKE (1858-1944) designated by monotypy the new genus *Zeapora*. He assigned it to cyclostomate bryozoans because the representative feature, 'a hollow central axis surrounded by only one row of prismatic cells', he thought to be unique for the bryozoan order. The history of *Zeapora* is one with many problems concerning the systematic assignment: RUKHIN (1938) included it in his new stromatoporoid family Amphiporidae, BASSLER (1953) assigned it to the Trepostomates, SOKOLOV (1955) to thamnoporid tabulate corals, FLUEGEL (1959) to dasycladacean and finally HUBMANN (2000) to halimedalean algae. The confusing story about *Zeapora's* systematics and its little adequate taxonomic description was probably the reason why this genus was ignored by palaeo-phycologists. Thus, *Zeapora* had the sad fate to remain endemic over 100 years! However, in our opinion younger synonyms of *Zeapora* PENECKE 1894 are hidden among Devonian algal genera, i.e. *Botrys* SCHIRSCHOVA 1985 and *Litanaella* SHUYSKY & SCHIRSCHOVA 1987. Both genera were recorded from the Lower to Middle Devonian (Emsian and Eifelian). Occurrences of *Botrys* are known from the eastern slopes of Northern Urals (Karpinsky horizon), and from Bosnia (Klek). Findings of *Litanaella* are reported from the eastern slopes of Northern Urals (Parminsky lot, Ivdel' region), Dinant Syncline, Belgium (Couvin Lmst.), New South Wales, Australia (Sulcor Lmst.), and Southern Tien Shan, Usbekistan (Norbonak Beds). The compilation of these localities on a Devonian geographic base map results in a peculiar distribution within the equatorial belt comparable to present-day *Halimeda*. This distribution pattern can be well explained by circum-equatorial currents.

Silurian non-calcified algal flora from the Kalana Lagerstaette, Estonia

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The non-calcified algal floras were probably widespread in the Paleozoic seas, but this view can be proved with exceptionally preserved fossils only.
The non-mineralized or weakly calcified algal species are rarely preserved and have been found in few Lagerstaetten only. Therefore the extent of their stratigraphic ranges and richness of their geologic history has probably been strongly been underestimated.
Up to now only 14 species of non-mineralized algae have previously been reported from the entire Silurian System around the world.

The Early Silurian algal Lagerstaette in Kalana, Estonia, has revealed rich non-mineralized algal flora, which on the basis of external morphology are assigned to Rhodophyta and Chlorophyta. Most of the material occurs within the light to dark brown organic-rich, microlaminated, partly dolomitized limestones.
Kalana quarry in Central Estonia is by far the richest and best preserved algal deposit in the Early Paleozoic. In the Kalana material we can distinguish at least ten morphological species. This marks a considerably higher diversity than has been documented in the Cambro-Silurian strata up to now.

The most common algal fossil in these shelf carbonates is a red algal species *Leveilleites hartnageli*, which was originally described by Foerste in 1923 from roughly coeval sediments in southern Ontario, Canada.

The thalli of this type are up to 7 cm high, with a 1-2 mm wide axis. Each specimen has 10-20 primary branches, most of them about equal in length and 12-25 mm long. These branches bear 10-30 so called tufts, consisting of 20-30 up to 1 mm long laterals and arranged in either side of the 1st-order laterals. We are able to designate two distinct macroscopic phases (a haploid and diploid phase) of the life cycle of *Leveillites*.
Many algal fossil of Kalana - *Medusaegraptus* sp., *Chaetocladus* sp., *Inopinatella* sp., and *Cymopolia* sp. - belong to the green algae of the order Dasycladales. Dasyclads are unicellular and radially symmetrical macroalgae with siphonous organization. This highly diverse group has a long geological history, but is dominated by calcareous forms.

The fossil evidence from the Kalana Lagerstaette suggests, that some of the algae may have maintained their basic morphology almost unaltered for over 400 million years, with the main innovation being the extracellularly laid calcium carbonate skeleton and the algal floras were probably widespread in the Paleozoic seas.

Non-geniculate coralline algae and foraminifers as main constituents in microfacies types of 'Leitha Limestone', Middle Miocene, north-eastern Leithagebirge, Austria

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The Historic Quarry Project aimed at the identification and investigation of natural stones that proved historically important for buildings and monuments by means of linking their quarry provenance with their applications. In this respect, Leitha Limestone, being one of the most famous building stones in Vienna, Bratislava and Graz, was chosen. To fill the blind spot due to the military inaccessibility of abandoned quarries distributed between Kaisersteinbruch and south of Bruck/Leitha these were selected for investigation and a permitted field trip carried out. Moreover, quarries in the Ruster Hills (e.g., so called Roemersteinbruch St. Margarethen) and in southern Styria (subsurface Roemerbruch Aflenz) were also part of the excursion. Further samples of Leitha Limestone quarries from Nußdorf (Vienna) and Pfaffenberg (Deutsch-Altenburg) were studied for comparison.

Carbonate microfacies analysis of 70 thin sections by stereo microscope was applied, quantity estimations are based on comparison charts.

From the 30 quarries that were subject to general survey, rock samples were taken for macroscopic identification and some of them chosen for preparation of thin sections. From 12 of these quarries additional cores (35 mm diameter, up to 15 cm long) were drilled. The core samples served for geophysical and geotechnical laboratory tests and for thin sections as well.

The field investigations and quarry descriptions contribute to the mineral raw-materials archive and database of the Geological Survey. Based on the available geological maps the Leitha Limestone succession covers a basement relief, which occurs as topographical heights, called Schieferberg, Zeilerberg and Königsberg with Semmeringquarzit and Middle Triassic dolomite and with the latter cropping out as erosional and quarry relics south of Kaisersteinbruch. Although the map differentiates between Badenian 'Leithakalk' and Sarmatian 'detritaerer Leithakalk', this was not obviously recognizable in the field.

The thin sections were grouped according to their microfacies characteristics and resulted in: Micro-breccias and conglomerates with reworked dolomite basement rocks, (par-)autochthonous bioclastic corallinacean-bryozoan boundstones as well as bryozoan-serpulid boundstones, pack- and rudstones with mainly corallinacean algae and eventually rhodolithes, well sorted grain- and rudstones (detrital calcareous sandstones) with varying amounts of corallinacean algae, bioclasts, foraminifers and lithoclasts. Occasionally important are mixed carbonate-siliciclastic types. Few samples are dominated by molluscs. Some textures, cements and diagenetic features are indicative of special environments. Concerning the coralline algae flora, up to now, mainly *Lithothamnium*, *Lithophyllum* and *Sporolithon* were recognized.

A preliminary age differentiation between Badenian and Sarmatian is mainly based on foraminifers and the occurrence of ooids.

It can be concluded that the microfossil record in the thin-sections from these isolated samples could be identified to a limited extend. The resulting microfacies types were tested for their regional extent. For further investigation, the significance of these samples should be proven as they should serve for recognition in stone monuments, and for lithostratigraphical contribution.

Acknowledgements: Fundings for the excursion were provided by the Austrian agency for international mobility and cooperation in education, science and research Action Austria - Slovakia, and by the EU-Culture Program 2007-13. The author thanks all participants, represented by the organizers M. Heinrich (Geological Survey), R. Holzer (Comenius University Bratislava) and C. Uhlir (University of Salzburg).

Microbial carbonates in Miocene reefs in the Mahakam Delta in East Kalimantan, Borneo, Indonesia

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Microbial carbonates are deposits that form by the activity of bentic microbial communities. Microbialites usually form domical, columnar or conical structures and can have laminated, clotted, dendritic or homogenous macrofabric. They have a broad distribution and can grow in a variety of different environments such as hot springs, freshwater lakes, hypersaline lakes, reefs and other marine environments. This research focuses on microbialites associated to coral reefs.

Coral patch reefs in the Miocene Mahakam Delta in East Kalimantan (Borneo, Indonesia) grew in shallow marine turbid waters. These patch reefs developed from delta front to deeper (prodelta) settings in areas with temporary reduced siliciclastic input. Langhian reef deposits are well exposed in limestone quarries in the Samarinda area and locally include microbial carbonates. Two different types of microbial carbonates have been found around Samarinda in two localities 2 km apart.

These sections were logged in detail and 208 samples were collected. Meso and macrostructure of microbialites were identified at the outcrops. Thin sections from carbonate samples were examined under optical microscope and microfacies were classified using the DUNHAM (1962) and EMBRY & KLOVAN (1971) terms. The carbonate content was analyzed using Total Inorganic Carbon analysis, with 12% carbon as a standard for carbon calibration. In the northern section, microbialites occur as low-relief domes, up to 2 m wide and 0.5 m high, with internal lamination, developed around large coral fragments at the transition from reef deposits to fine-grained siliciclastics.

The second type of microbialites has been found in the southern locality as decimeter-scale nodules ('megaoncoids') formed around nuclei of large coral fragments. Small nodules were bound together into bigger nodules. Microbial micrite with laminated to digitated fabrics intergrew with coralline algae to form the thick covers of these 'megaoncoids', which laterally change into coral boundstones.

In both sections microbialites are not components of the reef framework. They grew around large coral fragments on the flanks of the patch reefs. The microbialites that form low relief domes developed on a nearly flat, stable seafloor seawards of the patch reef. The 'megaoncoids' in the southern section formed as a result of downslope movement of coral fragments coated by microbialite/coralline algal crust. The steep slope at the flank of the patch reef favoured falling and overturning of encrusted corals and continued growth of microbial crusts on other sides of nodules.

Lower Cretaceous calcareous algae from Herisht Mount (Ardakan area, Central Iran)

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In spite of the several publications in the last decade, little is known about Lower Cretaceous calcareous algae from Iran. The calcareous algae association described here adds to the knowledge on algal paleobiodiversity in Central Iran, and brings new insights into the regional paleogeographic framework during the Lower Cretaceous.

Herisht Mount is located 14 km north of Ardakan town (Central Iran). Geologically, the area belongs to the Yazd tectonic block. The studied section is about 640 m-thick; it contains conglomerates at the base followed by 40 m-thick limestones. They are covered by a 63 m-thick green shale level, followed by several hundreds of stratified limestones with mollusks, foraminifers, and calcareous algae.

The foraminiferal association with *Balkhania balkhanica* (Mamontova), *Charentia cuvillieri* Neumann, *Everticyclammina* hedbergi (Maync), *Dictyoconus pachymarginalis* Schroeder, *Mayncina bulgarica* Laug, Peybernes & Rey, *Mesorbitolina texana* (Roemer), *Praeorbitolina cormyi* Schroeder, *Sabaudia minuta* (Hofker), *Torremiroella hispanica* Brun & Canerot and *Vercorsella scarsellai* (De Castro), indicates a Barremian-Aptian age for the whole succession.

Green algae (Dasycladales and Bryopsidales) dominate the calcareous algae association, consisting of ?*Conradella bakalovae* (Conrad & Peybernes), *Cylindroporella ivanovici* (Sokac), *Deloffrella quercifoliipora* Granier & Michaud, ?*Griphoporella cretacea* (Dragastan), *Kopetdagaria sphaerica* Maslov, *Montiella*? *elitzae* (Bakalova), *Morelletpora turgida* (Radoicic), *Neomeris* cf. *cretacea* Steinmann, *Salpingoporella* cf. *muehlbergii* (Lorenz), *Salpingoporella* sp., *Terquemella* div. sp., *Arabicodium* sp., *Boueina hostetteri* Toula, *Boueina* sp., ?*Halimeda fluegeli* Bucur, *Permocalculus* cf. *irenae* Elliott and *Permocalculus minutus* Bucur. The green algae are rarely accompanied by red algae: *Marinella lugeoni* Pfender, *Parachaetetes asvapatii* Pia, *Pycnoporidium* sp., *Polystrata alba* (Pfender) or the microproblematic *Carpathoporella occidentalis* Dragastan.

The algae association from Herisht Mount contains several species that were previously identified in Aliabad area (south-west from Yazd, BUCUR et al., 2012); exception is made by *Morelletpora turgida*. Nevertheless, the latter has been also identified in samples from Khur region (see Bucur et al., this volume), thus it can be considered as a common species for the whole Yazd tectonic block.

This algae association developed in depositional environments ranging from internal shelf to shelf margin. The presence of the identified species, corroborated with the absence of species *Salpingoporella dinarica* indicates a paleogeographic affinity with the central-northern Tethys domain during the Lower Cretaceous.

Aknowledgements: This work is partially a contribution to the CNCS PN-II-ID-PCE-2011-3-0025 project.

Late Cretaceous (Maastrichtian) dasycladalean algae from the Naghan area (Zagros Mountains, SW Iran): Preliminary results

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In the Zagros Mountains of southwest Iran, Campanian-Maastrichtian shallow water limestones that locally may pass the K/T boundary are known as Tarbur Formation. Biostratigraphic zonations of the Tarbur Formation are based on larger benthic foraminifera. The study area is located approximately 50 km south of Naghan town near Gandomkar village. Within the Early-Middle Maastrichtian interval of the Tarbur Formation, inner platform wackestones contain a rather diverse association of dasycladalean algae with *Uteria* sp., *Salpingoporella* div. sp., *Pseudocymopolia anadyomenea* (Elliott), *Cymopolia* sp. and further undetermined taxa currently under study. The material studied contains well-preserved specimens of *P. anadyomenea*, the type-species of the genus *Pseudocymopolia* Elliott yielding further data on this poorly known taxon that seems to the be palaeobiogeographically restricted to the northern rim of the Arabian plate.

Algal assemblage of some small Permian patch reefs from the Sirjan area, (south Iran)

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Permian deposits of Sannandj-Sirjan structural belt (STOECKLIN, 1968) are composed of three formations: Vajnan formation at the base, followed by the Abadeh formation in the middle and the Surmaq formation at the top. According to the Sirjan geological map (SABZEHEI et al., 1997) the basal part of the Permian deposits in south part of Sannandaj-Sirjan belt is called Jamal formation, a general terminus for the whole Permian sediments in central Iran. The name Jamal Formation was introduced by STOECKLIN et al. (1965) for the Permian strata in a section (type section) at the southern flank of the Mount Jamal (33° 21'N, 57° 19'E), about 60 km south of the town of Tabas.

The Permian deposits in the south of the town of Sirjan were studied by Sabzehei et al. (1997). Permian sediments in Sirjan area are divided to three units: The basal part is metamorphic, a kind of schist and started with red conglomerate, sandstone, and meta basic lava with angular unconformity surface. The middle and upper part are carbonatic units. The middle carbonate member is 351 m thick and is composed of medium to thick bedded gray limestone that crashed after the tectonic event. This member indicates shallow water deposits containing algae, fusulinids, sponges, bryozoans, brachiopods, and etc. The thickness of the upper part is about 224 m thick and the rocks are composed mainly by medium to thick bedded limestone. This unite contains carbonatic particles derived from the shallow water carbonates and deposited in the deeper water basinal sediments. The debris contains algae, sponges, fusulinid and some deeper water particles with calcisphaerids. The shallow water carbonates were transported by gravitational flows into the deeper marine deposits (turbidites).

Permian sediments were sampled in a section, about 60 km south of the town of Sirjan. 250 specimens were collected from carbonatic layers. There are some small reefal structures in the middle carbonate unit, which are composed mainly of dasycladales and phylloid algae, microbial crusts, bryozoans and sponges. Numerous thin sections were made from these reefal carbonate blocks. Two phylloid algal taxa were recognized. One of them assigned to *Anchicodium* sp., the second one (undeterminable) is strongly recrystallized, only some parts of the border are still recognizeable. These two taxa are extremely abundant algae within the small patch reefs. Most important dasycladales algae in carbonate layers and blocks are: *Mizzia velebitana* SCHUBERT 1908, *Gyroporella niponica* ENDO & HASHIMOTO 1955, *Physoporella* sp., *Epimastoporella* sp., *Paraepimastopora* sp., *Antracoporella* sp. Microbial crusts, without recognizable internal structure, are also very abundant.

Cyanobacterial 'whiting' origin of Devonian-Mississippian carbonate mud mounds?

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Carbonate mud mounds are unusually abundant in the Late Devonian-Early Mississippian. A sediment baffling origin has been suggested, but a suitable source of off-mound carbonate mud has been difficult to identify. Late Devonian changes in atmospheric composition, particularly pCO_2 reduction and pO_2 increase, may have been sufficiently large to induce CO_2 concentrating mechanisms (CCM) in phytoplankton. CCM act to maintain photosynthesis, and include active transport of HCO^{3-} into the cells that can lead to extracellular pH rise and precipitation of fine-grained carbonate ('whitings') in the water column when carbonate saturation state is sufficiently elevated. It is proposed that Late Devonian-Early Mississippian whitings promoted mound development by generating mud off-mound whose import substantially augmented any on-mound carbonate production. Coeval increase in benthic calcified cyanobacteria supports elevated carbonate saturation state and CCM induction, and potential increase in primary productivity stimulated by CCM induction is consistent with organic carbon rich anoxic sediments and large positive δ^{13}CPDB excursions at this time.

A number of the sedimentary features commonly associated with Late Devonian-Early Mississippian mud mounds are consistent with current-driven accumulation of fine-grained carbonate. These include: (i) formation in a wide range of water depths; (ii) orientation, asymmetry, lateral progradation and amalgamation, (iii) grainstone haloes; (iv) presence of current-reliant filter feeders (bryozoans, crinoids, sponges); (v) layered structure; (vi) collapse structures (stromatactis and slumps). Carbonate mud derived from phytoplanktic whitings can be rich in organic matter. This could have promoted microbial lithification (e.g., by bacterial sulfate reduction) that contributed to the formation of clotted-peloidal microfabric. Thus, whiting processes could have been the primary mud source and also have created conditions favoring syndepositional on-mound early lithification. In this view, on- and off-mound microbial processes were mutually related, with off-mound mud production being mediated by cyanobacterial oxygenic photosynthesis and on-mound lithification mediated by heterotrophic mineralization of whiting organic matter.

Peritidal cyclical sequences of Kimmeridgian-Berriasian-?Valanginian limestones from Piatra Craiului Massif (Romania); the role of microbialites and rivulariacean-type cyanobacteria

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The Kimmeridgian-Berriasian-?Valanginian limestones from Piatra Craiului Massif are part of the sedimentary cover of the Getic Nappe from Southern Carpathians. Within the Piatra Craiului carbonate succession, three major types of depositional systems have been separated which can be followed from base to the top: (1) slope and shelf margin system; (2) open shelf system (offshore) and (3) coastal and shoreline system.

The carbonate deposits belonging to the slope and shelf margin system are represented by reef breccias and bioconstructions. The bioconstuctions associated with gravity flows indicate a shelf slope environment related to the external flanks of the carbonate platform. Within the bioconstructions microbialites and encrusting organisms played an important role.

The middle and upper part of the succession is composed of normal and restrictive marine subtidal limestones. The vertical distribution of subtidal facies, reflects cyclic changes in wather depth. The first record in these deposits is marked by a fluctuation of the environmental deepening (from shallow to deeper domains) and/or ecological changes in the depositional environment (from restrictive to open marine conditions and returning to restrictive conditions).

In the upper part of the succession the peritidal limestones are dominant. The typical facies and facies associations for the peritidal environment are separated in three depositional subtypes: subtidal, intertidal and supratidal. The vertical stacking of the identified facies reflects cyclical changes in water depth. The deposits contain marine and marine restrictive facies acumulated in high or low energy environments. The facies evolution of individual beds or bed sets, indicates a transition between the three depositional zones, represented by lagoons, ponds, beaches, tidal bars, algal-microbial mats and swamps. Rivulariacean-type cyanobacteria played an important role in the carbonate accumulation.

The vertical succession of the carbonate deposits from Piatra Craiului indicate the existence of a gradual transition from slope and shelf margin to subtidal and shoreline facies. This fact indicates the progradation of the carbonate platform during the Lower Cretaceous. In the same time, due to the radical reduction of the accomodation space on the carbonate platform, the main carbonate sedimentary production was generated by cyanobacteria.

Acknowledgments: This work is a contribution to the research project financed through PN-II-ID-PCE-2011-3-0025 grant.

A coastal paradise for Aptian microbialites (Early Cretaceous, N Spain)

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Microbial carbonates are remarkably diverse and abundant in the early Aptian (~120 Myr) coastal carbonates of the Leza Fm (La Rioja, N Spain). They show a great variety of macro- and microfabrics, associated with differing sedimentary environments. This provides a unique opportunity to study the factors underlying development of microbial fabrics and structures.

The Leza Fm is part of the Early Cretaceous Cameros rift basin. Sedimentological analysis reveals that it was deposited in a system of carbonate coastal-wetlands with variable fresh- and seawater influence, composed of: a) carbonate water-bodies with charophytes and dasyclads; b) palustrine plains with common paleosols; c) siliciclastic alluvial environments; d) oncoid channels; e) carbonate water-bodies with ostracodes and miliolids; f) tidally-influenced water-bodies; and g) restricted carbonate-evaporite water-bodies. These environments interfinger throughout the unit, but also show a general retrogradational trend.

Most of the sedimentary environments of the Leza Fm are rich in microbial carbonates: (1) *Oncoids* are common in small channels and facies with strong freshwater influence, and have microfabrics dominated by calcified filaments. (2) *Skeletal stromatolites* occur in the western outcrops associated with cross-bedded sandy grainstones with charophytes and rare dasyclads. They have domical morphologies and well-calcified filamentous microfabrics. (3) *Fragments of dendrolites* are common throughout the coastal-lake facies with charophytes and dasyclads, showing microstructures of delicate branching calcified filaments. (4) *Thrombolites* occur in dasyclad-dominated coastal-lake carbonates of the western outcrops. Their microfabrics are commonly diagenetically altered, but show relict peloidal micrite and calcified filaments. (5) *Fenestral laminites* are common in facies with ostracodes and miliolids in the western outcrops. They show undulose lamination marked by elongate fenestrae. Vertical cracks and vadose calcite cements are common. Their microfabrics are micritic, clotted-peloidal and agglutinated, with some filament relicts. (6) *Agglutinated oolitic stromatolites* are found in tidally-influenced eastern outcrops with ostracodes and miliolids. They show domical morphologies and microfabrics dominated by trapped ooids and bioclasts and clotted-peloidal micrite. Calcified filaments are rare.

A clear link between particular facies and microbialite types is observed. For example, filamentous microfabrics (oncoids, skeletal stromatolites, dendrolite fragments) occur in freshwater-dominated facies, whereas non-filamentous microfabrics (thrombolites, fenestral laminites, agglutinated stromatolites) are found in facies with stronger marine influence. Thus, microbialite variability in the Leza Fm reflects the diversity of sedimentary environments. We conclude that at this time, coastal-wetlands at the crossroads of marine and freshwater realms provided a broad variety of hydrochemical and hydrodynamic settings that could promote the development of differing microbial communities and products.

Furthermore, the early Aptian was a period of microbialite abundance in many carbonate platforms located as far afield as Arabia, Western Europe, and the Pacific Ocean. Global oceanographic and climatic changes have been suggested as possible causal factors. Comparison of the Leza Fm transitional-coastal setting with coeval carbonate platforms could help to further understand these early Aptian microbialite paradises.

Microbial carbonate reef components in the mid-Triassic Italian Dolomites: A biogeochemical approach

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Triassic carbonate buildups of the Dolomites have for decades been regarded as classic examples of ancient coral reefs and have been the subject of extensive research. During the mid-Triassic reefs underwent important changes, evolving from reefs mainly composed by sponges, seafloor crusts, and calcimicrobes such as *Shamovella*, to more modern-looking coral-algal associations with clotted-peloidal crusts. We examined good examples of both types at Punta Grohmann and Alpe di Specie. The Punta Grohmann samples of high-rise platform margin reef rock are from erratic 'Cipit Boulders' in Late Ladinian-Middle Carnian basinal sediments (Wengen and San Cassiano formations). These blocks escaped the extensive dolomitization that affected the buildups, and preserved their original mineralogy and organic content. The Alpe di Specie samples are from small Late Carnian patch reefs in the Heiligkreutz Formation, and are widely regarded as in situ or nearly in situ. Their coral-sponge-algal framework cavities contain distinctive clotted-peloidal micrite microfabric. Despite their small size, these bioherms are among the earliest examples of skeletal framework reefs whose major components are broadly comparable with those of present-day tropical coralgal reefs. We carried out biogeochemical analyses on selected samples from both localities to characterize the organic matter and bacterial metabolic signatures. These included UV epifluorescence observations, Total Organic Carbon (TOC) content, FT-IR spectroscopy and biomarkers analyses. Rare Earth Elements (REE) distributions were also investigated to determine the oxidation state in which these deposits precipitated.

The Punta Grohmann and Alpe di Specie reefs are not very different in age but show significant differences in components, structure and fabrics, reflecting contrasting depositional environments. Punta Grohmann sponge-microbial reefs contain biomarkers for various bacteria including cyanobacteria but lack specific molecules typical of sulfate-reducing bacteria. This suggests that aerobic bacteria were able to directly degrade the organic matter from primary producers, and is consistent with well-oxygenated depositional conditions indicated by REE values, and with the high-energy platform margin setting in which they formed. Alpe di Specie scleractinian patch reefs contain sulfate reducing bacteria biomarkers and REE values indicative of sub-oxic conditions. These are consistent with their autochthonous clotted-peloidal crusts and the more muddy low energy conditions under which they formed. Their small growth cavities that apparently favored formation of clotted-peloidal sediments resemble those of present-day autochthonous reef crusts induced by sulfate reducing bacteria.

The division of the morphological groups of the Li Mei calcareous algal bioherms, Western Hunan, China

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In the late Early Cambrian, during deposition of the Qingxudong Formation, a homoclinal carbonate ramp was developed over what is now Li Mei village, Western Hunan Province. The ramp comprised three different sedimentary facies associations, which are referred to as the inner, mid- and outer ramp zones. A series of calcareous algal bioherms were developed in the mid-ramp zone.

The bioherm contains nineteen species of calcareous algae. The major constituent algae in the bioherm facies are *Epiphyton*, *Renalcis*, *Botomaella*, *Razumoviskia*, *Proaulopora*, *Batinevia*, *Chabakovia*, *Bija*, *Nicholsonia*, and *Girvanalla*.

The bioherm algae can be divided into four groups and seven sub-groups based on comparative morphology: (1)botryoide group; (2) dendritic group(sub-groups: i. short and small dendritic, ii. Cluster and ball-shaped dendritic, iii. Dendritic); (3) tubiform group(sub-groups: i. fan-like tubiform, ii. Isolated and loosely associated tubes, iii. Cluster tubiform, iv. Tangled, coiled and mass-like tubiform); (4) blanket hair-like group.

Since morphological groups can be environmental indicators, one or several algal morphological groups and/or sub-groups can be assigned to either of four algal environment zones in the bioherm: (1) low-energy zone-developed at the bottom and periphery of the bioherm; (2) & (3) relatively high-energy zone-located in the middle part of the bioherm; (4) very high-energy zone-developed on the top of the bioherm.

The division of the morphological groups of the Li Mei calcareous algal Bioherms are of great importance in determining sedimentary microfacies, and analyzing the correlations between algae morphology and sedimentary environment.

Field guides

Introduction to the Geology of the Eastern Alps

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1 Introduction

The Alpine orogen formed during the convergence of the African and European plates, which was a more or less continuous evolution since Cretaceous times. The geology of the Alpine –Mediterranean area is complex, however, because of the existence of more than one oceanic realm and several plates between Africa and Europe, as well as the interplay between shortening processes and lateral movements. This makes it difficult to determine the plate tectonic arrangement through time (HANDY et al., 2010). Models of Alpine tectonics have developed rapidly during recent decades, mainly as a result of modern structural, stratigraphic, petrological and geochronological investigations which, together with deep reflection seismic profiling and tomographic studies, have provided new insights into the present-day structures. Contrasting interpretations on the evolution of the Alpine orogen still remain, however, further complicated by the use of different nomenclatures.

This summary of the geology of the Alps is based on the tectonic interpretation by SCHMID et al. (2004) and on the review of Alpine metamorphic history by OBERHÄNSLI (2004) together with the literature cited therein.

In a geographical sense the Alps are divided into the Southern Alps (to the south of the Periadriatic lineament), the Eastern Alps, the Central Alps, and the arc of the Western Alps (Fig. 1). These subdivisions are each dominated by different paleogeographic elements that were incorporated at different stages in the Alpine tectonic evolution, resulting in distinct geological structures and a specific geomorphology.

In the following an overview on the plate tectonic and tectonic units of the Alps and an introduction in the different metamorphic cycles is given.

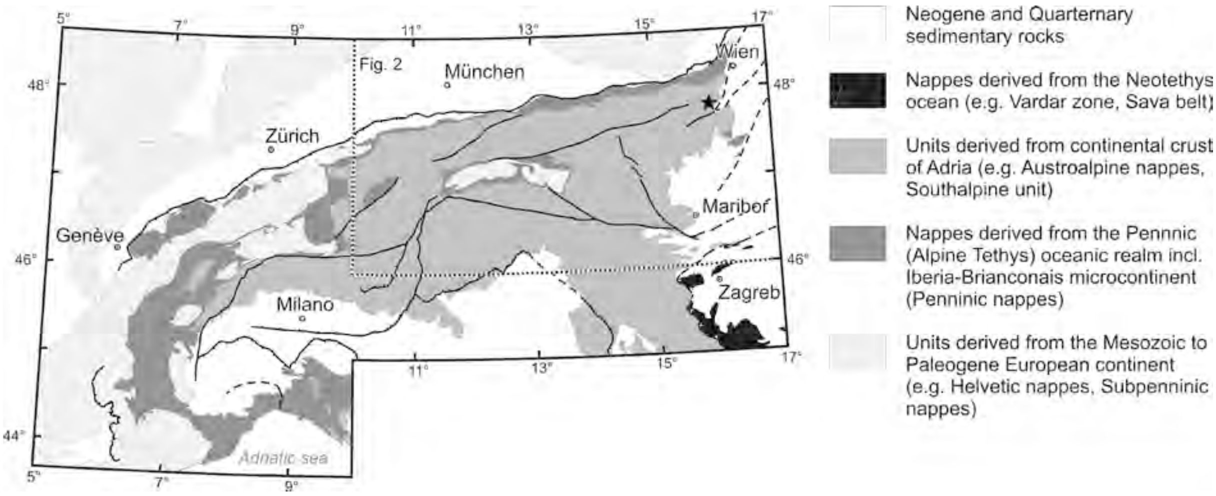

Figure 1: Map of the major paleogeographic and tectonic units in the Alps according to SCHMID et al. (2004).

2 Plate tectonics

The Alpine orogen is subdivided into plate tectonic units reflecting the Mesozoic to Paleogene paleogeography. From north to south, respectively from bottom to the top the Eastern Alps are formed by the following paleogeographic elements (Figs. 1, 2):

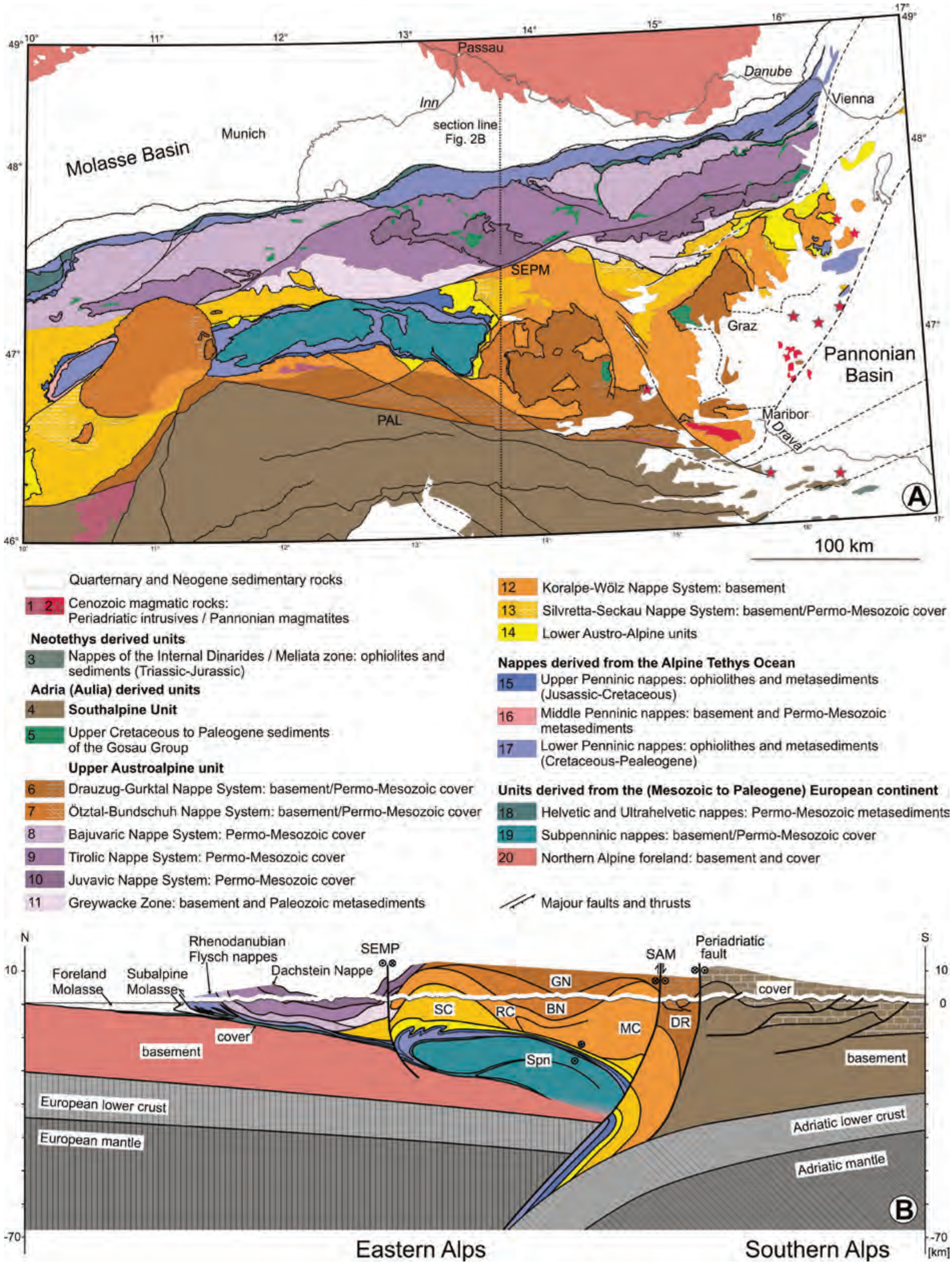

Figure 2: (A) Tectonic map of the Eastern Alps according to the nomenclature in SCHMID et al. (2004). The numbers of the units refer to the text. (B) Section through the Easter Alps according to SCHMID et al. (2004). GN…Gurktal nappe, DR…Drau Range, BN…Bundschuh nappe, RC…Radentherin Complex, MC…Millstatt Complex, SC…Schladming Complex, SEMP…Salzach-Ennstal-Mariazell-Puchberg fault, SAM…Southern border of Alpine Metamorphism (according to HOINKES et al., 1999), PAL…Periadriatic lineament.

The Mesozoic to Paleogene European continent is represented by the Helvetic, Ultrahelvetic and Subpenninic nappes. Relics of the former Penninic Ocean (Piedmont-Ligurian and Valais Ocean) are the overlaying Lower and Upper Penninic nappes which form the Rhenodanubian Flysch belt and the Penninic nappes of the Engadin, Tauern and Rechnitz Window. The Middle Penninic nappes present in the Engadine Window are the remnant of the Iberian-Brianconnais microcontinent. In the western part of the Alps this microcontinent separated the Penninic Ocean into the Piedmont-Ligurian and Valais oceanic basin. Above the Austroalpine and separated by the Periadriatic lineament (PAL) the Southalpine unit is situated. Both derived from the continental crust of the Adriatic plate. Remnants of the Neotethys oceanic realm (Meliata, Hallstatt, Vardar Ocean) occur in a few outcrops in the easternmost part of the Eastern Alps (MANDL & ONDREJICKOVA, 1993).

The Penninic oceans opened in Jurassic and Early Cretaceous times and were closed during the Alpine – Late Cretaceous to Paleogene – collisional event. Europe acted as the lower and the Adriatic plate as the tectonic upper plate. The Penninic oceanic suture zone can be traced all along the mountain belt. The eo-Alpine event is due to an intracontinental subduction zone within the recent Austroalpine unit (STÜWE & SCHUSTER, 2010). The subduction started in the Early Cretaceous (Valanginian; ca. 135 Ma), whereas maximum burial depth and peak metamorphic conditions were reached in the early Late Cretaceous (Turonian; ca. 92 Ma, THÖNI, 2006). During this event parts of the Austroalpine unit were in a lower plate position, whereas other parts were in an upper plate position.

The Neotethys Ocean formed an embayment into the Adriatic plate. Oceanic crust was formed during the westward propagation of the ocean in Triassic (Meliata), Jurassic (Vardar Ocean) and also in Cretaceous times (USTASZEWSKI et al., 2009). However, intraoceanic subduction processes and the emplacement of ophiolite nappes onto the Adriatic margin are documented since the Middle Jurassic. These nappes are widespread in the Dinarides but it seems that outlayers of these nappes were also present in the eastern part of the Eastrern Alps. Today all these outlayers are completely eroded, but redeposited material is present in the Upper Cretaceous sediments of the Gosau Group (SCHUSTER et al., 2007).

3 Description of the tectonic units of the Eastern Alps

This description of the tectonic units of the EasternAlps is based on the map and sections published by SCHMID et al. (2004). From bottom to top (from N to S, or NW to SE, respectively) the Alps are built up by the following tectonic units (Figs. 2, 3)

3.1 Units derived from the (Mesozoic to Paleogene) European continent

The European continent consists of a deeply eroded Variscan (Late Devonian to Carboniferous) metamorphic continental crust, rich in plutonic rocks (north of the Alpine front), covered by Carboniferous to Eocene sedimentary sequences (20). This crust is still in contact with its lithospheric mantle; it dips beneath the Alps and contains the Late Eocene to Neogene Molasse basin which is the northern peripheral foreland basin of the orogen. The External massifs represent windows in the European plate within the Western and Central Alps. They comprise basement rocks and Late Carboniferous to Cretaceous cover sequences. The Helvetic and Ultrahelvetic nappes (18) are a thin-skinned fold and thrust belt formed exclusively of detached cover sequences. At the northern margin of the Central Alps they cover wide areas, whereas in the Eastern Alps they are present only as thin slices. The Subpenninic nappes (19) represent the distal European margin, forming ductilely deformed basement and cover nappes which lost contact with their lithospheric mantle and served as the basement for the Helvetic nappes. They form the Gotthard, Travetsch and Adula nappes in the Central Alps and also, contrary to many earlier publications, the Venediger and Modereck nappe system in the Tauern Window of the Eastern Alps. This interpretation is based on the conclusion that the crustal material of the Venediger nappe system was not separated from the European margin by an oceanic basin (e.g. FROITZHEIM et al., 1996;

KURZ et al., 2001). The eclogitic Subpenninic basement units (Adula nappe, Cima Lunga nappe and Eclogite Zone in the Tauern Window) contain material derived from the Penninic ocean and developed in a subduction and accretion channel (ENGI et al., 2001; KURZ & FROITZHEIM, 2002).

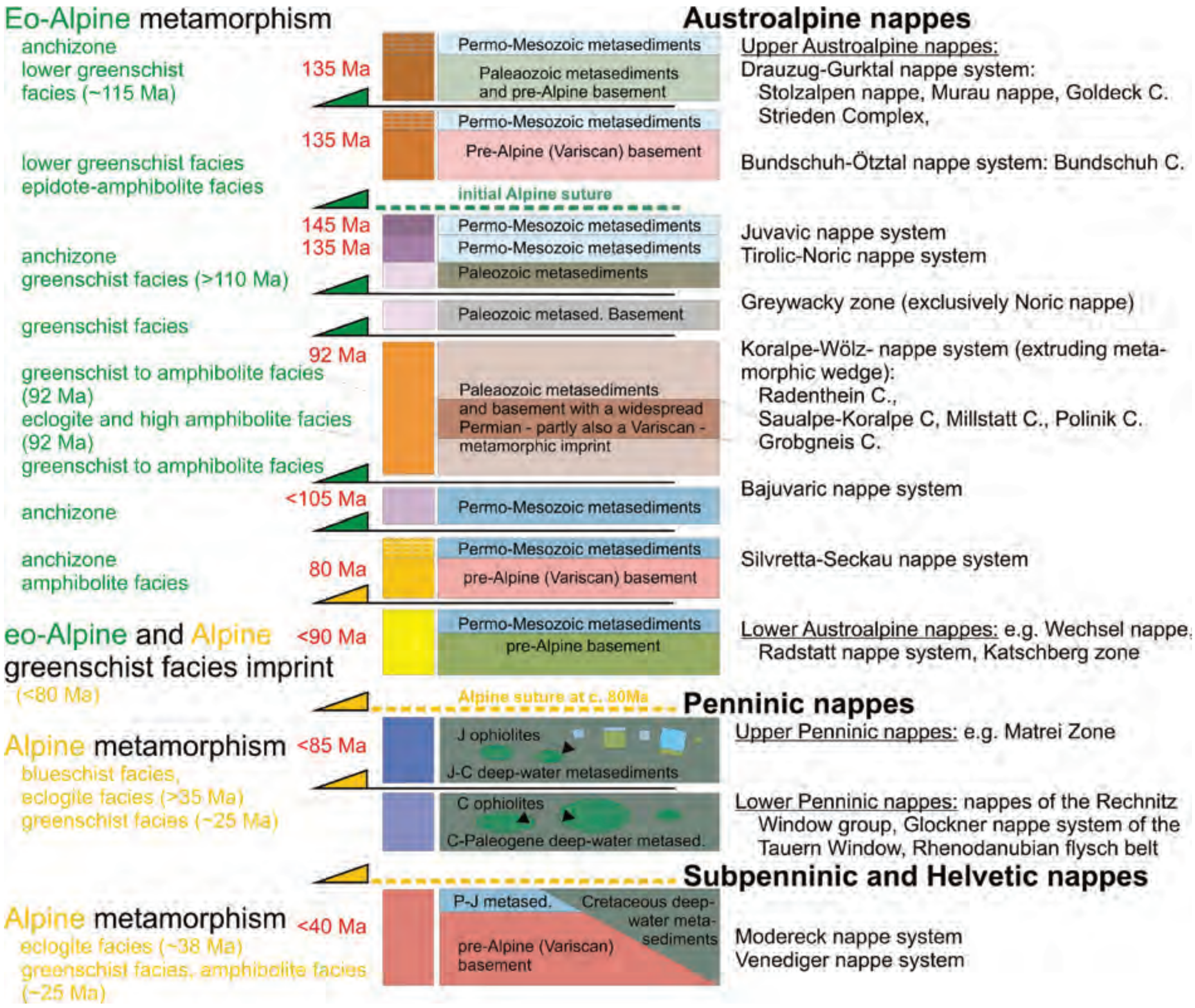

Figure 3: Block diagram showing the majour tectonic units of the Eastern Alps. In the left coloum the metamorphic grade during the eo-Alpine (Cretaceous) and Alpine (Cenozoic) events and the time of peak metamorphism is given. The red numbers indicate the time of incooperation into the Alpine orogenic wedge.

3.2 Penninic nappes

The Penninic nappes comprise three paleogeographic elements: the Piedmont-Ligurian ocean, the Brianconnais microcontinent and the Valais ocean.

The Piedmont-Ligurian ocean opened in Late Jurassic times. Its initial sea-floor formed by exhumation of the subcontinental mantle of the Adriatic plate (FROITZHEIM & MANATSCHAL, 1996). These mantle rocks are overlain by Jurassic radiolarites, aptychus limestones and Cretaceous calcareous turbiditic metasediments. The Brianconnais microcontinent was a part of the European distal margin until it was cut off by the opening of the Valais ocean in Cretaceous times. The Valais oceanic crust comprises Cretaceous ophiolites overlain by Cretaceous to Eocene calcareous turbiditic metasediments. Towards the east the Valais ocean merged into the Piedmont-Ligurian ocean, thus forming a single oceanic basin in the east (e.g. STAMPFLI, 1994; FROITZHEIM et al., 1996). Although this situation in the east makes any subdivision of the Piedmont-Ligurian from the Valais basin there somewhat artificial (KURZ et al., 2001), characteristic successions, analyses of the source areas of the clastic sedimentary successions and the age and chemical characteristics of the ophiolitic rocks allow the differentiation of elements from the northern or southern part of this joint oceanic basin.

The Penninic nappes can be subdivided into the Upper, Middle and Lower Penninic nappes, whereby each consists mainly of one of the paleogeographic elements mentioned above.

The Lower Penninic nappes (17) consist predominantly of material from the Valais oceanic province and from the northern parts of the joint oceanic basin in the east. The Lower Penninic nappes make up large parts of the Central Alps and the central part of the Lower Engadine Window. The lower nappes of the Rhenodanubian flysch zone, which are present along the northern margin of the Eastern Alps, represent a continuation of the Central Alpine Valais basin sediments into the Eastern Alps (KURZ et al., 1998); they comprise Cretaceous flyschoid sediments deposited in a basin along the European margin. The Glockner nappe system of the Tauern Window, as well as the nappes of the Rechnitz Window Group, consisting of calcareous flyschoid metasediments and metaophiolites, is thought to be a southern continuation of the lower nappes of the Rhenodanubian flysch zone.

The Middle Penninic nappes (16) are mainly derived from the Brianconnais microcontinent and are common in the Western and Central Alps. The easternmost nappes include material from the Brianconnais microcontinent and are represented by the Tasna nappe of the Lower Engadine Window.

Rocks derived from the Piedmont-Ligurian ocean and the accretionary wedge along the southern margin of the oceanic basin towards the Adriatic microcontinent make up the Upper Penninic nappes (15). They are widespread in the Western and Central Alps. In the Eastern Alps the Upper Penninic nappes form the uppermost tectonic elements in the Engadine and Tauern windows (e.g. the Arosa Zone, the Matrei Zone, and the Reckner Complex). In the northern part of the Eastern Alps the Ybbsitz klippen belt (DECKER, 1990) is a remnant of the Piedmont-Ligurian ocean, containing the typical sequence of serpentinites, Jurassic radiolarites and aptychus limestones. It is in contact with the Kahlenberg nappe of the Rhenodanubian flysch zone, which is also interpreted to be an Upper Penninic nappe (FAUPL & WAGREICH, 1992).

3.3 Adriatic microcontinent

The Adriatic microcontinent consists of a Cadomian continental crust (NEUBAUER, 2002) with Paleozoic metasedimentary sequences and with magmatic rocks related to rifting and subduction processes lasting until the Carboniferous. During the Variscan orogeny large parts of this crust were affected by metamorphic overprints and synorogenic magmatism. Post-orogenic Permian to Carboniferous sediments were deposited locally. In the Permian these units were affected by lithospheric extension expressed by basaltic magmatic underplating, intense acidic magmatism and related high-temperature / low-pressure (HP/LT) metamorphism. More than 3 km of Permo-Mesozoic sediments were subsequently deposited on top of the thermally subsiding microcontinent, which formed a broad carbonate shelf towards the Meliata ocean in the southeast and, from the Jurassic onwards, was bordered to the north by a passive continental margin facing towards the Piedmont-Ligurian ocean. In the Eastern Alps the Adriatic microcontinent is represented by the Austroalpine and Southalpine units, being separated by the Periadriatic lineament.

The Austroalpine unit forms a complex nappe stack of crustal material which can be subdivided into Lower and Upper Austroalpine units. The Lower Austroalpine unit (14) formed the continental margin towards the Piedmont-Ligurian ocean and was affected by extension and nappe stacking during the opening and closing of this oceanic realm, respectively. It overlies the Penninic nappes of the Eastern Alps. The Upper Austroalpine unit represents an eo-Alpine nappe pile. Its lowermost unit is the Silvretta-Seckau nappe system (13) consisting of a basement with a dominating Variscan metamorphic imprint and remnants of Permian to Triassic cover sequences. During the eo-Alpine event it was overprinted by sub-greenschist to amphibolite facies conditions.

To the north the Silvretta-Seckau nappe system is overlain by the nappes of the Greywacke zone (11), which consists of greenschist facies metamorphic Paleozoic sequences, and the Juvavic (8), Tirolic (9) and Bajuvaric (10) nappe systems. The latter form the Northern Calcareous Alps, comprising unmetamorphosed to lowermost greenschist facies metamorphic Permian to Mesozoic sediments deposited on the shelf facing originally towards the Neotethys ocean, with the sequences of the Juvavic nappe system representing the most distal shelf towards the oceanic basin.

To the south the Silvretta-Seckau nappe system is overlain by the Koralpe-Wölz nappe system (12) which represents an eo-Alpine metamorphic extrusion wedge. Its Permian to Mesozoic cover was completely stripped off during an early phase of the eo-Alpine orogenic event (Lower Cretaceous) and it therefore consists exclusively of polymetamorphic basement nappes with a Permian to Triassic HT/LP and an eo-Alpine LT/HP metamorphic overprint (SCHUSTER et al., 2004).

The Ötztal-Bundschuh nappe system (7) shows a similar lithological composition as the Silvretta-Seckau nappe system, but is positioned on top of the Koralpe-Wölz nappe system. The overlying Drauzug-Gurktal nappe system (6) is made up of a Variscan metamorphic basement, anchizonal to greenschist facies Paleozoic metasedimentary sequences and by unmetamorphosed Permian to Triassic sediments (RANTITSCH & RUSSEGGER, 2000). Within the Ötztal-Bundschuh and Drauzug-Gurktal nappe systems the eo-Alpine metamorphic grade decreases upwards from amphibolite facies at the base to diagenetic conditions at the top of the nappe pile.

The Upper Cretaceous to Paleogene sediments of the Gosau Group (5) represent syn- to postorogenic sediments with respect to the eo-Alpine orogenic event (FAUPL & WAGREICH, 2000).

The Southalpine unit (4) shows minor deformation localized along its margins. Its major part is in contact with a subcontinental lithosphere; this contact is visible at the surface in the Ivrea Zone in the Western Alps. The Southalpine unit is considered to be a southern external retro-arc orogenic wedge within the Alpine orogenic system (e.g. SCHMID et al., 1996). In the southeast the Southalpine unit continues into the External Dinarides.

3.4 Meliata unit

The Meliata unit (3) of the Eastern Alps contains remnants of the Neotethys (Meliata) oceanic basin. These include serpentinites, basic volcanic rocks and deep water Triassic sediments, redeposited in Jurassic metasediments. These rocks can be correlated with those from the Meliata zone in the Western Carpathians (MANDL, 2000). The Meliata zone occurs as tiny klippen within the eastern part of the Eastern Alps between the Tirolic and Juvavic nappe systems of the Austroalpine unit. They show a sub greenschist facies metamorphic imprint but no indications of subduction-related HP/LT metamorphism. Material from the Meliata oceanic basin is also present as detritus in Cretaceous sediments of Austroalpine units (FAUPL & WAGREICH, 2000) and in the Haselgebirge, an evaporite tectonite at the base of the Juvavic nappe system (SCHORN et al., 2013).

3.5 Eocene to Miocene magmatism

The Periadriatic intrusions (1) comprise calkalkaline tonalities, granodiorites and granites, and minor alkaline basaltic dikes. They are (Eocene to) Oligocene in age and related to the break-off of the Alpine Tethys oceanic lithosphere from the distal European margin (DAVIS & VON BLANKENBURG, 1995). Their intrusion is closely associated with contemporaneous strike-slip movements along the Periadriatic lineament.

The Pohorje pluton west of Maribor is not belonging to the Periadriatic intrusives sensu strictu. It is Miocene in age and related to the Pannonian magmatism (2) in the course of the extensional tectonics which leads to the development of the Pannonian basin (FODOR et al., 2008).

4 Distribution and timing of metamorphism within the Eastern Alps

In the following chapter a brief summary of the metamorphic events of the Eastern Alps is given. In the Eastern Alps four major metamorphic cycles can be recognized since Paleozoic time.

4.1 Variscan collisional event (Upper Devonian to Carboniferous)

The Variscan event is induced by the Upper Devonian to Carboniferous collision of Gondwana, Laurussia and the intervening plates (e.g. Avalonia), during the accretion of the Pangea supercontinent (KRONER & ROMER, 2013).

Age data of about 380 Ma are the oldest remnants of the Variscan event within the Eastern Alpines (HANDLER et al., 1997). A collision-related LT/HP imprint occurred prior to 350 Ma (MILLER & THÖNI, 1997) and the thermal metamorphic peak was reached at about 340 Ma at medium pressure conditions (c. 25° C/km). During exhumation the sillimanite stability field at a mean geothermal gradient of 35° C/km was crossed in the medium to high grade units (TROPPER & HOINKES, 1996). Typical Variscan cooling ages are in the range of 310-290 Ma (THÖNI, 1999). Due to the reworking in the Alpine tectonometamorphic cycle not much is known about the tectonic style of the Variscan orogene within the present day Eastern Alps. In general the recent Austroalpine nappes were located near the southern margin of the Variscan orogen. Top to the south-directed ductile shearing was recognized in the some of the basement units and Variscan thrust tectonics within Palaeozoic sequences is proved (FLÜGEL & NEUBAUER, 1984).

4.2 Permian extensional event

The Permian event in the Alps followed in the wake of the Variscan tectonic evolution. Lithospheric extension affected the recent Austroalpine, Southalpine and also Western Carpathian realm and caused magmatism and metamorphism. The onset of the Permian event may be considered as when crustal thickness decreased below normal, and thus cannot be related to gravitational collapse of the Variscan orogen.

Evidence for active thinning in Permian time is the formation of grabens, intense magmatic activity and high temperature metamorphism (SCHUSTER & STÜWE, 2008). The metamorphic imprint reached a geothermal gradient of up to 45° C/km. Peak metamorphic conditions were reached at about 280-260 Ma and were accompanied by the formation of pegmatitic veins in upper amphibolites facies metamorphic rocks. After that the continental crust was not exhumed and the lithosphere cooled down slowly to the steady state geotherm of c. 25° C/km at about 200 Ma.

4.3 Alpine collisional event (Cretaceous to Neogene)

The convergence between the African, Adriatic and Eurasian Plate since Lower Cretaceous time caused shortening in the Alpine realm. This leads to the formation of the Alpine orogenic belt by “tectonic progradation” (FRISCH, 1979) from south to north. This process started with an intracontinental subduction within the Austroalpine unit in the Lower Cretaceous (KURZ & FRITZ, 2003; SCHUSTER, 2003) which was followed by the Upper Cretaceous-Eocene subduction of the Piedmont-Ligurian and Valais ocean and prograding continental collisional events that continued until recent times. This mechanism produced high-pressure metamorphism in different tectonic units, decreasing in age from south (internal) to north (external). A brief summary of this evolution is given below. Detailed reviews of the metamorphic conditions and the timing of metamorphism in the individual units, together with maps showing the distribution of the metamorphic grade, are given by FREY et al., (1999) and OBERHÄNSLI (2004) (Fig. 4).

In Early Cretaceous time (c. 135 Ma) a southeast-directed subduction zone developed which was at least in part situated within the continental crust of the Adriatic plate (e.g. JANAK et al. 2004; SCHUSTER & STÜWE, 2008). Along this subduction zone the Upper Austroalpine nappes formed an orogenic wedge which was continuously growing during the Cretaceous. During this tectonic event - which is referred as the Eo-Alpine tectonometamorphic event -

the northwesternmost part of the Adriatic plate, represented by the main part of the Austroalpine nappes, acted as the tectonic lower plate, whereas the main part of the Adriatic plate including some Austroalpine nappes and the recent Southalpine unit were parts of the upper plate. Today the Eo-Alpine suture is obscured by Cenozoic tectonics. Nappe stacking related to the initial eo-Alpine subduction was W- to NW- directed. Large parts of the sedimentary sequences of the Austroalpine unit were stripped off from their basement, which was buried and metamorphosed up to eclogite facies conditions. Geochronological data suggest peak metamorphic conditions of the high-P metamorphic event at about 92 Ma (THÖNI, 2006) and a subsequent medium pressure overprint during exhumation of the high pressure rocks. In the eastern part of the Eastern Alps exhumation of the deeply buried units occurred by N- or

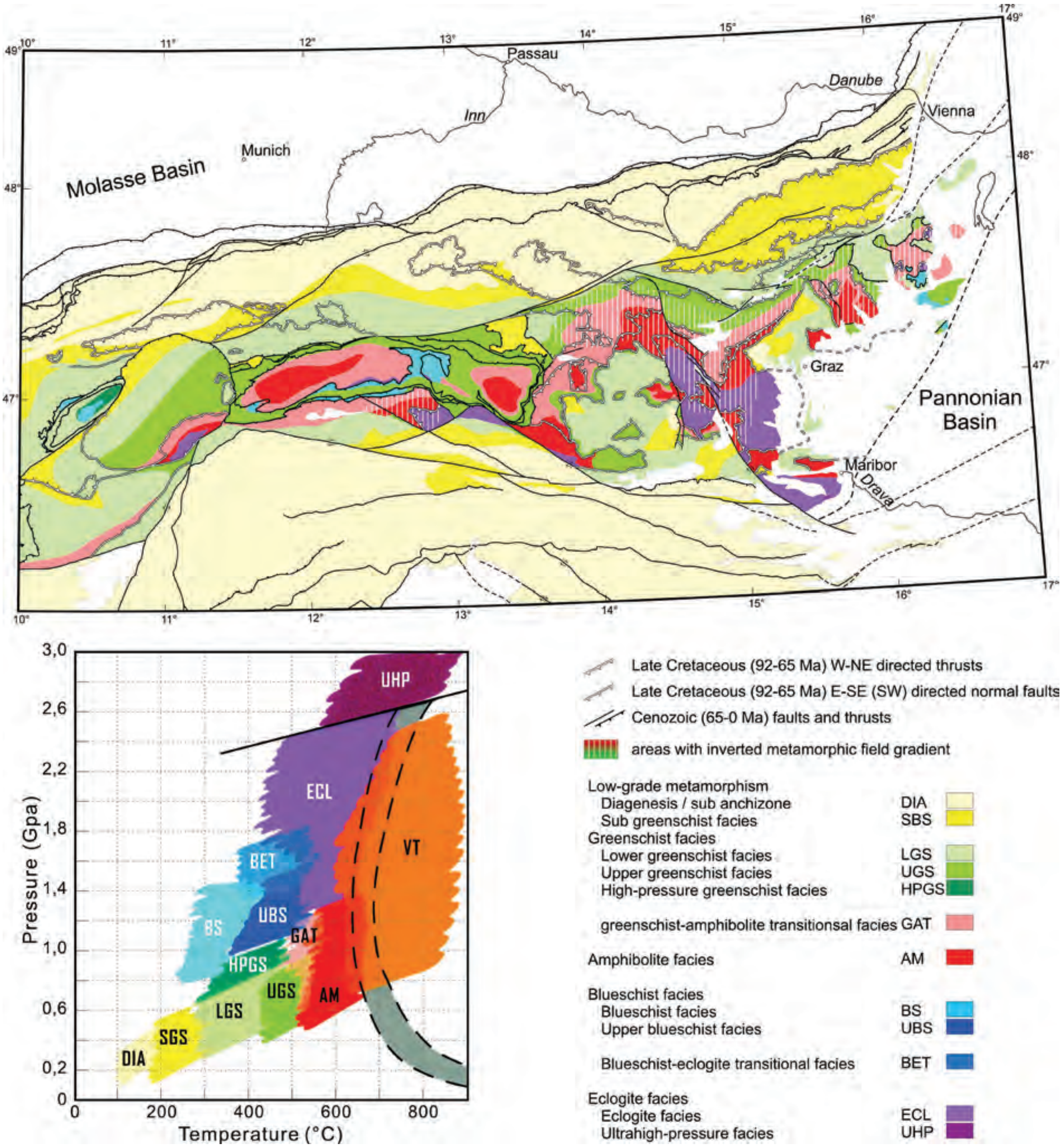

Figure 4: Map of the Eastern Alps showing the distribution of the Alpine metamorphic imprint according to OBERHÄNSLI (2004). Additionally areas with an inverted metamorphic field gradient and the most important Cretaceous and Cenozoic structures are given.

NW- directed thrusting and S- to SE- directed extensional tectonics. During this process a metamorphic extrusion wedge formed. The latter shows a lower part with an inverted metamorphic field gradient and an upper part with an upright metamorphic field gradient. Cooling ages are in the range of 90 to 70 Ma (HOINKES et al., 1999; THÖNI, 1999).

Ongoing subduction of the lithospheric plate caused the entrance of the Penninic oceanic domain into the subduction zone at about 85 Ma and after the closure of the ocean the European continent entered the subduction zone in the Paleogene at about 45 Ma (SCHMID et al., 2013). These processes are referred to as the Alpine event, which is the mayor event in the Western Alps. It resulted in the formation of the Penninic, Subpenninic and Helvetic nappes. In the Eastern Alps the Alpine event caused a LT/HP metamorphism in the Penninic and Subpenninic nappes at c. 40 Ma (THÖNI, 1999) and medium pressure overprint at about 30-25 Ma. Typical cooling ages are in the range of 25 to 15 Ma (LUTH & WILLINGSHOFER, 2008). Exhumation of these units is related to E-W extension since Miocene time. It caused the formation of the Engadine, Tauern and Rechnitz Windows. Adjacent to the windows the Austroalpine unit shows a structural and very-low to low grade Alpine metamorphic overprint (HOINKES et al., 1999).

Subsequent exhumation of the underlying Penninic and Subpenninic nappes within windows (GENSER & NEUBAUER, 1989; FÜGENSCHUH et al., 1997) and lateral extrusion of the orogene in the Miocene (RATSCHBACHER et al., 1989) generated a system of normal and strike slip faults. These faults have a major influence on the recent morphology and are responsible for the exhumation of the Saualpe-Koralpe Complex in the Pohorje region. Depressions like the Styrian, Knittelfeld and Klagenfurt basin developed along these faults. The major strike-slip faults are the Periadriatic lineament, Inntal, Salzach-Ennstal-Mariazel-Puchberg or the Lavanttal fault.

5 Geology of the Nockberge area

In the section from Villach up to the Königsstuhl a complex eo-Alpine nappe pile composed of different crystalline units as well as Palaeozoic and Mesozoic metasediments is preserved (Fig. 5). This section is a key area for the understanding of the eo-Alpine history of the Austroalpine unit. It is under discussion for a long time and was one major argument for the subdivision of the Austroalpine by TOLLMANN (1977). It bears important informations on the plate tectonic arrangement and the exhumation history in the western part of the Austroalpine unit.

From SSW to NNE, respectively from bottom to the top the following units are present:
The Millstatt Complex is bordered to the southwest by the Mölltal fault. The dominant lithology are monotonous metapelites and metapsammites, which are dipping to the north. Only in the lowermost part they sometimes contain two generations of staurolite, kyanite and garnet. Also calcsilicate rocks and massive marbles with intercalation of amphibolite lenses occur in this southern part. Within the lowermost amphibolite layers, relic eclogite bodies are present. Pegmatites of Permian age are common in the whole unit (SCHUSTER et al., 2001).

The pre-Alpine history of the Millstatt Complex is not well constrained. However, a Permian low-P event is indicated by the occurrence of Permian pegmatites and textures similar to those in units where a Permian low-P event is proved. Peak eo-Alpine metamorphic conditions reached ~1.38 GPa and 630 ± 20° C estimated from garnet-clinopyroxene thermometer and jadeite contents in omphacite (HOINKES et al., 1999). Reaction textures of the eclogite assemblages reflect decompression with a change from constant to decreasing temperatures during the exhumation of the Millstatt Complex.

In the overlying, north dipping, Radenthein Complex the most abundant lithologies are white mica-rich, garnet-bearing micaschists. Garnets are up to several centimeters in size, kyanite- and/or staurolite are present especially in biotite-bearing schists. Frequent are amphibole-garnet-plagioclase schists, mica-bearing amphibolites and marbles. A large magnesite body had been of economic interest. The microtextures and the chemical zoning indicate one prograde metamorphic imprint except in one locality where garnet contains older cores. Peak metamorphic temperatures are in the range of 550-600°C at pressures of 0.6-1.0 GPa (SCHIMANA, 1986; KOROKNAI et al., 1999; KAINDL & ABART, 2002). Sm-Nd garnet isochron ages of an amphibolite yielded c. 100 Ma (SCHUSTER & FRANK, 1999), K-Ar and Rb-Sr ages determined on micas and whole rock samples are in the range of 78 to 125 Ma. These data prove an eo-Alpine age of observed assemblages (BREWER, 1969; HAWKESWORTH, 1976; SCHIMANA, 1986).

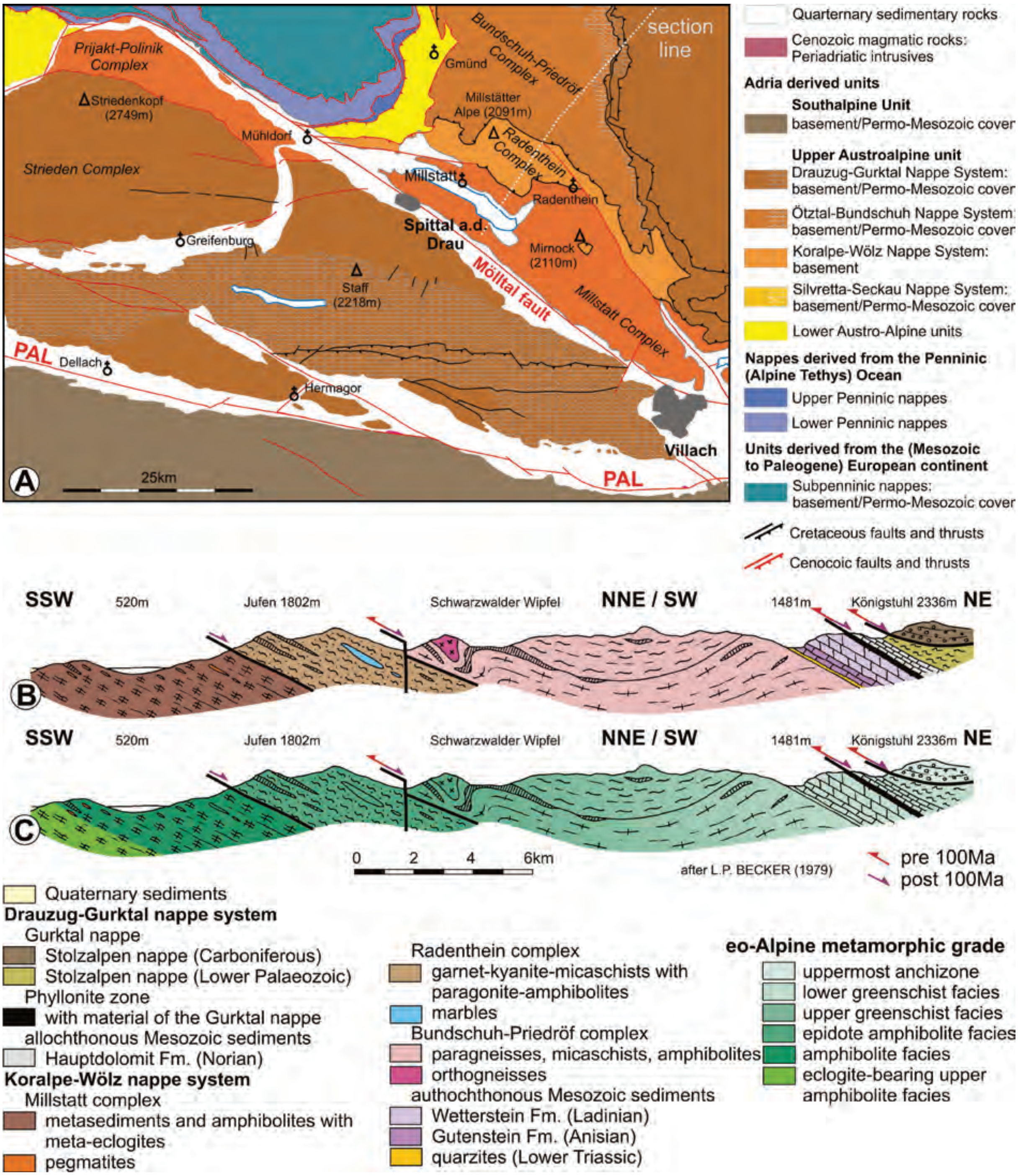

Figure 5: (A) Tectonic map of the western part of Carinthia. (B, C) Section trough the western part of the Nockberge area showing the geologic units and the distribution of the eo-Alpine metamorphic grade.

The Bundschuh Complex is overlying the Radenthein Complex with an eo-Alpine thrust contact (SCHUSTER & FRANK, 1999). Its lower part consists of fine-grained paragneisses with some intercalations of felsic biotite-free orthogneisses and amphibolites (Priedröf paragneisses, Bundschuh orthogneisses). Micaschists and interlayered amphibolites are restricted to the uppermost part of the unit in the center of a large scale gentle syncline structure. The Priedröf paragneisses contain a mineral assemblage of garnet + biotite + plagioclase (albite and oligoclase) + muscovite + quartz. In the micaschists additional staurolite and pseudomorphs after staurolite (rarely containing chloritoid) may be present. Garnets are very characteristic in the whole unit. In the paragneisses they have an average grain-size of less than 0.5 mm, whereas in the micaschists they are up to 2 cm in diameter. Optically an inclusion-rich, often idiomorphic core can clearly be distinguished from an inclusion-free rim. The cores are compositionally homogenous with low CaO contents of 3-5 wt%. Their age is presumed to be Variscan, because Variscan Rb-Sr ages (c. 350 Ma) were determined on muscovites of orthogneisses from the uppermost part of the unit (FRIMMEL, 1986). In the rim the CaO content is much higher (6-8 wt%), FeO, MgO and also XMg is lower. Based on the regional metamorphic history this garnet generation is eo-Alpine in age. Eo-Alpine metamorphic conditions reached up to 600 °C and 1.0 GPa in the lowermost parts in the south and greenschist facies conditions below the transgressive Mesozoic unit.

The Mesozoic Stangalm Unit is unconformalbly transgressing onto the pre-Alpine syncline structure. The lowermost part consists of Permian to Early Triassic quarzites. Above Anisian carbonates and Carnian phyllitic schists are preserved (TOLLMANN, 1977). A phyllonite horizon, composed of highly sheared Paleozoic and Mesozoic rocks marks the border to the overlying Pfannock unit (nappe). The Pfannock orthogneiss, which is very similar to the Bundschuh orthogneisses (FRIMMEL, 1988) forms the stratigraphically deepest part. It is transgressed by Carboniferous to Permian clastic sediments. Continuing Mesozoic carbonates and schists reach up to the Rhaetian Kössen Formation. The sediments show a lower greenschist facies metamorphic imprint.

The uppermost tectonic position is hold by the Gurktal nappes (Murau, Stolzalpen, Ackerl nappe; NEUBAUER & PISTOTNIK, 1984). The latter comprises clastic metasediments with some intercalations of carbonates and metatuffitic layers, which were deposited in Lower Palaezoic times. During the Variscan tectonothermal event they experienced a greenschist facies metamorphic imprint. After that Carboniferous sediments of an intramontane basin (KRAINER, 1984) and Permo-Mesozoic sediments were deposited on top. During the eo-Alpine event the whole sequence suffered anchizonal to lower greenschist facies metamorphic conditions.

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Field Trip A1: Southern Alps of Slovenia in a nutshell: paleogeography, tectonics, and active deformation

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Abstract

The field trip deals with different aspects of the evolution of the easternmost part of the Southern Alps in Slovenia. We will see and discuss:

- Middle Triassic to the Early Cretaceous paleogeography of the Julian Alps (Late Anisian carbonate-platform break-up, Late Triassic progradation of the Dachstein Platform and coeval formation of the intraplatform Tamar basin, Late Triassic - Early Cretaceous successions of the Slovenian Basin. Paleogeographic domains are now positioned in different tectonic blocks of the overlapping South Alpine and Dinaric thrust structures.
- Periadriatic fault system, major Oligocene-Miocene tectonic feature of the Alps, dextral strike-slip Sava fault, remarkable morphologically expressed tectonic line, which separates Julian and Kamnik-Savinja Alps and an active Vodice reverse fault at the contact between the Southern Alps and the Dinarides.
- The Upper Oligocene Smrekovec Volcanic Complex, one of several small and marginal sub-basins in the south-west of the Pannonian back-arc realm, considered to be post-collisional and related to slab breakoff processes.

Introduction

The field-trip area is located in the eastern part of the Southern Alps (NW and central N Slovenia, Fig. 1). They are situated between the Periadriatic fault, Labot (Lavanttal) fault and Ljutomer fault which are in the broader sense a part of the Balaton fault zone in the north, and South-Alpine thrust border and Sava fault in the south (PLACER, 2008) (Fig. 2). Julian Alps and Kamnik – Savinja Alps are predominately composed of Mesozoic carbonate rocks. In the Southern Karavanke also Paleozoic rocks are exposed. In the Julian Alps South Alpine and the Dinaric structures now overlap. They consist of two south-verging tectonic units, the Tolmin Nappe and the Julian Nappe. The Tolmin Nappe consists of several thrust sheets. Also Julian Nappe consists of minor thrust sheets, but it has not yet been satisfactorily resolved. The K–S Alps were displaced by approximately 40 km with respect to the Julian Alps along the Neogene dextral strike-slip Sava Fault. The Julian Alps and the K–S Alps exhibit a remarkably similar stratigraphic evolution in the Triassic. North of the Julian Alps and the K–S Alps the South Karavanke Mts. form a strongly elongated strike-slip-related system of sheared tectonic lenses south of the Neogene Periadriatic Line (PLACER, 2008). During the extensional evolution of the Pannonian Basin, connected with the activation of the Periadriatic Line (PAMIĆ & BALEN, 2001), volcanic activity created the Smrekovec Volcanic Complex, part of the small and marginal sub-basin, positioned on the Mesozoic basement of the Southern Alps. In the releasing overstep between major dextral strike–slip Sava and Žužemberk faults, Ljubljana Basin, filled with Quaternary sediments is positioned (VRABEC & FODOR, 2006). Smaller E-W oriented reverse faults that displace Quaternary sediments in the basin may indicate a recent change in the deformational regime from transtensional subsidence to transpression.

Figure 1: Geographic location of all field-trip stops.

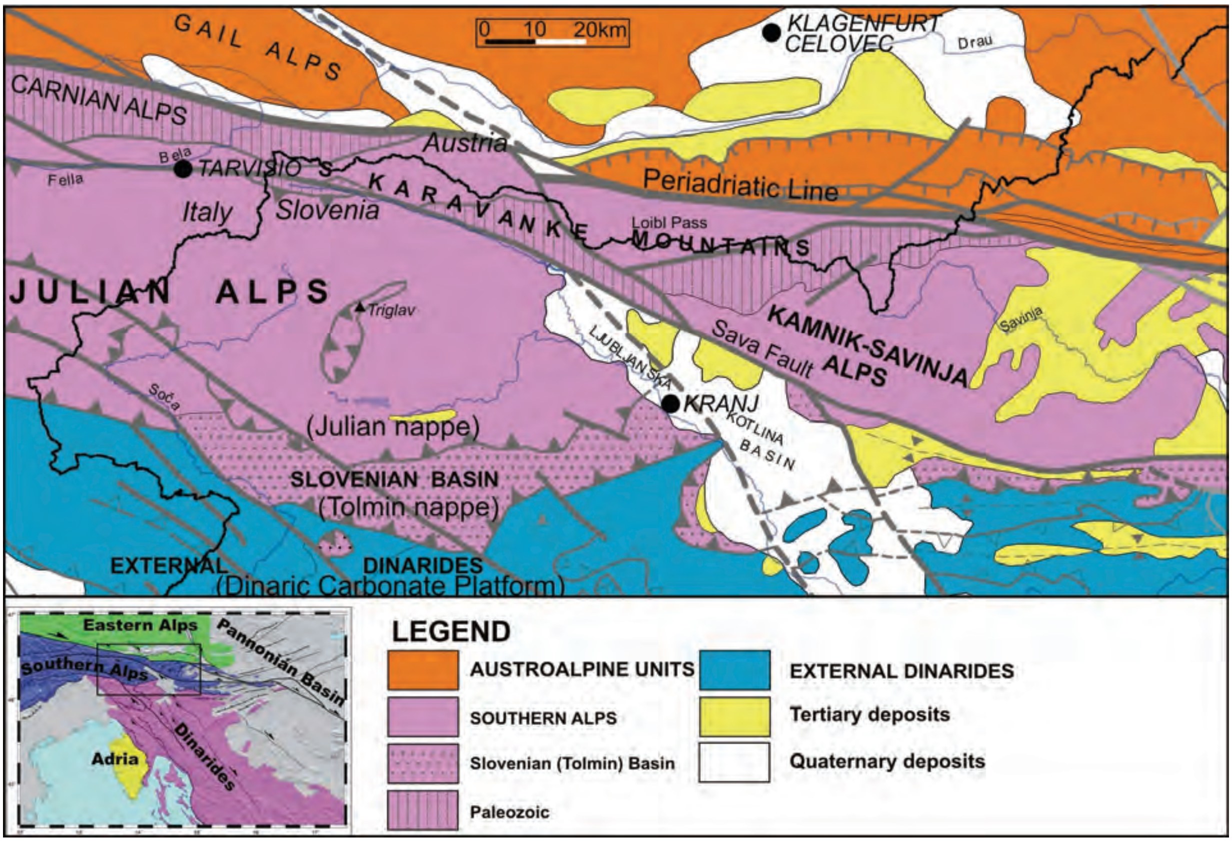

Figure 2: Macrotectonic subdivision of the NW and central N Slovenia (after PLACER, 2008).

Day 1

Middle Triassic carbonate-platform break-up and formation of small scale half-grabens (guided by Bogomir Celarc)

Introduction

The Late Anisan extension associated with differential subsidence, the rotation of blocks, coeval drowning and exposure of carbonate platforms was a widespread event in the Southern Alps and has been documented by numerous authors (e.g. BECHSTÄDT et al., 1978; FARABEGOLI et al., 1985; DE ZANCHE et al., 1993; GIANOLLA et al., 1998 and references therein; VENTURINI, 2006; Berra & CARMINATI, 2010). During the Middle and and also Late Triassic, this area was located on the southwestern shelf of the opening Meliata-Maliac Ocean (STAMPFLI & BOREL, 2002) that is now mostly considered to be an embayment of the Neotethys (e.g., SCHMID et al., 2008).

Throughout the Southern Alps during the Illyrian, most of the previous platforms drowned with the onset of the basinal Buchenstein/Livinallongo Formation (GIANOLLA et al., 1998). However, there are reports of red-coloured radiolarian and locally ammonite-rich limestones (Ammonitico Rosso-type limestones) on top of shallow-water carbonates (FARABEGOLI & LEVANTI, 1982; KRAINER & MOSTLER, 1992; KOZUR et al., 1994; KOZUR et al., 1996; KRAINER, 1996). They are usually very thin and are overlain by volcanics and/or polymict conglomerates and sandstones which are equivalents to the Uggowitz Breccia, a well-known formation from the Carnian Alps and the western (Italian) part of the Julian Alps (GIANOLLA et al., 1998). Above those units, the Buchenstein (Livinallongo) Formation occurs and, in the upper part, this interfingers with the Schlern Dolomite which records platform progradation.

Map-scale geometry, neptunian dykes, the onset of volcanism, the presence of (mega)breccia and related palaeo-escarpments, the lateral variations in thickness and the wedge-shaped geometry of the lithological units provide evidence of syn-sedimentary block faulting and the formation of small-scale, relatively shallow half-grabens within the previously uniform Slovenian Carbonate Platform and indicates a clear tectonic control over the development of the Middle Triassic stratigraphy. The described extensional event is well correlated and genetically connected with the syn-rift formation of the neighbouring Slovenian Basin and other Southern Alpine basins that formed in connection with the opening of the Meliata-Maliac branch of the Neotethys Ocean.

Figure 3: Geographic location of Stops 1 and 2.

Stop 1 – Vratica Saddle (1799m): view to the Mt. Prisojnik (Middle Triassic) with small-scale halfgraben (Fig. 3)

In the ESE direction from the Vratica Saddle, the NW face of the Mt. Prisojnik (2547 m) exhibits well-exposed Middle Triasic succession (CELARC et al., 2013) (Fig. 4a, b). The lower part of the NW face of Mt. Prisojnik is composed of well-bedded, in places stromatolitic, Anisian (probably Pelsonian) dolomite and limestone with *Meandrospira dinarica* and *Physoporella pauciforata* (JURKOVŠEK, 1987; RAMOVŠ, 1987a). These rocks are overlain by an about 40 m thick succession of thin-bedded to platy dark-grey dolomite intercalated with thin horizons of reddish marlstone. In the upper part, around 2 m of green-coloured marl is intercalated.

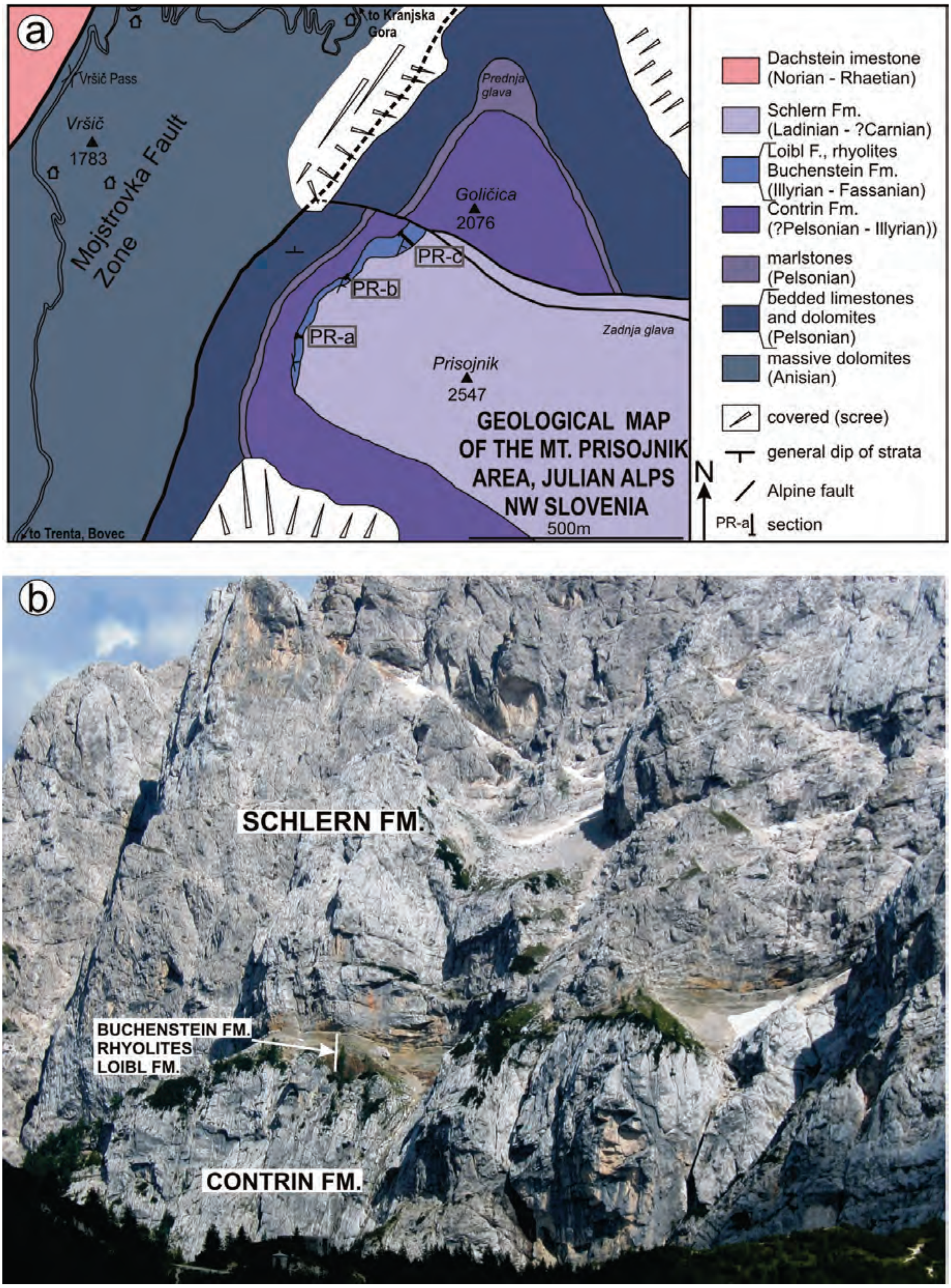

Figure 4: (a) Geological sketch map of the Mt. Prisojnik area. (b) Field photography of the NW face of Mt. Prisojnik with formations as shown on the geological map.

Above this there occur up to 200 m thick massive limestone of the Contrin Formation (?Pelsonian – Illyrian). The succession above the Contrin Formation and below the Schlern Formation (massive, partly dolomitized limestone) consists of the laterally discontinuous, up to several metres thick, Loibl Formation, tuff and rhyolite (0 to 20m), and the Buchenstein Formation (0 to 25 m thick). A slight angular unconformity is observable between the Contrin Formation and the overlying units. The upper part of the Contrin Formation is cross-cut with neptunian dykes which can reach several metres in the undeformed limestone. The Loibl Formation overlies the Contrin Formation with a sharp contact. In the lower part, it consists of distinctive nodular, light-red radiolarian-rich wackestone. Their age is Illyrian (upper part of the *Paraceratites trinodosus* Ammonoid Zone), according to the radiolarian and conodont dating.

The contact with overlying tuffs is not exposed. Red rhyolite with flow structures emerges from the scree around 10m above the tuffs. Toward the SW, they are thinning and onlapping the Contrin Formation and the Loibl Formation. The Buchenstein Formation lies with sharp contact on the rhyolite and is approximately 25 m thick. In the lower part, the formation consists of grey platy nodular limestone, mostly wackestone, with thin laminated siltstone-sandstone intercalated between individual layers. In the upper half of the section, the bedding planes are planar and there is no siltstone or marlstone intercalated. In some beds, abundant, well-preserved resedimented algae are present.

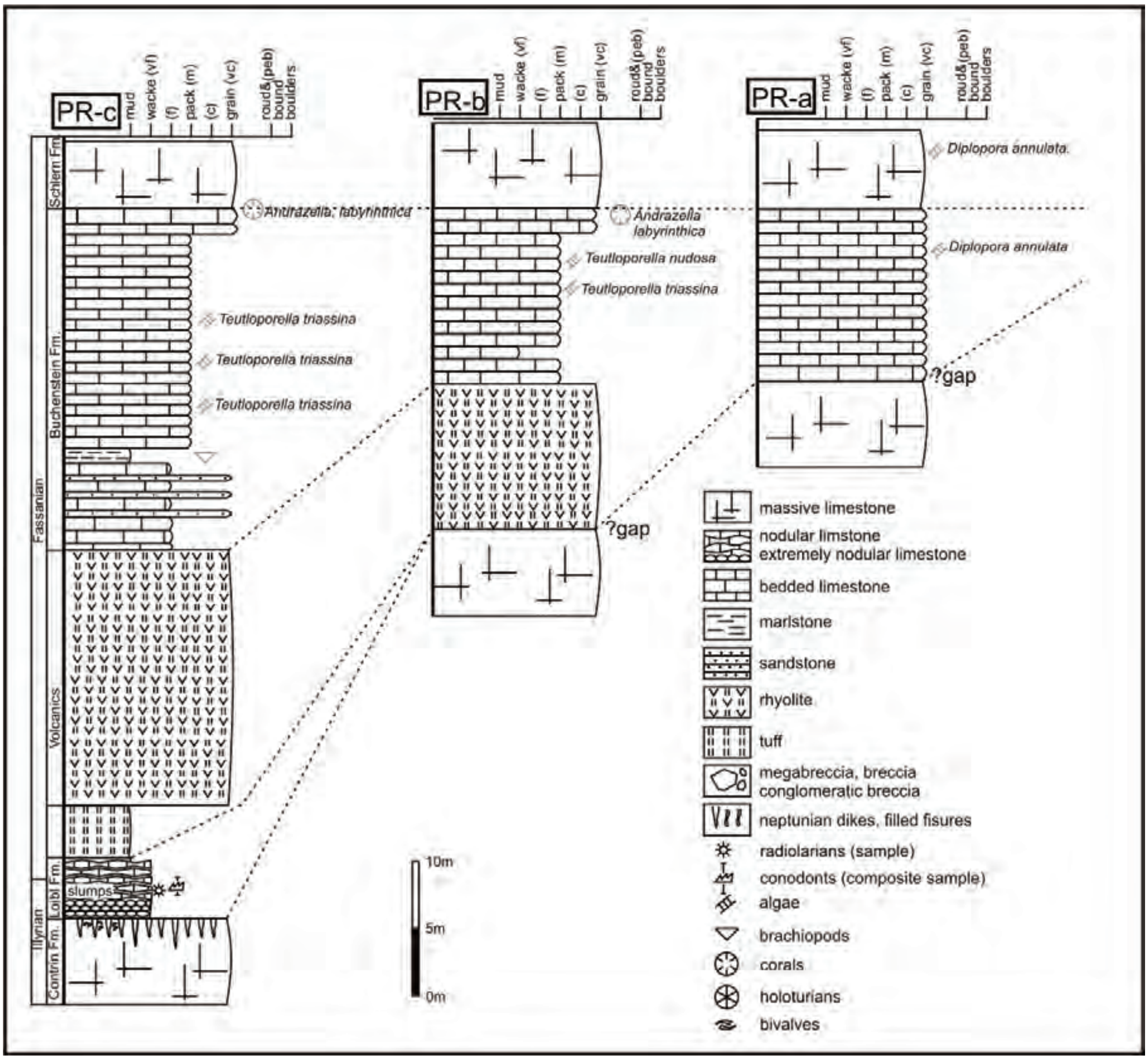

Figure 5: Stratigraphic logs of the sections in the Mt. Prisojnik and their correlation. For location of the sections see Fig. 4a.

Laterally, the red limestone of the Loibl Formation wedges out, also rhyolites thickness decreases. Limestones of the Buchenstein Formation directly overlie the Contrin Formation and consist predominantly of thin-bedded peloidal packstone and wackestone with subrounded algal fragments. Grainstone prevails in the upper part. Even more laterally, the Buchenstein Formation gradually wedges out. Between the Contrin Formation and the Schlern Formation, only a few metres of thin-bedded, graded predominately algal grainstone and rudstone are present.

Small-scale hafgraben geometry in the Mt. Prisojnik is evident from: (1) mapping-scale geometry of the basin infill between the underlying Contrin Formation and the overlying Schlern Formation and their mutual boundaries; (2) lateral and vertical variations in facies types and (3) lateral variations in thickness of the basin fill (Fig. 5).

Progradation of the Dachstein carbonate platform (guided by Bogomir Celarc)

Introduction

A distinct transgression pulse, recognized above the former Ladinian – Carnian platforms or Raibl Group, deepening, formation of the basin(s) and progradation of the rimmed Main Dolomite or Dachstein Limestone platforms, was recognized in the Julian Alps (LIEBERMAN, 1978; RAMOVŠ, 1986a, 1986b, 1987b; JURKOVŠEK, 1987; SCHLAF et al., 1997a, 1997b; DE ZANCHE et al., 2000; GIANOLLA et al., 2003; CELARC & KOLAR-JURKOVŠEK, 2008). According to paleogeographic studies, the Slovenian part of the Julian Alps formed an isolated platform between the Slovenian Basin and the Hallstatt – Meliata Ocean (e.g. HAAS et al., 1995; ZIEGLER & STAMPFLI, 2001; STAMPFLI & BOREL, 2002).

Stop 2 – Mt. Slemenova špica (1909m): view to the Mt. Škrlatica (progradation of the Dachstein carbonate platform)

From the Mt. Slemenova špica, in the E direction, the NW face of the Mt. Škrlatica (2740 m, part of the Martuljek Mountain Group), the progradation geometry of the Dachstein platform is exposed at the seismic-scale. This is one of the rare "text-book" examples where complete transect from basin floor, adjacent slope (clinoforms), reef and lagoon is exposed (Fig. 6a).

In the lower part, the mountain face consists of the Razor limestone (Lower Carnian), with cyclic bedded limestones, organized into 1-1,5m thick, predominately shallowing upward symmetric cycles. Shallower subtidal facies is represented by an abundant oncoidal horizonts. Intertidal - supratidal facies is recognizable by laminated grainstones, which are often dolomitized, and with horizontal microbial laminites. Fenestral pores (loferites) are very common in these horizons.

With the sharp, discordant contact, follows, thin, up to 25 m thick, darker band of the Martuljek platy limestone (Upper Tuvalian - Lower Norian – dated with conodonts), consisting of reddish, platy pelagic limestones. The Lower member is composed of reddish (rarely grayish) sometimes indistinctly bedded pelagic limestone (bioclastic wackestone to packstone). The Upper member is composed of light grey to white platy and thin bedded often dolomitized limestones (coral and crinoid grainstones and rudstones) and represents toe-of-the-slope facies (Fig. 6b).

Around 300 m thick Dachstein reef limestone with corals and sponges as main frame-builders (Upper Tuvalian – Norian), consisting of hard-to-distinguish slope and reef margin facies is positioned on top of the Martuljek Platy Limestones and they partially interfinger. Due to the steep terrain, these limestones haven't been yet studied in detail in order to establish classic reef zones (fore reef, reef front, reef crest, back reef). The highest stratigrafic unit in the upper part of the mountain is well bedded, cyclic bedded Dachstein Limestone (Norian – Rhaetian), more than 1000m thick, onlapping reef limestones (Fig. 6c).

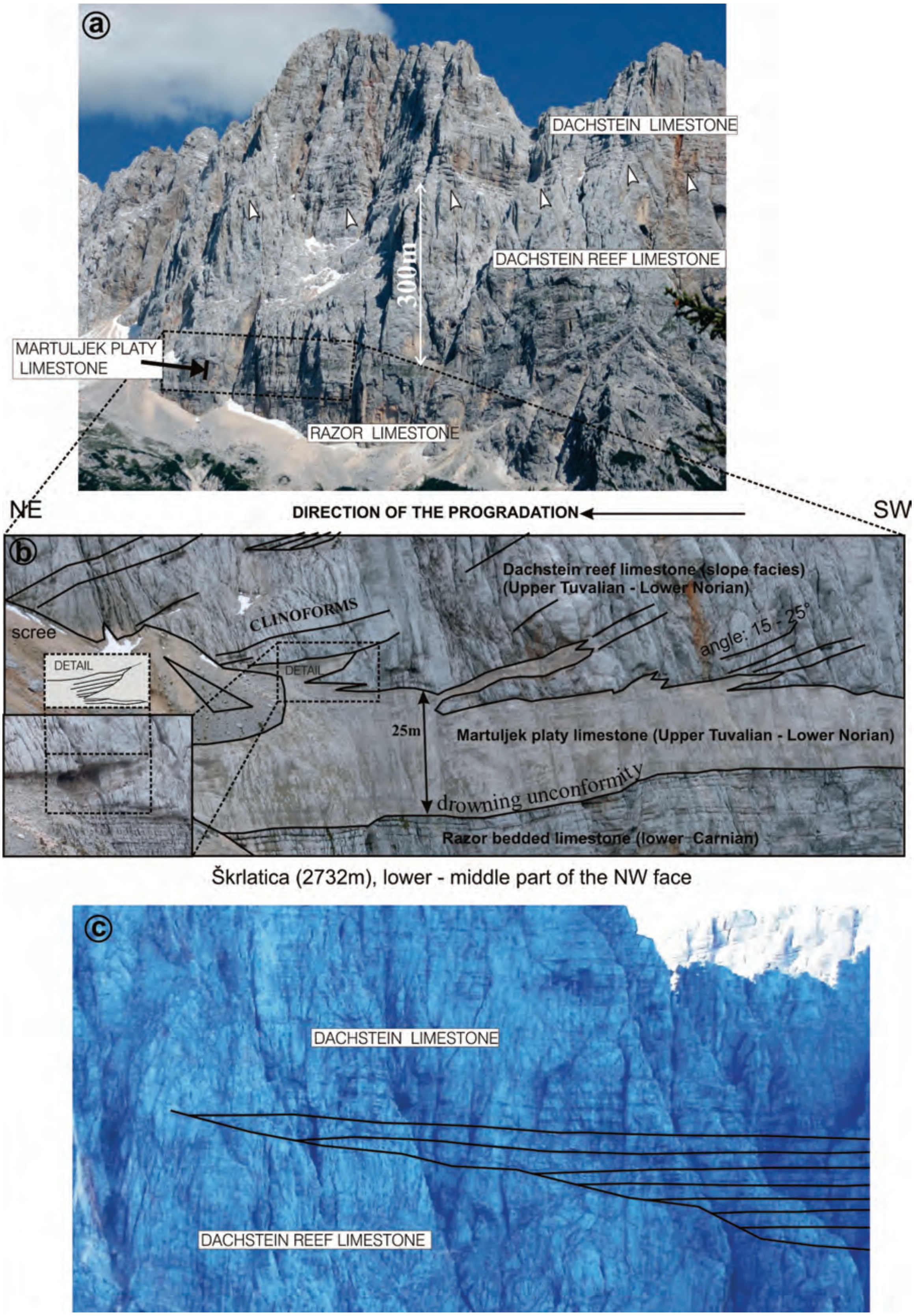

Figure 6: Facies interpretation and progradational geometry in the NW face of Mt. Škrlatica. (a) Large scale facies interpretation. Arrows indicate contact between Dachstein reef limestone (slope and margin facies) and bedded Dachstein Limestone (inner plarform facies). (b) Interpretation of facies relationship with detail of toe of slope interfingering between Martuljek platy limestone (Upper Member) and reef limestone. (c) Bedded Dachstein limestone onlapping massive reef limestone.

Progradation geometry of the Dachstein platform passing into the basin is exposed parallel to the direction of the platform advance.
Interfingering of the thin bedded reef-debris limestones (Martuljek platy limestone – Upper member) and clinostratificated reef-debris limestones of the slope facies (Dachstein reef limestone) is clearly visible. The lithologic boundary in Mt. Škrlatica can be interpreted as a climbing progradadion in the sense of BOSELLINI (1984), yet generally, the boundary is horizontal. Thin bedded limestones exhibit low angle onlap against the upper boundary of the intermediary wedge of the slope limestone intercalated in the Martuljek platy limestone. The Upper member of the Martuljek platy limestone slightly thickens basinward, while individual beds thin in the same direction.

Clinoforms are expressed as discontinuities in the slope limestones with an inclination of around 15-25° and dip in the NE direction. Their configuration is oblique-parallel. We interpret this pattern as the horizontal downlap plane (BOSELLINI & STEFANI, 1991; MAURER, 2000) which indicates rapid progradation of the platform.

The upper boundary of the slope and the margin with the Dachstein Limestone is expressed as low angle onlap against a massive margin. This relationship points to the slow relative subsidence in the Early Norian and progradational dominated highstand systems tract.

The coral reef margin in the upper part is macroscopically similar to the slope, so its exact thickness is unknown. Based on the clinoform dip and the opposite direction of the onlapping surface, the progradation is in the SW – NE direction.

Estimating the water depth at the Hallstatt basin – Dachstein reef platform connection in the NCA is a topic of recent debates. KENTER & SCHLAGER (2009) calculated at least 300m, probably more than 500m for the Gosaukamm. At the Gosausee deep estimating ranges between 200-250m (MARTINDALE et al., 2013). In the Mt. Škrlatica it could be directly measured and amounts 300m.

Tamar Valley (Carnian-Norian–Rhaetian intraplatform Tamar Basin in the footwall block and Dachstein platform in the hangingwall block of the Resia – Val Coritenza backthrust) (guided by Bogomir Celarc)

Introduction

Julian Nappe with the Dachstein limestone is thrusted in the Tamar Valley on the Norian-Rhaetian basinal succession, while on the Italian side of Mt. Mangart, thrusted blocks consist also of Jurassic (and partially Lower Cretaceous) lithological units on top of the basinal and platform Triassic succession, respectively (ASSERETO et al., 1968). The similar succession is described also in the South Karavanke between Frauenkogel/Dovška Baba and Kahlkogel/Golica (KRYSTYN et al., 1994) and probably belongs to the same basin, now displaced along Sava Fault. A Late Tuvalian – end Triassic facies polarity (Fig. 7), characterized by the SW-NE progradation of the Dolomia Principale platform (DE ZANCHE et al., 2000; GIANOLLA et al., 2003) is clearly represented. In the west (Dogna Valley, Raibl area in Italy), terrigenous influenced Julian and Lower Tuvalian formations filled Middle Triassic, while more to the east, Cassian Dolomite conformably overlies the Schlern Dolomite. The area was sealed and flattened with deposition of the widespread Tor (Heiligkreuz) Formation and the carbonate bank of the Portella Dolomite (DE ZANCHE et al., 2000; GIANOLLA et al., 2003; PRETO et al., 2005). In the Late Tuvalian, drowning triggered deposition of the basinal Carnitza Formation and coeval progradation of the Dolomia Principale in the west (from direction of Dolomites), while in the Mangart area (Mt. Privat), and in the Tamar Valley, basinal conditions prevail from Late Tuvalian to the end of Triassic, with Norian cherty dolomites, followed by basinal dolomites and Rhaetian platy limestones.

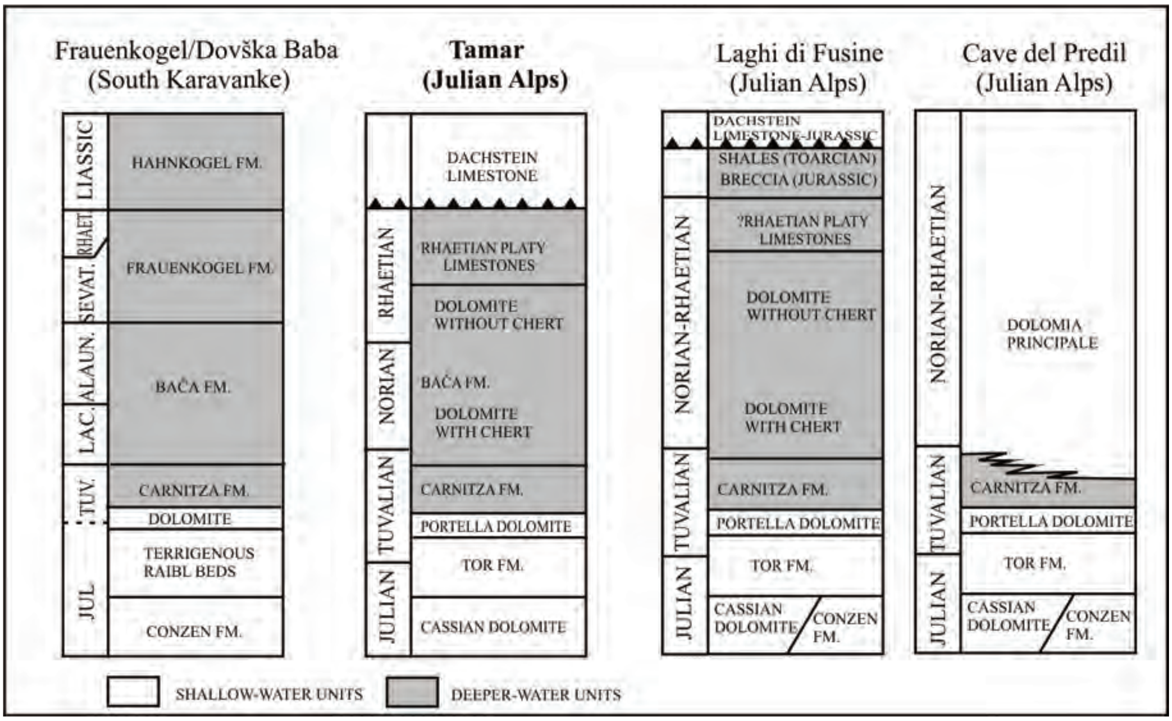

Figure 7: Upper Triassic stratigraphic columns and correlation of the Tamar Basin between Cave del Predil (Julian Alps – Italy), Laghi di Fusine (Julian Alps – Italy), Tamar (Julian Alps – Slovenia) and Frauenkogel/Dovška Baba (Karavanke – Austria and Slovenia)

Stop 2 – Mt. Slemenova špica (1909m): Tamar Valley

The stratigraphic succession in the lower parts of the NNW – SSE to N-S directed Tamar Valley belongs to the footwall block of the north-verging Resia – Val Coritenza backthrust (Fig. 8), probably related to the Alpine thrusting (PONTON, 2002).

Figure 8: Mountains above Tamar Valley. Resia – Val Coritenza north verging backthrust separates Tamar Basin (Upper Tuvalian – Rhaetian basin interval) in the footwall and Dachstein limestone in the hangingwall. Photography taken from Mt. Ponca ridge.

Stratigraphy of the Tamar Basin

The stratigraphic succession is exposed in the lower slopes of the Mt. Mojstrovka and Mt. Travnik in the S to SSW direction from Mt. Slemenova Špica. Cassian Dolomite is the lowest unit, composed predominately of massive to the indistinctly bedded dolomites, with rarely present stromatolites and oncoides. With the sharp contact follows the Tor Formation. This, 50m thick unit is thin – layered shallow-water fossil rich terrigenous carbonate unit, with alternation of marlstones, marly limestones, thin-bedded dolomites and limestones, suordinately calcarenites, rich in bivalves, gastropods, foraminifers. The age of the formation is Julian – Tuvalian. Above the Tor Formation is positioned 12 m thick massive dolomitic unit, without sedimentological textures and fossils. It corresponds to the Portella dolomite from Cave del Predil area (GIANOLLA et al., 2003). Carnitza Formation is around 55 m thick and is composed of well-bedded gray to dark-grey platy dolomites with rare up to 7 cm thick black (rarely green) claystone intercalations. Bedding is planar or wavy. Parallel lamination and bioturbation are common. According to the conodonts, the age of formation is Middle to Late Tuvalian. Above the Carnitza Formation, Bača Formation (sensu KRYSTYN et al., 1994) is positioned. The transition is gradual, marked by appearance of chert nodules and a decrease of the clay content. It is composed of the thin to medium-bedded dolomites with abundant black, brown or red colored chert nodules. Dolomite-cherty breccias and synsedimentary slides are common. In the upper part massive or indistinctly bedded dolomites without chert prevail. The total thickness of the formation is around 300 m. In the lower part of the dolomites with chert, conodonts indicate Middle – Late Tuvalian age, in the upper part of the dolomites with chert condonts indicate Middle – Late Norian age. In the lower part of the dolomites without chert, conodonts indicate Late Norian – Early Rhaetian age and in the uppermost part of the dolomites without chert, conodonts indicate Rhaetian age. The uppermost formation is 49 thick, and is cut with thrust at the top. It starts with 10-20 cm thick marlstone beds, interchanging with fine- to medium- coarse graded, 40 cm thick rudstone. A fairly uniform sequence of the dark bituminous and laminated platy limestone follows, interchanging with few up to 1cm thick marlstone beds. Small nodules and thin lenses of chert are rare. Bedding is often disturbed by folds and slumps. In the upper part of the sequence, up to 3m large "cipit" boulders of beige wacke- to packstones and dark grey packstones lie among platy limestones. The Rhaetian age is determined with foraminifers from rudstones and "cipit" boulders, derived from the platform.

The hangingwall block above Canin – Val Coritenza backthrust is composed of the cyclic bedded sub- to peritidal Dachstein Limestone, which builds prominent steep faces of the Mt. Mojstrovka and Mt Travnik and also Mt. Ponce ridge at the opposite side of the Tamar Valley.

Day 2

Stop 3 – Koroška Bela: Sava fault (Fig. 9) (guided by Marko Vrabec)

The dextral strike-slip Sava fault is a major NW-SE-trending regional fault in the easternmost exposed part of the Periadriatic fault system (e.g. VRABEC & FODOR, 2006; Fig. 10). Between the Sava fault and the Periadriatic fault proper a complex transpressional shear lens developed, where complex rotations of fault-bounded blocks were documented with paleomagnetic data (FODOR et al., 1998).

The Sava fault is traditionally interpreted to connect westward with the E-W trending Fella reverse fault of the northeastern Italian Southern Alps, although its direct linkage with the Periadriatic fault accross the Carnic Alps seems more plausible from both geometrical and kinematic considerations (FORKE et al., 2008). Due to incision of the upper Sava river valley along the fault trace, the fault has a marked topographic expression, which continues into central Slovenia where the fault separates the Quaternary Ljubljana basin from the northbounding mountain ranges (Fig. 11). Further to the east, the fault is interpreted to bend in the E-W orientation and to eventually connect with other faults of the Periadriatic fault system, like the Šoštanj fault and the Labot (Lavanttal) fault (KAZMER et al., 1996; PLACER, 1996; FODOR et al., 1998).

The amount of displacement on the fault was estimated from dextral separation of various Oligocene formations that crop out on both sides of the fault. Estimates range from 25 km (HINTERLECHNER–RAVNIK & PLENIČAR, 1967), 40 km (KAZMER et al., 1996) to 65–70 km

(PLACER, 1996), though we find the lower estimates more realistic. The time span of the activity of the fault is also not very well constrained by geological criteria. Folding and reverse faulting of mid-Miocene sediments in the restraining bend of the fault north of Ljubljana limit the main slip phase to post 12 Ma (VRABEC, 2001).

Several indications exist for the recent activity of the fault. The rectangular Ljubljana basin, filled with Quaternary sediments, is interpreted as a pull-apart depression in a releasing overstep between the Sava fault and the Žužemberk fault (e.g. VRABEC, 2001). A GPS study of active displacements in the eastern part of the Peraidriatic system implies a slip rate of around 1 mm/yr on the Sava fault (VRABEC et al., 2006). More recently, a line of supporting geomorphological evidence, like dextral shifts of the drainage network and displacements of Quaternary-Holocene alluvial fans was documented along the fault (JAMŠEK-RUPNIK et al., 2012, 2013a; JAMŠEK-RUPNIK in preparation).

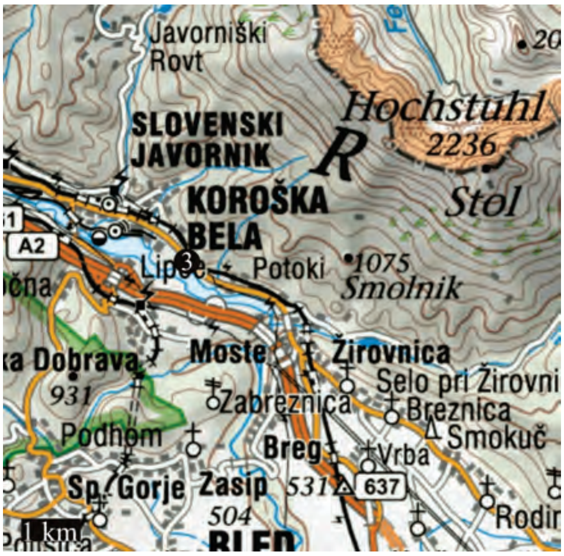

Figure 9: Geographic location of Stop 3.

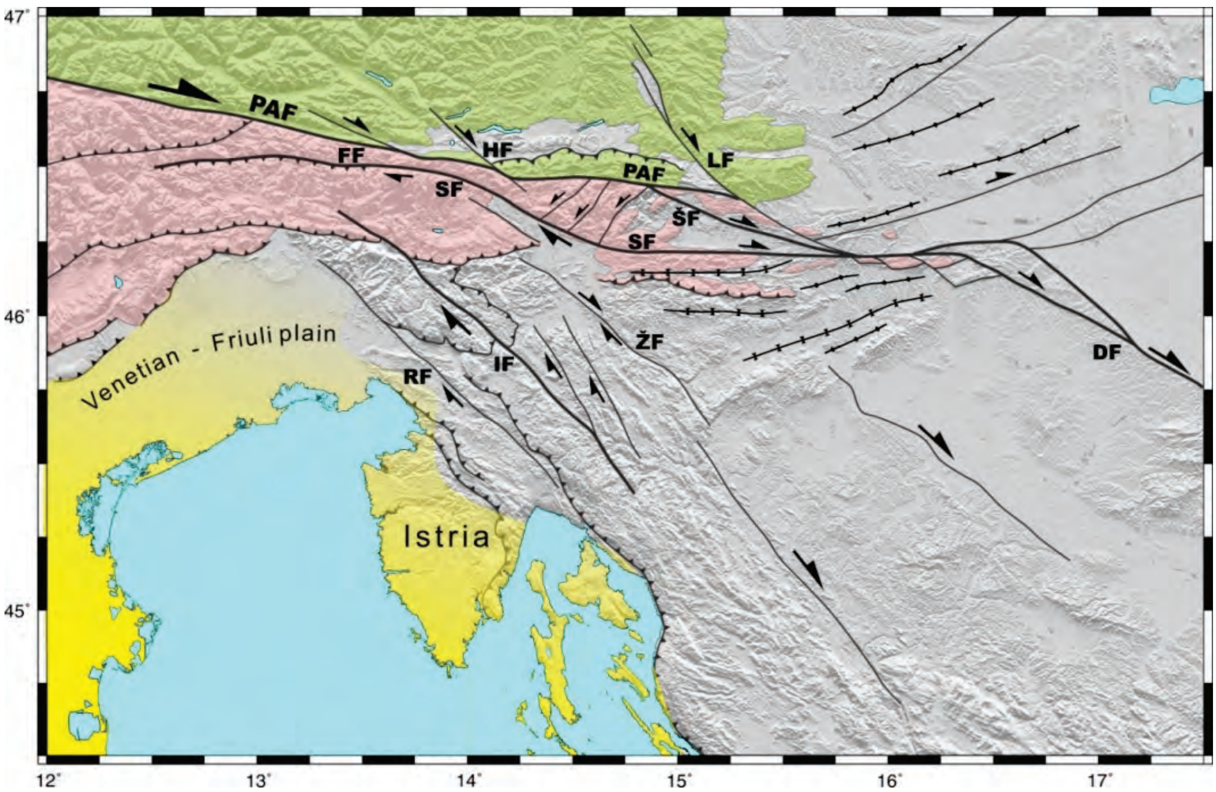

Figure 10: Trace of the Sava fault on the simplified tectonic map of the region (modified after VRABEC & FODOR, 2006). Digital terrain model from SRTM data (Shuttle Radar Topography Mission), accessible from Global Land Cover Facility (http://www.landcover.org). DF – Drava fault, FF – Fella fault, HF – Hochstuhl fault, IF – Idrija fault, LF – Labot (Lavanttal) fault, PAF – Periadriatic fault, RF – Raša fault, SF – Sava fault, ŠF – Šoštanj fault, ŽF – Žužemberk fault

Figure 11: Spectacular topographic expression of the Sava fault in northwestern Slovenia. View is towards the east from the exit of the upper Sava river valley towards the Ljubljana basin. In front of the image the linear Završnica valley and its parallel ridge run along the Sava fault. Further towards the southeast, a prominent break in hillslope and faceted mountain faces, both indicating the location of the fault, are clearly visible. Image source: Google Earth.

Stop 4 – Mt Kobla, trail from Vrh Bače: key-area for understanding geology of the eastern Southern Alps (guided by Boštjan Rožič)

Mt Kobla (southern Julian Alps, NW Slovenia, Fig. 12) is a key-area for understanding the paleogeography, as well as the structure of the Julian Alps. These form the eastern continuation of the Southern Alps and are characterized by south-vergent thrusting (PLACER, 2008). Julian Alps are composed almost exclusively of Mesozoic sedimentary rocks, deposited on the southern passive continental margin of the Neotethys and the Alpine Tethys Oceans. On a smaller scale, two major paleogeographic units are recognized: Slovenian Basin (SB) that exhibits continuous Middle Triassic – Cretaceous pelagic sedimentation, and the Julian Carbonate Platform (JCP), that is characterized by Triassic to Early Jurassic shallow-water carbonates and occasional small-scale intraplatform basins (BUSER, 1996). In the Early Jurassic this unit was dissected into blocks with different subsidence rates. During the Middle Jurassic, major part of the subsiding platform turned into submarine plateau known as a Julian High, whereas some parts subsided more drastically and become deep-water basins known as Bovec Through and Bled Basin (ŠMUC & GORIČAN, 2005, KUKOČ et al., 2012). Until the end of the Jurassic the entire area became leveled with the SB. JCP Successions cover major part of the Julian Alps and structurally form the Julian Nappe and a Slatna Klippe, whereas the successions of the SB outcrop in the southern foothills of Julian Alps and compose the structurally lower Tolmin Nappe. The latter is further divided in three lower-order thrust units: basal Podmelec Nappe, intermediate Rut Nappe and the highest Kobla Nappe (BUSER, 1986).

Figure 12: Geographic location of Stop 4 (beginning and end of the trail). For the trail course, see Fig. 13.

Julian Alps are predominantly composed of Late Triassic Dachstein Limestone that is more than 1200 meters thick, whereas younger beds occur only sporadically (BUSER, 1986). Unique area that exhibits continuous Late Triassic to earliest Cretaceous succession is the Mt Kobla (Figs. 13 and 14): southern slopes are composed of SB succession, whereas on the northern slopes the chronostratigraphic equivalents of the JCP outcrop. In the Mt Kobla the tectonic contact between the units is exceptionally not a thrust but a N-ward dipping steep fault that presumably postdates the main Miocene thrusting. Additionally, a small Krevl tectonic block is nestled between the major units and is composed of SB-JCP transitional zone (TZ) successions (ROŽIČ & ŠMUC, 2009).

Climbing the Mt Kobla from northern or southern side thus represents a walk through Late Triassic to earliest Cretaceous sedimentary history of the two main paleogeographic units of present-day Julian Alps.

Norian-Rhaetian: JCP is characterized by Dachstein Reef Limestone (TURNŠEK & BUSER, 1991) that passes to loferitic facies towards inner platform (Fig. 15a). SB succession is characterized by Norian Bača dolomite; a bedded dolomite with chert nodules. Two intervals of dolomitic breccias occur in the lower part of the formation and indicate Norian tectonic events (GALE, 2010). It is overlain by late Norian-Rhaetian Slatnik Formation composed of bedded hemipelagic limestone with chert nodules and calciturbidites that become more abundant towards the top of the formation and record platform progradation (Fig. 15b). Triassic/Jurassic boundary is marked by several meters thick interval composed almost exclusively of thin-bedded hemipelagic limestones (ROŽIČ et al., 2009; GALE et al., 2012).

Hettangian –Pliensbachian: After demise of reefs, the Jurassic JCP succession starts with ooidal/peloidal limestone (Fig. 15c). In the Pliensbachian it is replaced by crinoidal limestone, limestone breccias and bioclastic limestone with abundant juvenile ammonites, sponge spicules and crinoids (ROŽIČ & ŠMUC, 2009). Neptunian dykes with crinoids and reddish matrix cut all lithologies (Fig. 15e). Equal facies association starts the succession of the TZ. Similar turnover is directly reflected in SB, where this period is marked by Krikov Formation that is dominated by calciturbidites composed firstly of ooids and peloids (Fig. 15d) and later of crinoids and lithoclasts (Fig. 15f) (ROŽIČ, 2009, GORIČAN et al., 2012a). Neptunian dykes, limestone breccia and abundant lithoclasts in calciturbidites indicate that initial drowning of the platform is a result of accelerated subsidence and tectonical disintegration of the platform margin.

Toarcian: Very thin layer of marls that are presumably of Toarcian age mark the JCP and TZ as well as SB successions (Fig. 15f,g). Basin-ward the equal succession thickens to 130 meters (ROŽIČ, 2009, ROŽIČ & ŠMUC, 2011). Marls are known here as the Perbla Formation, reflecting Toarcian Oceanic Anoxic Event.

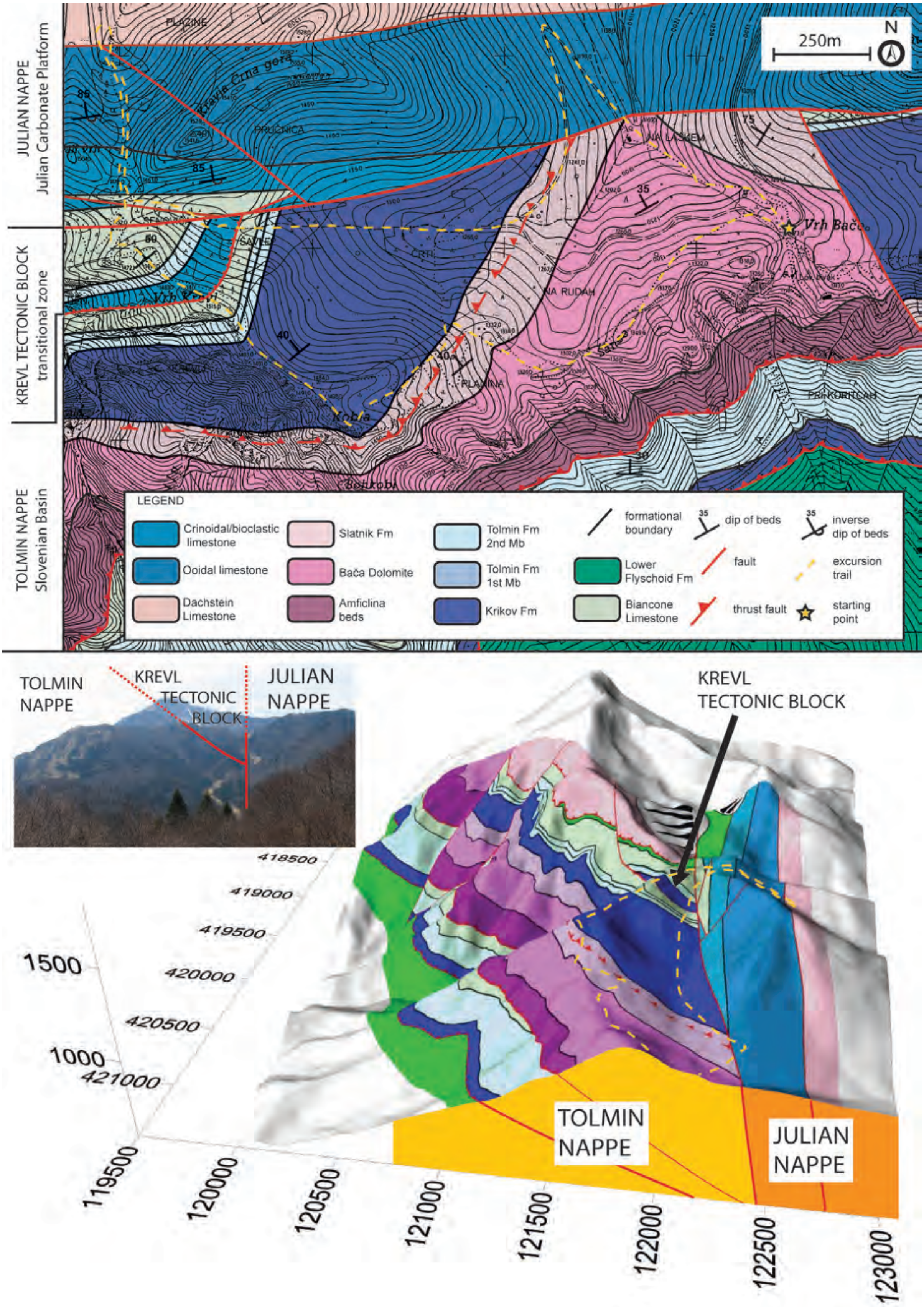

Figure 13: Geological map and 3D model (view from E to W) of Mt Kobla area with excursion trail. Photograph: Kobla area with main tectonic units as viewed from east-located Mt. Slatnik.

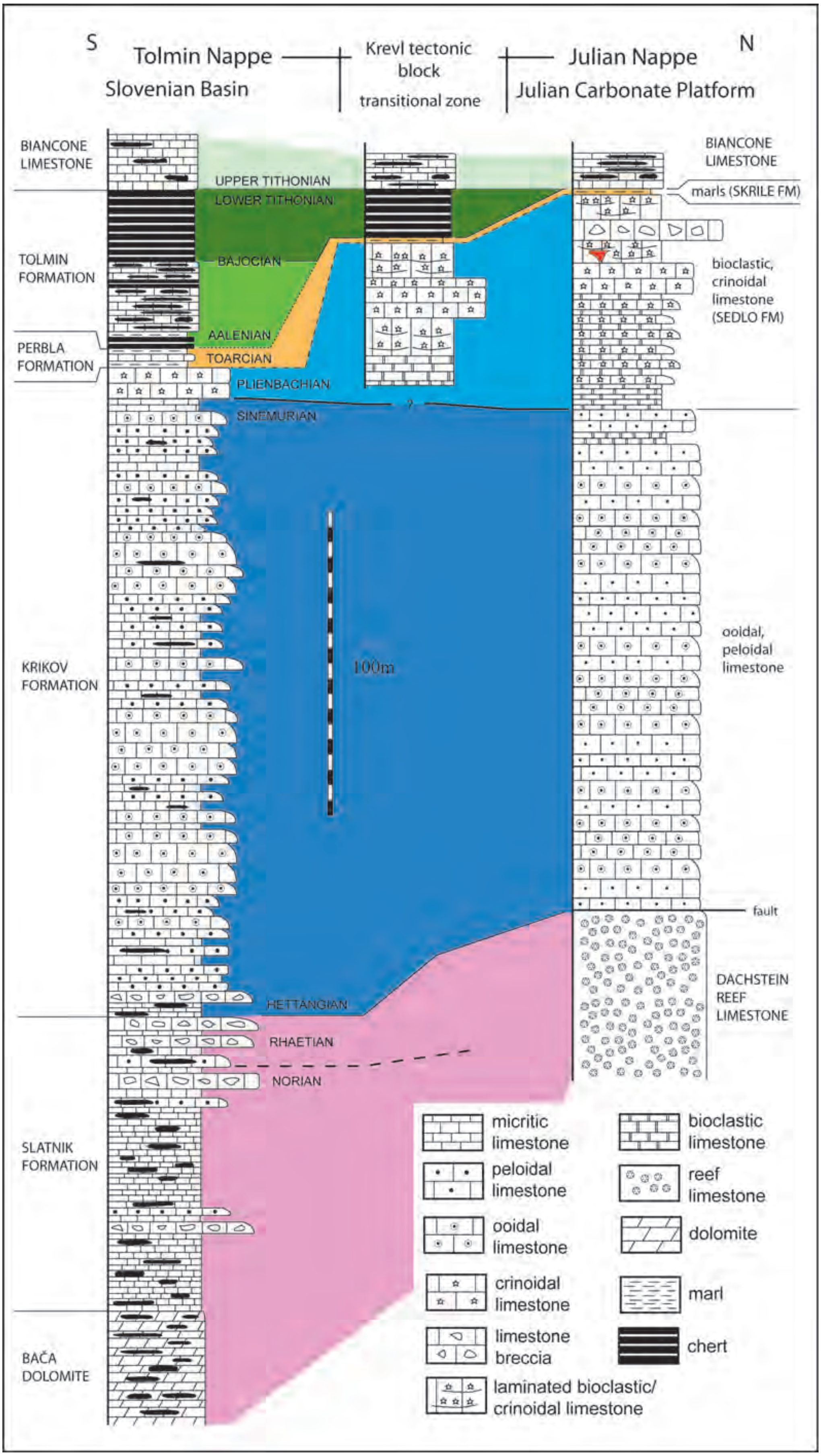

Figure 14: Schematic stratigraphic columns of the three tectonic units of the Mt Kobla Area.

Aalenian: There is no sedimentary record on the JCP and TZ and consequently it is not known if this unit was subaerially exposed or subjected to submarine erosion or at least non-deposition. In the SB the marls are gradually replaced by hemipelagic siliceous limestones (ROŽIČ, 2009).

Bajocian-Lower Tithonian: These are still no sediments on a JCP on Mt Kobla, but condensed Ammonitico Rosso-type limestone is known from the central part of the drowned platform (ŠMUC, 2005, ŠMUC & ROŽIČ, 2010). Simultaneously, the SB succession turns into pure siliceous pelagic sedimentation (ROŽIČ, 2009; GORIČAN et al., 2012b) (Fig. 15h) that is deposited also on the TZ that obviously subsided to basinal depths. Manganese nodules are known at the base of siliceous depostis on the TZ. A facies change in all units is simultaneous and is related to regional subsidence. The entire Aalenian to Lower Tithonian succession of the SB was defined as Tolmin Formation (ROŽIČ, 2009).

Upper Tithonian-Berriasian: SB, TZ and JCP successions are characterized by Biancone-type limestone; i.e. limestone with calpionellids (Fig. 15g, h), which indicates that entire region at the end of the Jurassic became paleotopographically leveled (ŠMUC, 2005, ROŽIČ, 2009, KUKOČ et al., 2012).

Figure 15 (next page)**:** Lithologies and microfacies of discussed formations. (a) Dachstein reef limestone (Norian-Rhaetian): colonial corals. (b) Slatnik Formation (Late Norian-Rhaetian): hemipelagic limestone with irregular chert nodules. Micrograph: reef-dwelling foraminifera *Kaeveria fluegeli* in a calciturbidite. (c) Ooidal/peloidal limestone (Hettangian-Pliensbachian): steep (inverse) bedding on the Mt Kobla skiing ground. Micrograph: peloidal grainstone with rare ooids. (d) Krikov Formation (Hettangian-Pliensbachian): thick calciturbidic beds in western cliffs of Mt Kobla. Micrograph: large, compacted ooids in a calciturbidite. (e) Redish neptunian dykes in a pliensbachian crinoidal limestone. Micrograph: bioclastic wackestone with ammonite(f) Sharp contact between Krikov Formation and Toarcian Perbla Formation characterized by marls. Micrograph: crinoidal grainstone in topmost calciturbidites of Krikov Formation. (g) Thin ?Toarcian marl between Pliensbachian bioclastic limestone (left) and Lower Tithonian-Berriasian Biancone Limestone (right). Micrograph: mudstone with calpionellids from Biancone Limestone. (h) Sharp contact between radiolarinan cherts of the Tolmin Formation (upper member; Middle Bajocian-Lower Tithonian) and Biancone Limestone.


Julian Carbonate Platform
Slovenian Basin
a
b
c
d
e
f
g
h
1mm
1mm
1mm
1mm
1mm
0,5mm

Stop 5 – Hraše: Vodice fault (guided by Petra Jamšek Rupnik)

The Vodice fault is located in the Ljubljana Basin (Fig. 16) at the contact between the Southern Alps and the Dinarides (Fig. 17). The basin is bounded by two NW-SE-striking dextral faults, the Sava fault to the north and the Žužemberk fault to the south, interpreted as master faults that control the subsidence of Ljubljana basin in a releasing overstep between them (VRABEC & FODOR, 2006). Smaller ~E-W oriented reverse faults that displace Quaternary sediments in the basin (VERBIČ, 2006) may indicate a recent change in the deformational regime from transtensional subsidence to transpression. Geological and geomorphological observations, earthquake focal mechanisms, and geodetic measurements suggest that the NW-SE-striking dextral faults and ~E-W-striking reverse faults may be active in the current regional stress regime with ~N-S oriented axis of maximum horizontal compression (POLJAK et al., 2000; VRABEC & FODOR, 2006; VERBIČ, 2006; BAVEC et al, 2012; JAMŠEK RUPNIK et al., 2012).

Figure 16: Geographical location of Stop 5.

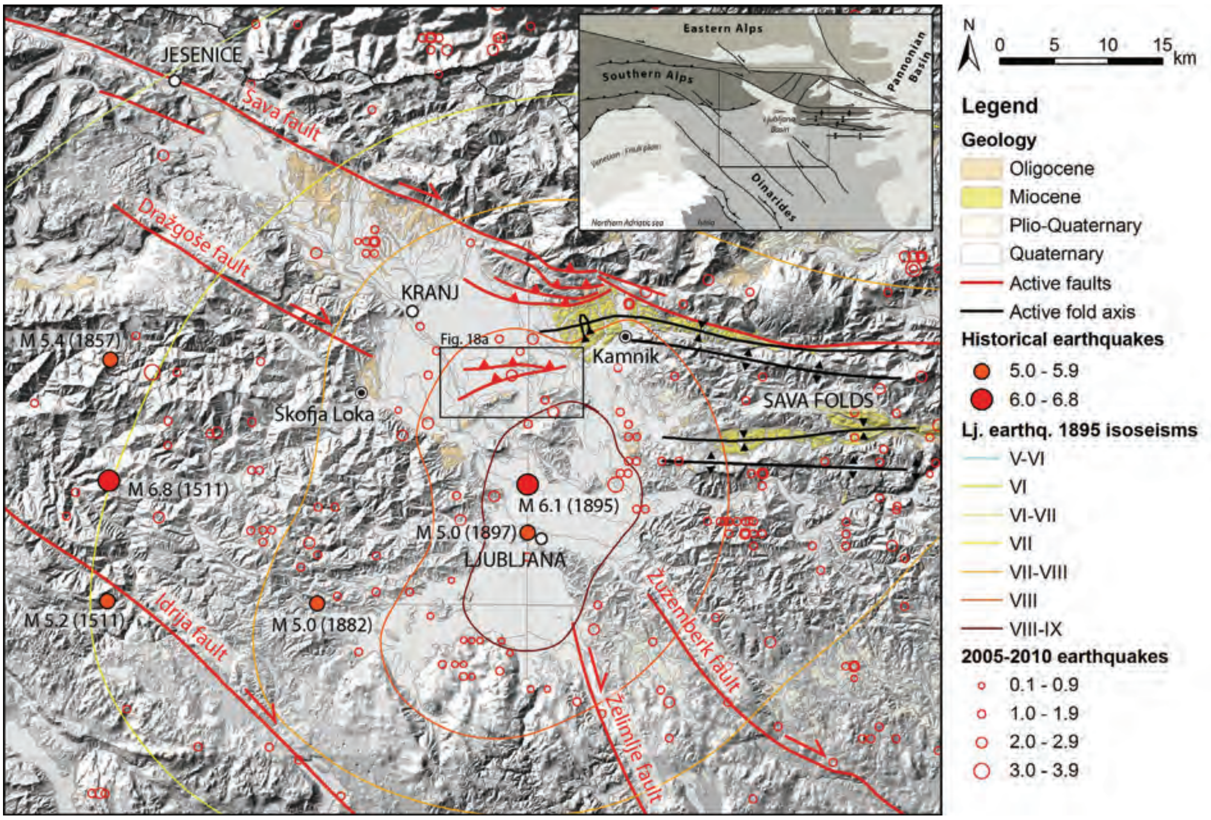

Figure 17: Seismotectonic map of the Ljubljana Basin showing main active structures, Oligocene to Quaternary geological units (BUSER, 2009), historical earthquake epicenters with magnitude above 5.0 (ŽIVČIĆ, 2009), isoseisms of the Ljubljana 1895 M=6.1 earthquake (LAPAJNE, 1989) and instrumental seismicity 2005-2010 (, 2006-2011). Inset figure: simplified tectonic map of the Alps-Dinarides junction (VRABEC & FODOR, 2006) showing the location of Fig. 17.

The Ljubljana Basin is the most densely populated and a highly urbanized region of Slovenia, experiencing continuous seismic activity with earthquake magnitudes frequently reaching 3-4 (ŽIVČIĆ, 2009). The largest recorded event in the basin was the destructive 1895 Ljubljana earthquake with macroseismic magnitude 6.1 (RIBARIČ, 1982) and maximum intensities of VIII-IX EMS-98 (CECIĆ, 1998). The fault responsible for this earthquake is still unknown. The seismic hazard is further increased by the unconsolidated Quaternary sedimentary infill of the basin, reaching up to 280 m of thickness, which may significantly enhance site effects during earthquakes (GOSAR et al., 2010).

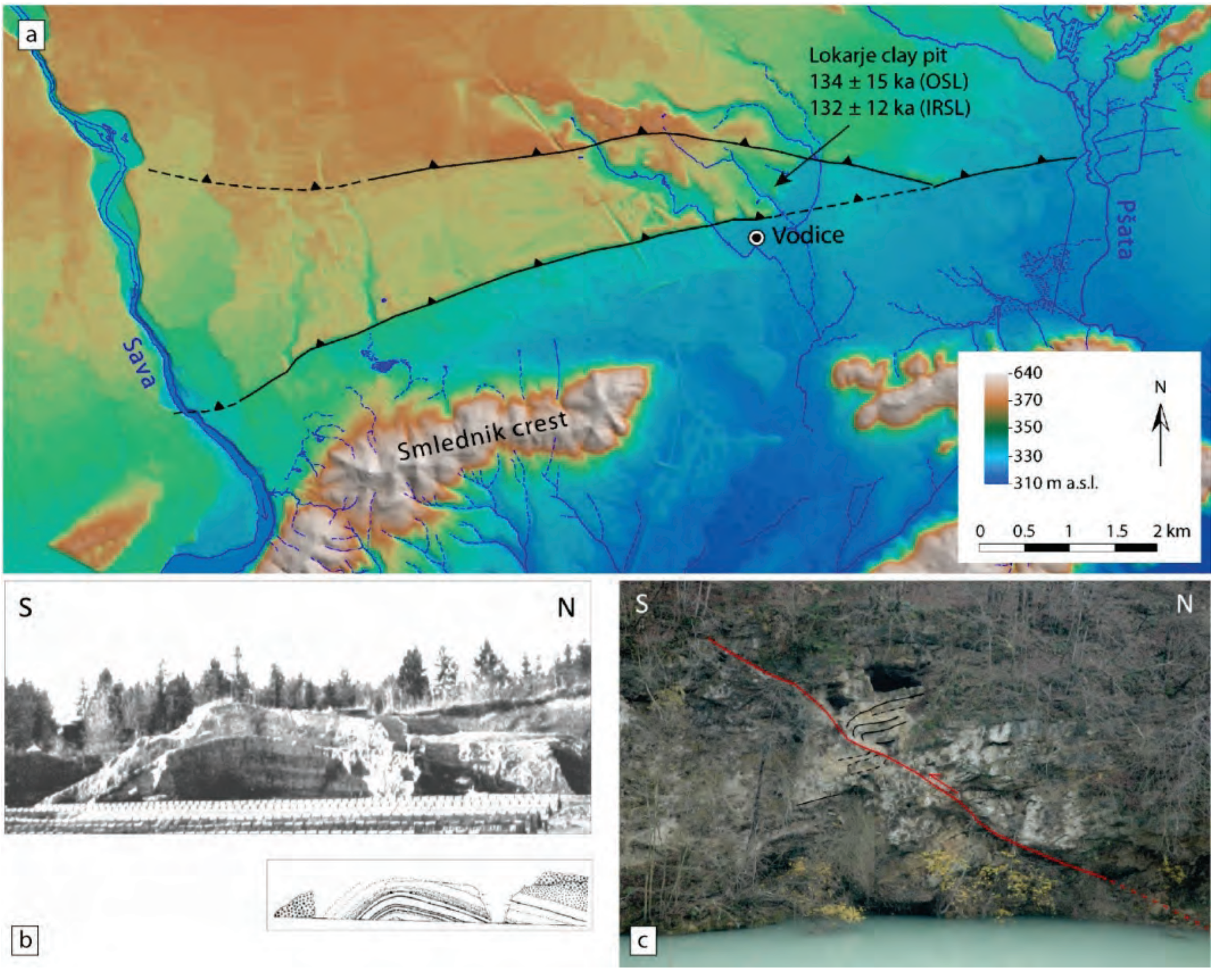

Figure 18: (a) The Vodice fault scarps as seen on the DEM 5 m (Public Information of Slovenia, the Surveying and Mapping Authority of the Republic of Slovenia, DEM 5, 2006). (b) Asymmetric anticline in Quaternary sediments in the now abandoned Lokarje clay pit (ŠIFRER, 1961). (c) fault plane of the southern Vodice fault and associated fault drag folds exposed on the Sava River bank.

The Vodice fault presents one of the active and possible seismogenic reverse faults in the Ljubljana Basin (JAMŠEK RUPNIK et al., 2013a). In the area of Vodice, 15 km north of Ljubljana, two prominent fault scarps are clearly visible (Fig. 18a). Oriented in WSW-ENE direction, perpendicular to the general trend of fluvial terrace risers in the area, they displace Quaternary alluvial surface along a length of 10-11 km for 5-25 m, and 3-18 m, respectively. Both scarps are the highest in the central part with heights decreasing towards their eastern and western tips. At the top of both scarps, the alluvial surface that was originally sloping southwards is today sub-horizontal or even dipping gently to the north. The top of alluvial surface is strongly incised by recent rivers and creeks. Several dry valleys and perched valleys are observed near the scarps. Folding of Quaternary sediments was reported in the now abandoned Lokarje clay pit (ŠIFRER, 1961) located in between the two scarps, where an asymmetric anticline was exposed, with the southern limb dipping 40° towards SSE, the northern limb dipping around 10° towards NNW and with the ENE-WSW oriented anticline axis parallel to the strike of the scarps (Fig. 18b). Westward, where the fault cuts the N-S running Sava River, Quaternary conglomerates are also folded and offset, with a fault plane dipping 35° to the north (Fig. 18c). Drag folds in conglomerate layers indicate reverse offset along this fault plane. All geomorphic and structural observations suggest that the scarps are the surface expression of an active emergent reverse fault, which was recently confirmed also by geophysical investigations and paleoseismological trenching (BAVEC et al., 2012; ATANACKOV, 2013).

Dating using Optically Stimulated Luminescence (OSL) of quartz and Infrared Stimulated Luminescence (IRSL) of K-feldspar yielded an OSL age of 134 ± 15 ka and an IRSL age of 132 ± 12 ka for the upper alluvial surface (JAMŠEK RUPNIK et al., 2013b). By using this age, and taking into account the height of the southern scarp and the observed dip of 35°N of the fault plane, we estimate Late Quaternary slip-rate of the Vodice fault at 0.1 to 0.3 mm a^{-1} over the last 133 ka. According to empirical scaling relationships (WELLS & COPPERSMITH, 1994), 10 km long Vodice fault could trigger an earthquake of M 5.9 to 6.5 with a coseismic displacement of 0.1 to 0.9 m. In the case of constant slip-rate the recurrence time of such earthquakes could be from 300 to 9,000 a.

Day 3

Upper Oligocene Smrekovec Volcanic Complex, Periadriatic Lineament (Fig. 19) (guided by Polona Kralj)

Stop 6 – Krnes : Lithofacies architecture of volcaniclastic deposits in the Upper Oligocene Smrekovec Volcanic Complex – The secton Krnes 1

Introduction

The Upper Oligocene (28-22 Ma; HANFLAND et al., 2004) Smrekovec Volcanic Complex (SVC) occurs in a sequence of Tertiary marine silts deposited in the Smrekovec Basin (MIOČ, 1983), one of several small and marginal sub-basins in the south-west of the Pannonian back-arc realm (ROYDEN, 1988).

Figure 19: Geographic location of Stops 6, 7 and 8.

Volcanic activity that created the Smrekovec Volcanic Complex (SVC) is considered to be post-collisional and related to slab breakoff processes (VON BLANCKENBURG & DAVIS, 1995). It occurred in the initial stage of extensional evolution of the Pannonian Basin, particularly during the activation of the Periadriatic Line. Magmas erupted in the SVC show calc-alkaline and medium-K affinity, and produced a suite ranging in composition from basaltic andesite to dacite (KRALJ, 1996; ALTHERR et al., 1995).

The SVC forms a part of a wider, approximately 70 km long belt of Upper Oligocene and Lower Miocene (Lower Egerian) volcanic deposits (Fig. 20) that outcrop south of the Smrekovec Fault and the Šoštanj Fault. This belt is locally termed the Smrekovec Series and mainly consists of volcaniclastic deposits (MIOČ, 1983).

The SVC is the lower (Upper Oligocene) unit of the Smrekovec Series, and belongs to the remains of a former submarine stratovolcano edifice. Today, the SVC extends in an area of about 200 km^2 and its maximum thickness ranges from about 800 m to 1100 m (MIOČ, 1983). Lavas and shallow intrusive bodies are subordinate in occurrence and mainly outcrop along the mountain range encompassing Mt. Komen, Mt. Krnes, Veliki Travnik and Mt. Smrekovec. The most widespread are volcaniclastic deposits, and they show a diverse and complex development. Lithofacies classification and initiation processes are shown in Table 1. The complexity of lithofacies architecture is shown in a simplified section Krnes 1, sub-section Vodnik (Fig. 21).

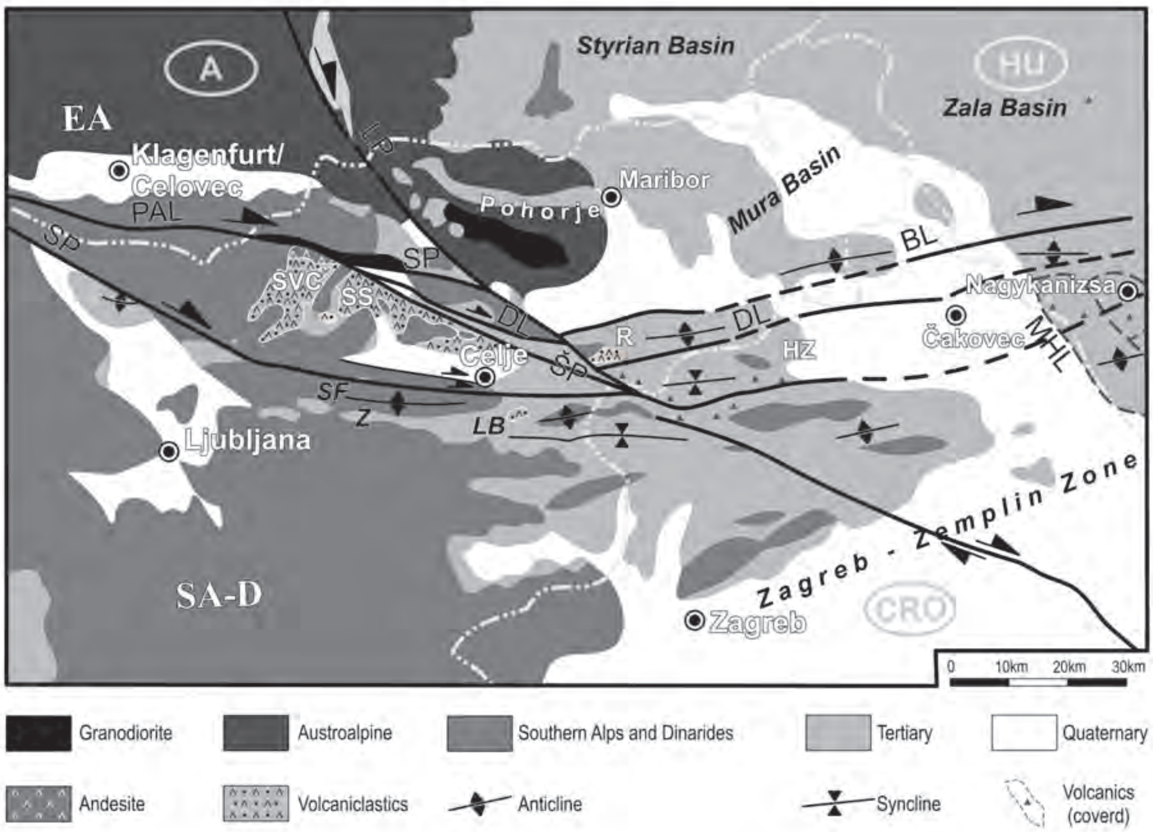

Figure 20: Simplified geological map of north Slovenia (after MIOČ, 1978; FODOR et al., 1998; JELEN & RIFELJ, 2002). EA—Eastern Alps; SA-D—Southern Alps and Dinarides; PAL—Periadriatic Line; BL — Balaton Line; MHL — Mid-Hungarian Line; DL — Donat Line; LP — Lavanttal Fault; SF — Sava Fault; SP — Smrekovec Fault; ŠP — Šoštanj Fault; SVC — Smrekovec Volcanic Complex; SS — Smrekovec Series; LB — Trobni Dol; Z — Zasavje; R — Rogaška Slatina; HZ — Hrvatsko Zagorje (Croatian Zagorje).

Lithofacies Group	Lithofacies	Thickness	Initiation process
Autoclastic deposits (A)	Autobreccia (AB) Hyaloclastite breccia (HB) Hyaloclastite (mH) Peperite (P) Blocky peperite (PB) Fluidal peperite (P)	1-5 m 1-5 m several dm - 3 m 0.5-3 m < 1 mm - 1m	*Quench fragmentation* *Quench fragmentation* *Quench fragmentation, phreatic explosions* *Quench fragmentation and mixing and mingling with the enclosing wet sediment* *Mixing and mingling of lava or magma and the enclosing wet sediment*
Resedimented hyaloclastite deposits (Hr)	Horizontally bedded lapilli-sized hyaloclastite(sHL) Horizontally bedded ash-sized hyaloclastite (sHT) Crudely bedded hyaloclastite [s(c)HT] Massive resedimented hyaloclastite [s(m) HT] Chaotic hyaloclastite [s(x)HT]	1-10 cm thick lamination-thin bedding thick lamination-thin bedding, bed-sets up to 12 cm 5–15 cm 1-5 dm	*Resedimentation of mH by grain flows and small debris flows*
Pyroclastic deposits (Py)	Massive pumice lapilli tuff [mLT(p)] Massive coarse- to fine-grained tuff [mT(p)] Massive to diffusely bedded tuff [dT(p)] Horizontally bedded tuff [sT(p)] Horizontally laminated fine-grained tuff [sF(p)] Cross-laminated fine-grained tuff [xF(p)] Subtly lenticular fine-grained tuff [cF(p)] Wavy laminated fine-grained tuff [vF(p)]	several dm–several m 3-20 cm 2-5 m very thin to medium-thick beds laminae, in 1-20 cm thick unit laminae, in 1-5 dm thick unit laminae, in 1-5 dm thick unit laminae, in several cm thick unit	*Gas- and water-supported eruption-fed density flows*
Volcaniclastic debris	Polymict volcaniclastic	2-15 m	*Debris flows*

flow deposits (Vd)	breccia (Bx) Massive coarse-grained tuff (Sx)	0.3-5 m	*Sandy debris flows*
Volcaniclastic turbidite deposits (Vt)	Volcaniclastic tuff-breccia (Bt) Massive lapilli tuff [mLT(v)] Horizontally bedded coarse-grained tuff [hsT(v)] Horizontally bedded fine-grained tuff [hlF(v)] Vaguely laminated fine-grained tuff [vlF(v)] Cross-bedded coarse- to fine-grained tuff [xF(v)] Massive fine-grained tuff [mF(v)]	0.1-3 m several cm – 0.5 m thin to medium thick beds laminae, in 1-20 cm thick unit laminae, in several cm thick unit laminae, in 5-15 cm thick unit 1-25 cm	*Low-density turbidity currents and settling from suspension clouds*
Mixed volcaniclastic-siliciclastic deposits (M)	Massive tuffaceous sandstone [mS(v)] Horizontally laminated tuffaceous sandstone [hS(v)] Cross-bedded tuffaceous sandstone [tS(v)] Massive tuffaceous mudstone [mM(v)]	several mm – several cm laminae several mm – several cm several mm – several cm	*Settling from suspension clouds, reworking by oceanic bottom currents*

Table 1: Synopsis of the characteristics for the SVC volcaniclastic deposits (from KRALJ, 2012).

Lithofacies encountered in the section Krnes-1 (Fig. 21)

Autoclastic deposits (A): autobreccia (AB) and fluidal peperite (P): Lithofacies AB consists of blocky, angular, subangular or subrounded, essentially non-vesicular clasts attaining 1-50 cm in size. Fluidal peperite occurs at the bottom division of autobrecciated lava flows along the contacts with the underlying fine-grained sediment. Peperite forms globular or semi-globular granules or pillows, attaining < 1mm to 1m in diameter.

Pyroclastic deposit units (PDUs): Two varieties of pyroclastic deposit units, Type 1 PDU and Type 2 PDU, have been distinguished on the basis of lithofacies architecture.Type 1 PDU is more common in occurrence, and the architecture resembles that of volcaniclastic turbidite deposits. The thickest units attain up to 5 m. Lithofacies $mL_1T(p)$ occurs at the base, and is overlain by the intermediate, horizontally bedded division, composed of lithofacies sT(p), which becomes upward more thinly bedded and finer-grained. Some coarser lithofacies sT(p) occurring at the base of thicker bedded divisions are amalgamated. Thicker Type 1 PDUs are commonly topped by [sF(p)] or [vF(p)] and [sF(p)]. In thicker units, massive division predominates and forms from 60-80 % of the bulk pyroclastic depositional unit.
The Type 2 PDU is less abundant in occurrence. Thicker units attain several metres and are composed of lithofacies $mL_2T(p)$ at the base. Transition into the overlying lithofacies dT(p) is indistinct and gradual. Lithofacies dT(p) may show indistinct grading from somewhat coarser ash-sized tuff at the base and somewhat finer ash-sized tuff at the top. Lithofacies dT(p) is overlain by sF(p), and there is a sharp distinction in the degree of lithification, colour and

internal structure. Whilst $mL_2T(p)$ and dT(p) are very well lithified and dark-green, the overlying sF(p) is much softer and brownish, and columnar jointing never continues from $mL_2T(p)$ and dT(p) to sF(p). The Type 2 PDU has been interpreted to be settled from hot, gas-supported pyroclastic flows, with internal organization that resembles thin and mainly non-welded ignimbrite facies (MANDEVILLE et al., 1996; WHITE, 2000).

Volcaniclastic debris flow deposits (Vd): In the section Krnes-1, volcaniclastic debris flow deposits occur as lithofacies Bx (volcaniclastic breccia). It is massive, ungraded and extremely poorly sorted. The lower boundary is erosive. The formation of Bx is possibly related to a laminar, volacniclastic debris flow.

Volcaniclastic turbidites (Vt) and internal organisation of a turbidite sedimentation unit (TSU):
An ideal turbidite sedimentation unit (TSU) is typically 1-5 m thick and consists of lithofacies Bt or mLT(v) at the base, hsT(v), or interlayered hsT(v) and hlF(v) in the intermediate division, hlF(v), xT(v), and more rarely, vlF(v) in the upper division, and mF(v) at the top, and is the deposit of a single flow event.
Lithofacies thickness obtained by field measurements of several TSUs was calculated as lithofacies abundance in a single TSU, and is given as percents by volume (%) of the bulk lithofacies. Based on the calculated lithofacies abundance, three TSU subgroups, Type 1, Type 2 and Type 3, respectively, have been recognised. In Type 1 TSU, the lower, intermediate and upper divisions amount to 50-75 %, 20-35 % and 5-15 % of the bulk lithofacies, respectively. The lower division consists of Bt and mLT(v) is absent. The intermediate division consists of hsT(v) which may show bed amalgamation. In the upper division hlF(v) is common, mF(v) may occur but is thin and attains less than one centimetre. Type 1 TSU ranges in thickness from about 2-5 m.
In Type 2 TSU, the lower, intermediate and upper divisions amount to 30-50 %, 35-45 % and 15-25 % of the bulk lithofacies, respectively. In the lower division Bt very seldom occurs; far more abundant is mLT(v). The intermediate division shows general upward grain-size fining and bed-thinning. Amalgamation is common in the lower- and middle portion of the bedded division, and it gradually changes into distinct bedding of hsT(v) and interlayering of hsT(v) and hlF(v). The upper division consists of hlF(v) and sometimes xT(v), and the upperost positioned mF(v). Type 2 TSU ranges in thickness from about 0.7-3.5 m.
In Type 3 TSU, the lower, intermediate and upper division amount to 0-30 %, 50-60 %, and 20-40 % of the bulk lithofacies, respectively. The lower division, if present, consists of lithofacies mLT(v). The intermediate division is well developed and shows general upward grain-size fining and bed-thinning, and bed amalgamation is rather uncommon. The upper division consists of low- and high-angle cross-laminated and thinly bedded tuffs, vaguely laminated tuffs, horizontally laminated tuffs and massive fine-grained tuffs. Type 3 TSU ranges in thickness from about 0.1-1.5 m.

Sedimentation units recognised in the sequence of volcaniclastic turbidites in the Smrekovec Volcanic Complex can be compared with turbidites emplaced from low-density currents (LOWE, 1982; MCPHIE et al., 1993). The Bouma a, b, c, d and e divisions (BOUMA, 1962) correspond to Bt and/or mLT(v), hsT(v), xF(v) and/or vlF(v), hlF(v), and mF(v), respectively. The change of TSUs from the Type 1 to Type 2, and from Type 2 to Type 3 can be related to the evolution of turbidity currents along the flow length, from the initiation of deposition to the final settling.

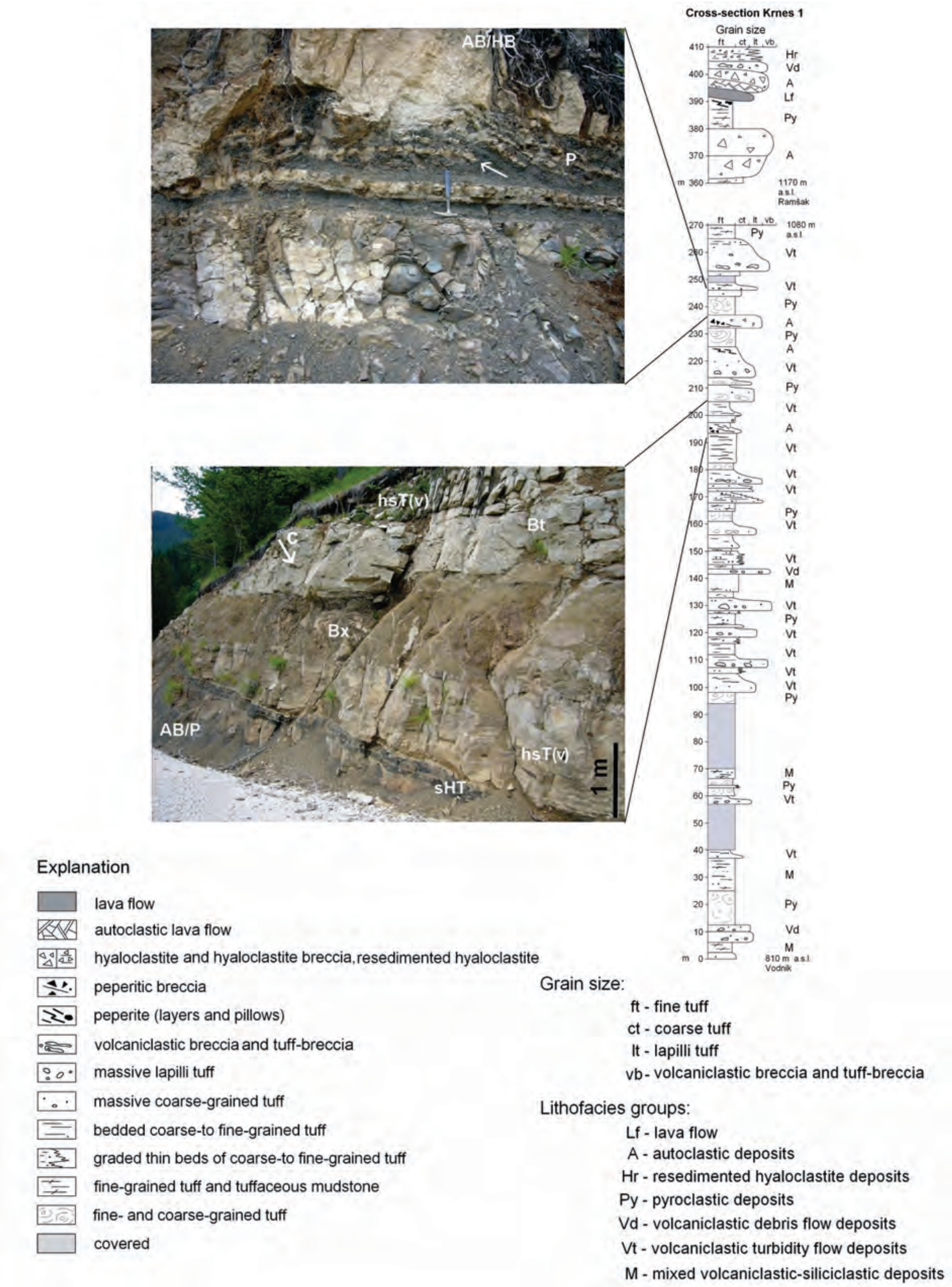

Figure 21: Cross-section Krnes 1 with the sub-sections Vodnik and Ramšak (from KRALJ, 2012). Upper photography: autoclastic breccia and hyaloclastite breccia (AB/HB) with a peperite layer (P) at the base. Hammer (33 cm) is for scale. The position is in the sub-section Vodnik at 237–247 m. Lower photography: a succession of volcaniclastic debris flow (Bx) and turbidite deposits showing a Type 2 TSU with the massive (Bt) and bedded [hsT(v)] divisions. Note large intraclasts (c) of fine-grained tuff in Bt. The position is in the sub-section Vodnik, at 193–205.

Periadriatic Line (guided by Marko Vrabec)

Stop 7 – Bistra valley: outcrop of Oligocene tonalite (Fig. 19)
Stop 8 – Quarry on the northern slope of Smrekovec: brittle Periadriatic fault (Fig. 19)

Introduction

The Periadriatic fault system (PFS) is a major Oligocene-Miocene tectonic feature of the Alps. The main segments along its strike of more than 700 km are the Canavese line, the Insubric/Tonale fault, the Giudicarie fault system, and the Pustertal-Gailtail fault (Fig. 22). The fault kinematics is both dip-slip north-side-up (particularly in the Central Alps, where the faults accomodated northward underthrusting of the South Alpine units) and dextral strike-slip, which mainly overprints earlier dip-slip movement (e.g. SCHMID et al., 1989). In the Eastern Alps, the Tertiary collisional shortening was to a large degree facilitated by lateral extrusion of the central eastalpine domain (also known as the “ALCAPA unit”, see Fig. 22) towards the east (RATSCHBACHER et al., 1991; FRISCH et al., 1998). Dextral motion on the eastern part of the PFS accomodated these large-scale orogen-parallel displacements, and the PFS is commonly regarded as the discrete southern boundary of the extruding unit.

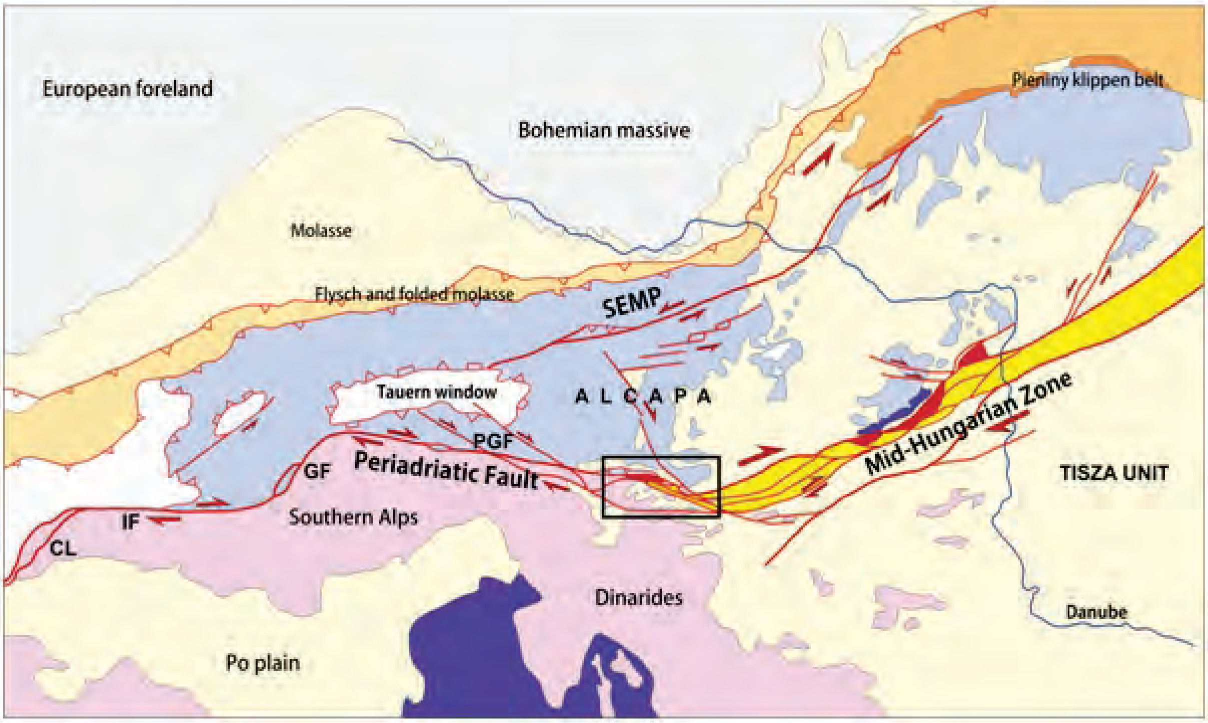

Figure 22: Simplified tectonic map of the Alps, highlighting the faults of the Periadriatic fault system and its proposed eastward continuation, the Mid-Hungarian Zone (from FODOR et al., 1998). The inset box shows the position of map presented in Fig 24. CL – Canavese line; IF – Insubric fault; GF – Giudicarie fault; PGF – Pustertal-Gailtal fault; SEMP - Salzachtal-Ennstal-Mariazell-Puchberg fault.

The magnitude of dextral slip on the eastern PFS is a matter of controversy, which is complicated by the fact that the northern side of the fault was extended both synchronously with and after the main slip episode. In the kinematic reconstruction of FRISCH et al. (1998) the amount of slip on the main Periadriatic fault (Pustertal-Gailtal segment) is estimated to ~100 km. FODOR et al. (1998) used displaced parts of the formerly united Hungarian-Slovenian Paleogene basin, occuring today in central Slovenia and in central Hungary, to argue for ~300 km of dextral separation (Fig. 23). This value, however, is to a large part produced by significant mid-Miocene extension of the area during the Pannonian basin subsidence, which postdated the main (Oligocene-Early Miocene) slip episode on the PFS.

The same paleogeographical argument was also used to propose that the PFS formerly continued into the Mid-Hungarian Zone (MHZ), which bounds the northern displaced part of the Paleogene basin, and contains isolated occurences of those Paleogene sediments inside the fault zone between the displaced parts (FODOR et al., 1998; Fig. 23).

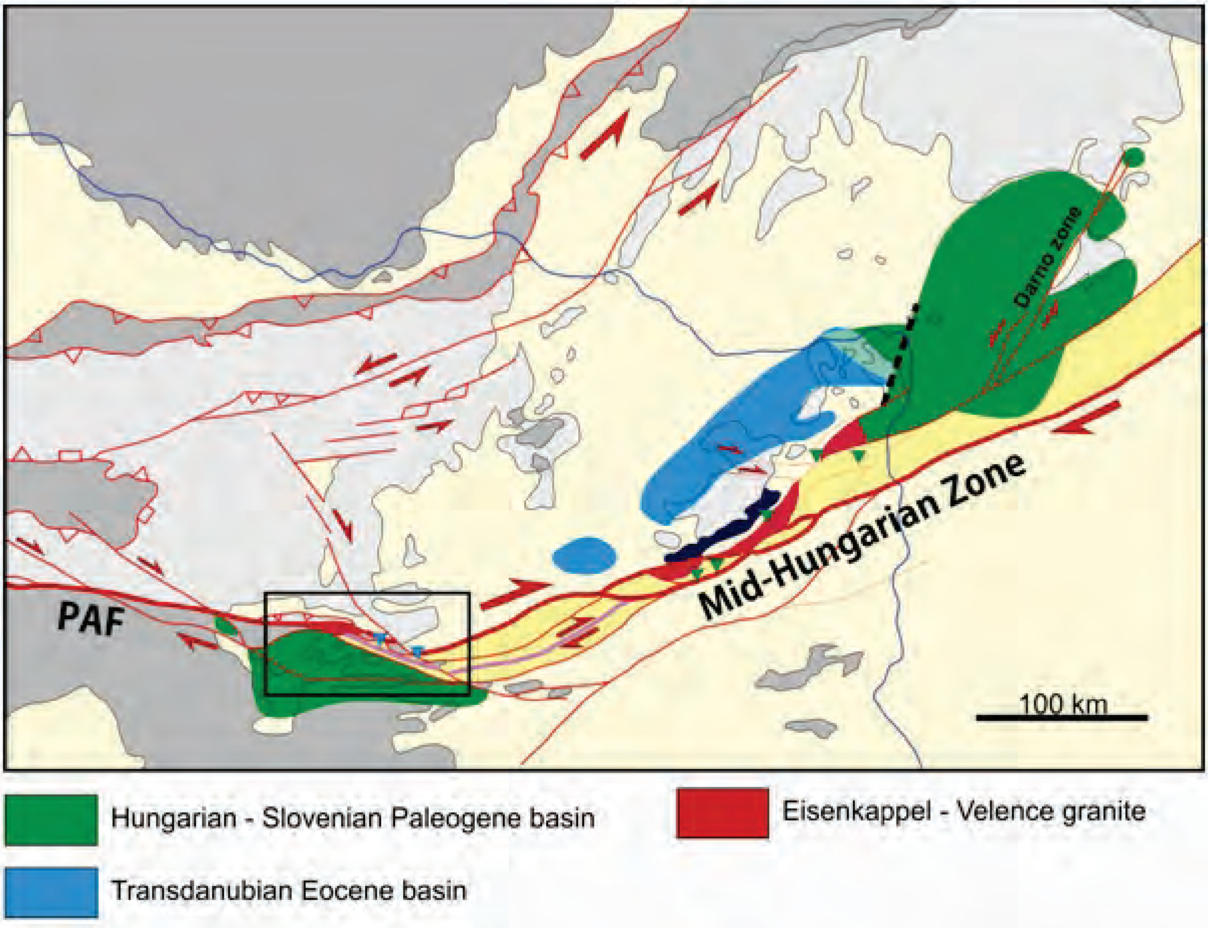

Figure 23: Present-day position of Paleogene sedimentary basins along the Periadriatic fault – Mid-Hungarian Zone corridor, implying ~300 km of dextral separation (from FODOR et al., 1998). The inset box shows the position of map presented in Fig. 24.

The easternmost outcrops of the Periadriatic fault occur in northern Slovenia, where the fault zone eventually disappears below mid-Miocene and younger sediments of the Pannonian basin (Fig. 24). The geometry of the PFS in this structurally complex region, the inferred fault kinematics, and timing of deformation as constrained by Tertiary to Quaternary sediments, provide valuable insights into Oligocene to present-day tectonic history of the eastern PFS.

The Periadriatic fault proper is a highly deformed, up to 5 km wide fault zone, consisting of lenses of various magmatic and metamorphic rocks, which are interpreted as strike-slip duplexes (FODOR et al., 1998). Their dextral separation is clearly visible in map view (Fig. 24). The synkinematic tonalite intrusion (the Karawanken pluton) of Oligocene age, which is the easternmost outcropping Periadriatic intrusive, was emplaced along the fault and was subsequently cut by late brittle faults. The narrow and subvertical magmatic body continues westward into Austria along the strike of the Periadriatic fault for about 40 km.

North of the Periadriatic fault, the Mesozoic carbonates of the Northern Karawanken are thrust northward over the Miocene sediments. This structural unit is a part of the Karawanken transpressional flower structure, which in Klagenfurt basin (Austria) overthrusts Quaternary deposits (POLINSKI & EISBACHER, 1992; NEMES et al., 1997), indicating that dextral wrenching along the eastern PFS persisted into Quaternary times. In fact, a regional study of active deformation in the Central European GPS network (GRENERCZY, 2002) suggests that eastward extrusion in the Eastern Alps is still active, and GPS measurments of active displacements in the Slovenian part of the PFS confirm that the Periadriatic fault is the southern boundary of the extruding unit with a slip rate of ~ 1 mm/yr (VRABEC et al., 2006).

Eastward, the Periadriatic fault is sealed by 17 Ma old syn-rift sediments of the Pannonian basin (Fig. 24), which mark the end of the main slip episode on the fault, dated to 24 – 18.5 Ma (FODOR et al., 1998; see also Fig. 25a). At that time, the amalgamation of the extruding ALCAPA unit with the Tisza block along the MHZ, and coeval rotational disintegration of the ALCAPA, documented by paleomagnetic data, prevented further dextral motion along the PFS-MHZ corridor (Fig. 25b). Throughout the mid-Miocene period, the deposition of sediments that occur today between the Labot (Lavanttal) fault and the Šoštanj fault (Fig. 24) was uninterrupted, and no evidence was found for significant mid-Miocene slip on the faults of the PFS (Fig. 25b). However, those mid-Miocene sediments are faulted and tighty folded inside the dextrally sheared zone betwen the Periadriatic fault proper and the Šoštanj fault (Fig. 24). Pliocene and Quaternary age of deformation is implied from youngest deformed sediments, occuring in the strike-slip Velenje basin along the dextral Šoštanj fault (e.g. VRABEC, 1999). This evidence is interpreted as post-12 Ma transpressional reactivation of the PFS (FODOR et al., 1998; Fig. 25c), when in northern Slovenia the dextral slip in the PFS was transferred from the immobilised Periadriatic fault proper to southward-lying segments like the Šoštanj fault (Fig. 24).

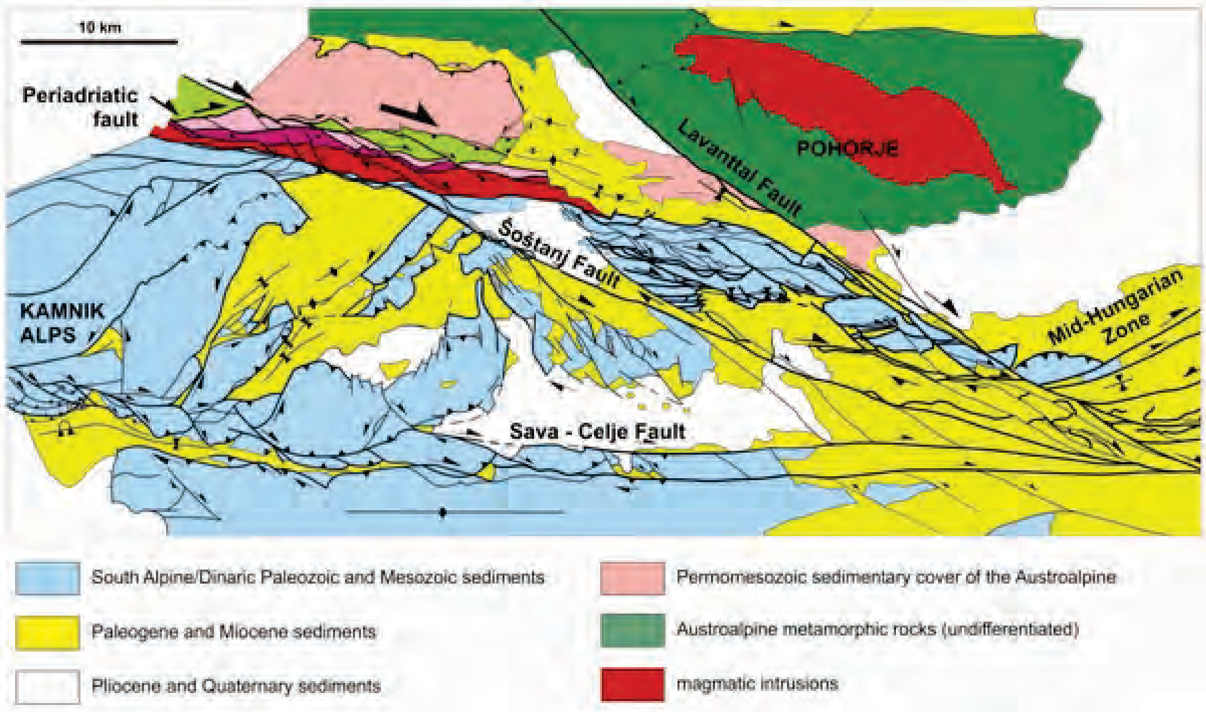

Figure 24: Tectonic map of northern Slovenia, showing the easternmost outcrop of the Periadriatic fault and associated faults of the Periadriatic fault system. From FODOR et al. (1998), based on 1: 100.000 regional geological maps (BUSER, 1978; MIOČ & ŽNIDARČIČ, 1977, 1983; PREMRU, 1983). See Fig. 22 for location.

Stop 7 – Bistra valley: outcrop of Oligocene tonalite

The tonalitic Karawanken pluton is a ~40 km long and extremely elongate intrusion, which runs parallel to the Periadriatic fault, on the northern side of the fault. Excellent outcrops of tonalite can be found in creeks and roadcuts south of the town of Črna na Koroškem. A subvertical, fault-parallel foliation is clearly expressed in the rocks. The fabric formed in the

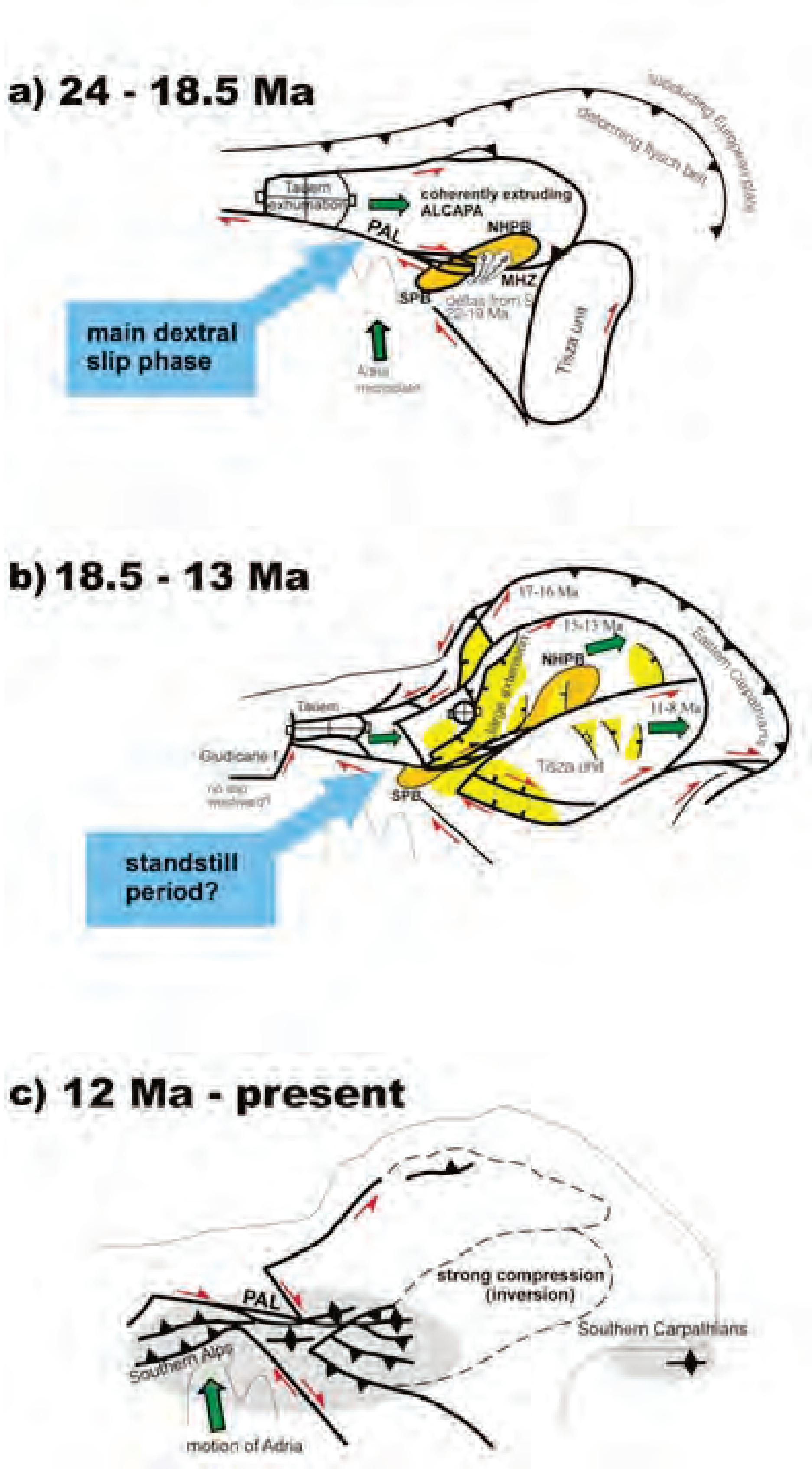

Figure 25: Summary of the evolution of the eastern Periadriatic fault system (from FODOR et al., 1998). See text for further discussion. PAL – Periadriatic line; MHZ – Mid-Hungarian Zone; SPB – Slovenian Paleogene basin; NHPB – North-Hungarian Paleogene basin.

magmatic state and was latter overprinted by greenschist facies deformation (e.g. ROSENBERG, 2004). The aspect ratio of flattened mafic enclaves suggests nearly plane-strain deformation (VON GOSEN, 1989) which is interpreted as indicative of transpressive conditions (ROSENBERG, 2004).

Stop 8 – Quarry on the northern slope of Smrekovec: brittle Periadriatic fault

The southern contact of the tonalite intrusion is a brittle fault, which is locally known as the Smrekovec fault. The fault zone is up to several 100s of m wide and may contain narrow slivers of Permian and Mesozoic carbonates (see Fig. 24). Excursion will visit a small quarry along the forest road, where the incohesive cataclastic rocks of the fault core are exposed. Slickensides on weakly preserved small secondary fault planes exhibit subhorizontal slip direction.

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Field Trip A2: Structural evolution of the Silvretta-Seckau nappe system in the area of the Schladminger Tauern

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The topic of this field trip is to visit and understand the structure of the Austroalpine nappes northeast of the Tauern Window. The excursion will start and end in Schladming. A transfer by minibuses to the Ursprungalm (47°17'47,44''N; 13°37'28,11''E) will be provided. From there, a cross section exposing the Silvretta-Schladming-Seckau nappes will be discussed during a two day walking tour (Figs. 1, 2). This, however, requires good weather conditions as well as experience in Alpine regions.

In the area of the Schladminger Tauern the Austroalpine nappes generally comprise a pre- Alpine basement and a Permian to Mesozoic cover. Both are overprinted by low-grade Eoalpine metamorphism. The basement units are additionally characterized by a pre-Alpine amphibolite facies metamorphic evolution. The Silvretta-Seckau nappe system in the area of the Schladminger Tauern is subdivided into two sub-units (Golling Complex and Riesach Complex). In the field trip area, the units of the Golling Complex are exposed. This Complex can be subdivided into two nappes. Within the higher unit, exposed in the area of the Giglachsee (47°16'55,00''N; 13°38'54,20''E), the basement and the cover sequences are exposed mainly in an inverted succession. An inverted sequence of probably Permian meta-conglomerates, quartz phyllites, quartzites and lower Triassic carbonates is exposed below pre-Alpine amphibolite facies metamorphic basement units. The basement-cover contact is overprinted and sheared at greenschist facies metamorphic conditions. The Triassic platform carbonates are well exposed in the area of the Steirische Kalkspitze (47'16'59,72''N; 13°37'19,82''E) and Lungauer Kalkspitze (47°16'20,00''N; 13°37'29,42''E) (2456m and 2470m, respectively) (Fig. 1).

Figure 1: View from the Lungauer Kalkspitze (2470 m) towards northwest to the Steirische Kalkspitze (2456 m), and to the Dachstein (2797m) (Northern Calcareous Alps) the back.

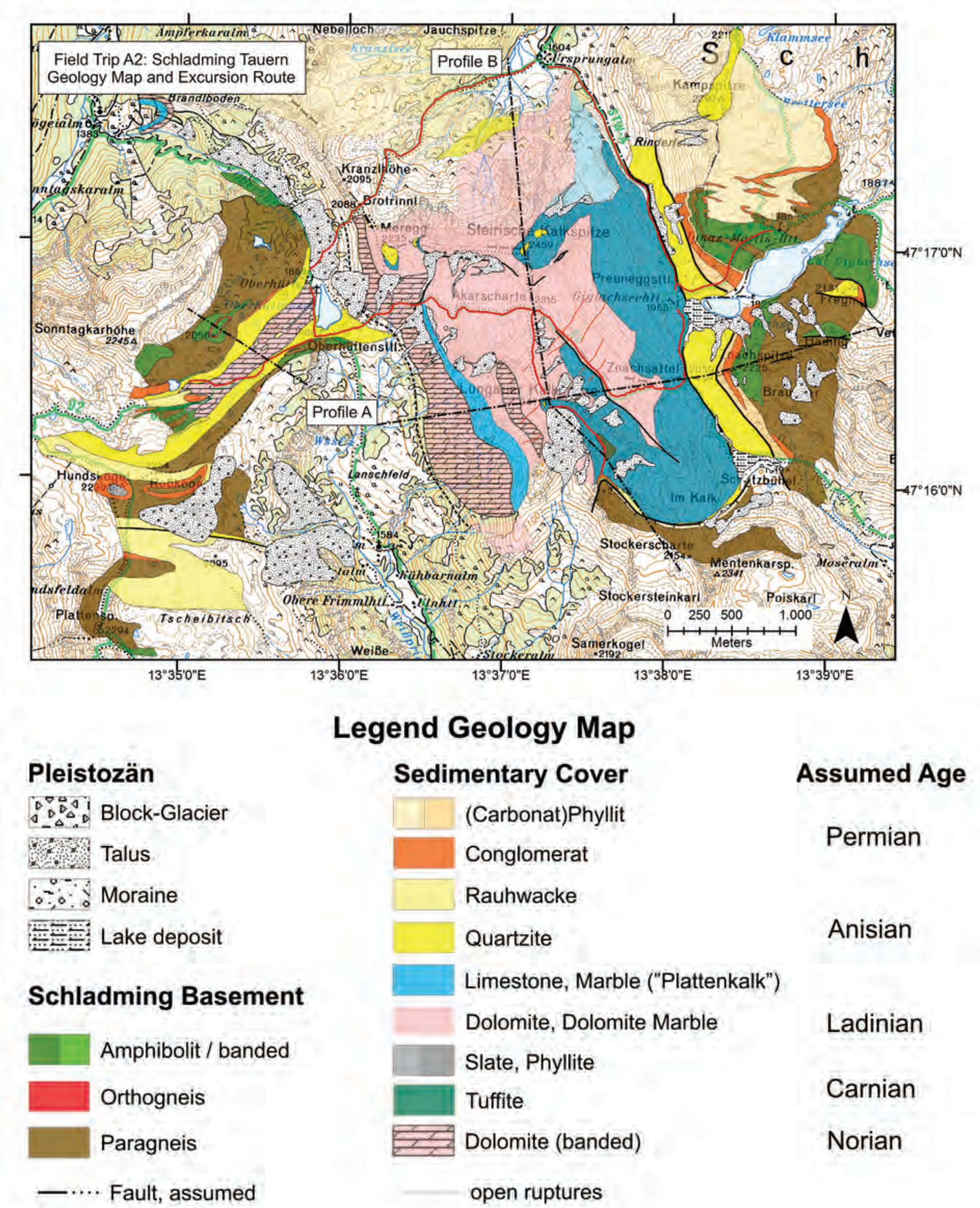

Figure 2: Geological map and excursion route (red line) of field trip A2.

Within the lower unit, exposed in the area of the Oberhüttensee (47°16’47,46’’N; 13°36’03,50’’E), a normal sequence of Permian to probably Triassic metasediments discordantly overlies a pre-Alpine basement. Also here, the basement (orthogneisses, paragneisses, amphibolites) is characterised by a pre-Alpine metamorphic evolution at amphibolite facies conditions, and by (lower) greenschist facies Eoalpine metamorphic overprint.

Structural evolution

The area is subdivided into three domains with distinctly different structural inventory and separated by major tectonic boundaries (Fig. 3). The eastern part (domain 1), between Ignaz Mattis- and Giglachsee-Hütte exposes retrogressed Schladming basement conformly overlain by Permo-Triassic clastic sediments. Both, the upright and inverted limbs of a map-scale NW-vergent fold are mapped. A narrow-spaced axial plane foliation dominates this domain, associated second order folds being responsible for a lense-shaped geometry of units exposed in fold hinges. The inferred thrust direction was top-to-the NW during the first Alpine deformation phase followed by N-S shortening in a subsequent stage. The tight axial plane cleavage is overprinted by a prominent dextral shear zone along the contact to domain 2.

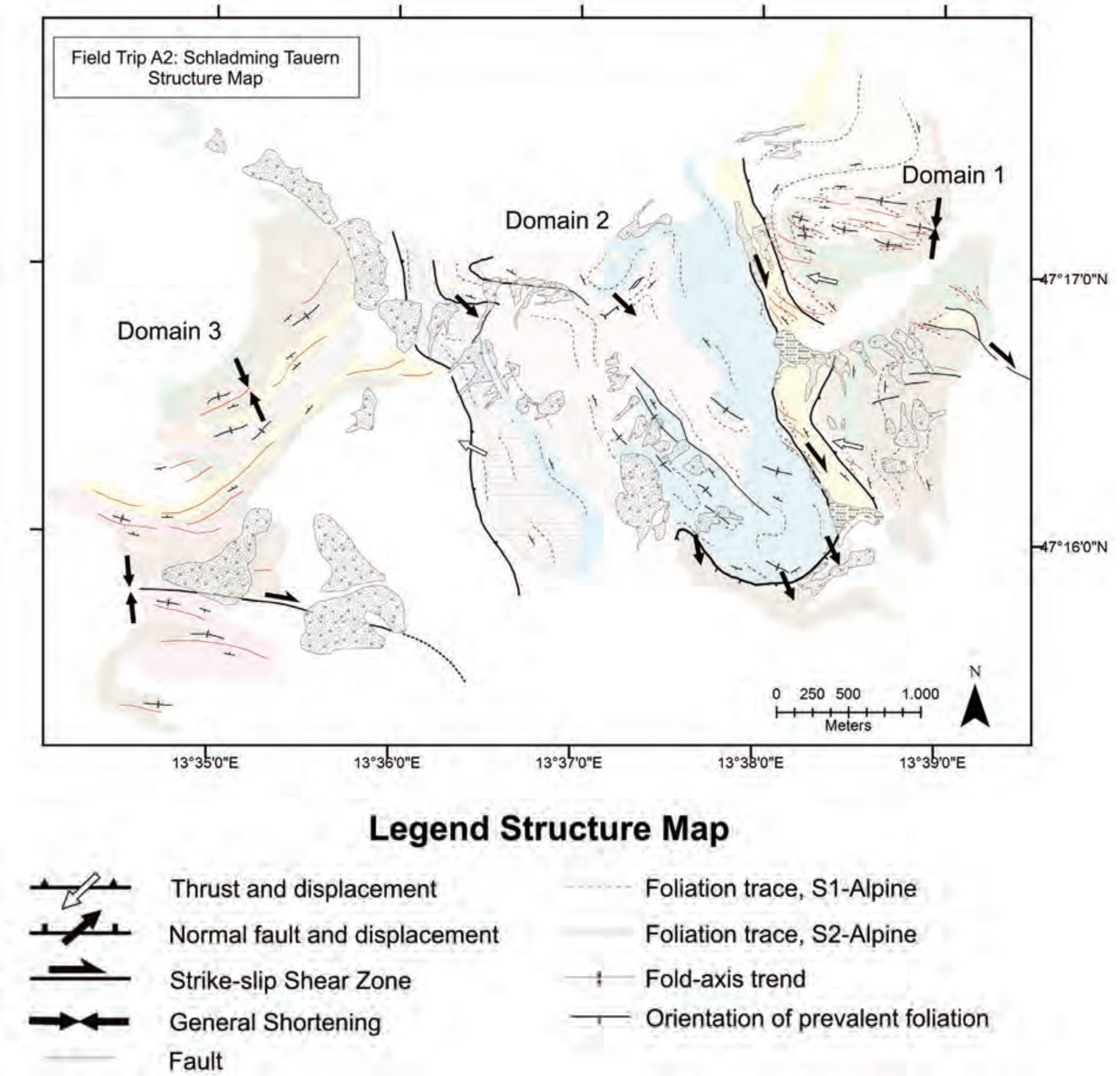

Figure 3: Structure map with main structural features and lithology in pale colours (see Fig. 2 for legend of lithologies).

The central part (domain 2) constitutes a fault bounded and inverted section with slivers of Schladming basement (now exposed on the summits of Lungauer Kalkspitze), underlain by Permian clastic rocks and Triassic carbonates (Fig. 3). A prominent south- to southeast-dipping ductile normal fault marks the boundary between domains 1 and 2 in the south (Fig. 4). The western boundary constitutes the above mentioned shear zone. The eastern border of domain 2 is not exposed but assumed to be a thrust separating domain 2 from domain 3. Internal portions of domain 2 contain localized top-SE extensional shears and NNW-SSE trending folds.

The western domain (domain 3) exhibits tight folding of Permian to Mesozoic cover units and basement. Fold traces trend NE-SW and occupy high angles to structural elements and lithology trends of domain 2. Younger dextral shear zones evolved preferrantly within tight limbs of folds.

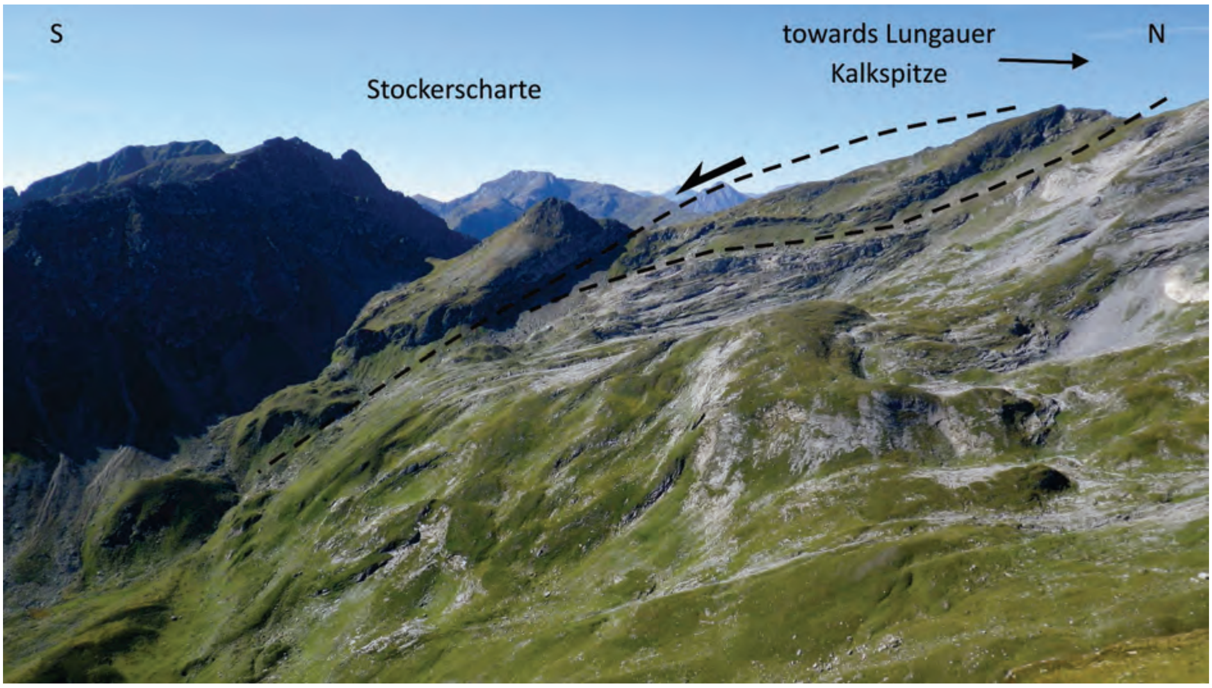

Figure 4: The southern low-angle normal fault separating domain 1 from domain 2. View form Znachspitze towards west.

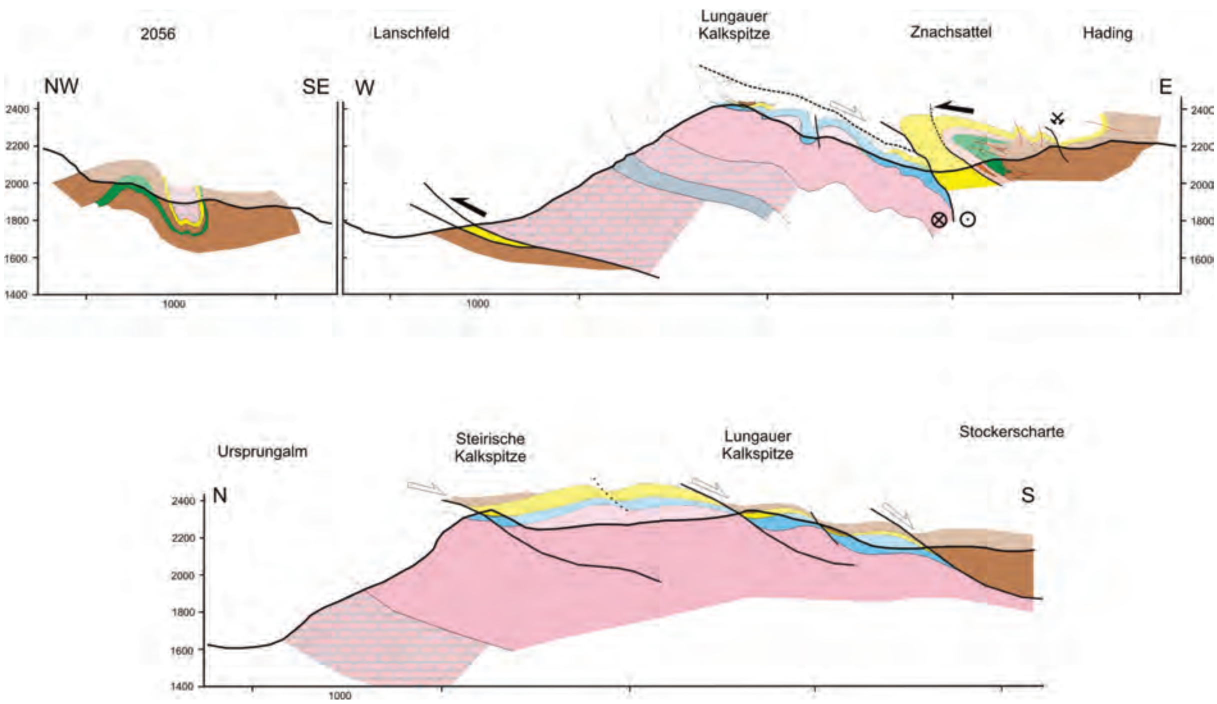

Figure 5: W-E (upper panel; location of the section: Profile A in Fig. 2) and N-S (lower panel; location of the section: Profile B in Fig. 2) sections from the excursion area. For legend see Fig. 1 and 2.

The upper panel in Fig. 5 shows a W-E section across the three domains. The eastern sector (domain 1 – from Hading to Znachsattel) illustrates the older Alpine thrusting and folding phase overprinted by normal and strike-slip folds. Domain 2, between Znachsattel and Lanschfeld is the inverted Permian to Mesozoic section underlain by folded basement and cover units of domain 3 (point 2056 m).

The lower panel from the Urprungalm (south) to the Stockerscharte (north) displays southward extensional shearing as typical for domain 2 (compare Fig. 4). All in all domains 1 and 3 are characterized by N-S shortening structures, domain 2 by N-S extensional structures.

Day 1

We start the excursion at Ursprungalm (1604m) (47°17'47''N; 13°37'10,5''E) and take the footpath to the Giglachseehütte (1955m) (47°16'46,62''N; 13°38'15,38''E). The trail mainly follows the boundary between lower Triassic quartzite and "Plattenkalk" that is also the right lateral shear zone separating domain 1 from domain 2. From Giglachseehütte we proceed to Ignaz Mattis Hütte (1986m) (47°17'05,88''N; 13°38'54,90''E).

The cross section from the Ignaz Mattis Hütte to the Giglachseehütte shows an inverted section from basement rocks of the Schladming basement to Permian to Mesozoic metaclastic rocks of the cover suite. In this area the Schladming crystalline basement consists of fine grained biotite-plagioclase gneiss and fine grained amphibolite, both contain occasionally garnet (for detailed description of basement rocks see day 2). Characteristic is the strong retrogression during Eo-Alpine deformation and replacement of amphibole by chlorite within amphibolites. At 47°16'55,8''N; 13°38'22,7''E the contact between basement and cover rocks is exposed, here represented by pebble bearing carbonate phyllite and conglomerate. This boundary is heavily fluid infiltrated as to be recognized from numerous carbonate veins within basement rocks and the sedimentary cover. On the opposite side of Giglachsee red debris from the dump of the Giglachsee mine is seen that aligns with a shear

Figure 6: Stretched and sheared pebbles within carbonate bearing phyllite.

zone close to the basement-cover contact and continues from Freying (2131m) (47°16'49,8''; 13°39'4,7''E) eastwards to the mines at Vettern-Zinkwand. Polymetalic sulphide ore was mined for Ni-Co-Ag-Cu since the 13th century with variable activities and ended 1875.

The inverted sedimentary succession starts with carbonate - sericite - phyllite and reddish – brown conglomerate composed mainly of quartz pebbles with a size up to 10cm. In all, a fining upward sequence is present, although meta-sandstone and phyllite beds alternate with meta-conglomerate beds. Stratigraphically upwards pure quartzite, described in different terms in different areas (e.g., Semmering Quartzite, Lantschfeld Quartzite,...), with characteristic pale green colour occurs. Apparently, the metasedimentary suite conformably overlays the basement rocks. Both basement and cover experienced NW-directed shear (Fig. 6) as evidenced from stretched pebbles that include numerous shear sense indicators. The Giglachseehütte is close to the contact between Anisian quartzite and Triassic carbonate platform sediments.

From the Giglachseehütte to Znachsattel (2059m) (47°16'29,4''N; 13°38'6,3'') the trail leads along the boundary between quartzite and platy limestone (Plattenkalk) of presumably Anisian age. This boundary represents a shear zone where early formed folds were transposed into dextral shear structures (close to Giglachseehütte). At Znachsattel S-vergent folding is seen as expression of this shearing. From Znachsattel we climb up to Akarscharte (2315m) (47°16'47,15''N; 13°37'9,2''). Anisian platy limestone contain nests of dolomite and are followed by Ladinian dolomite (Wetterstein Dolomite ?) with rare occurrences of tuffite in between. Half way up (47°16'29,4''N; 13°37'30,6'') an alternation of steeply dipping limestone and dolomite is seen as expression of tight folding around NNW trending axes (Figs. 3, 5)

The top of the Lungauer Kalkspitze exposes Anisian quartzite and biotite gneiss (Schladming basement). Heading towards south we reach the prominent SE-dipping semi-ductile normal fault close to point 2348 (47°16'2,07''N; 13°37'36,63''). Here the sedimentary cover of the Schladming basement appears to be extremely reduced by low-angle normal faulting. Numerous shear sense indicators are found in carbonate phyllite and conglomerate (Figs. 4, 7).

Figure 7: Low-angle normal shear zone with ecc-fabrics, point 2348m (47°15'58,56''N; 13°37'52,11'').

The trail from Akarscharte to Oberhütte (47°16’49,9’’N; 13°35’45,5”E) exposes the complete, inverted section of Ladinian to possibly Norian rocks. Massive Ladinian? dolomite, in rare places interleaved by Carnian? slate is underlain by banded dolomite and limestone. The entire, inverted section of domain 2 with Norian? dolomite at the base, tectonically overlays Anisian quartzite of domain 3 near Oberhüttensattel (1866m) (47°16’36,1’’N; 13°35’48,9”E). Unfortunately the tectonic boundary is not exposed. We draw attention to the fact that the structural style changes at this boundary. The dominant Swvergent extensional structure that dominate much of domain 1 is replaced by N-S compressional structures best seen in tight folding of basement and cover sequences in domain 3.

Day 2

Cross section from Oberhütte (1845m) (47°16’49,00”N; 13°35’59,89’’) to point 2056m (47°16’36,30’’; 13°35’25,25’’) and lake at 47°16’24,00’’; 13°35’13,20’’.

This cross section provides an overview of the structure of the lower nappe within the Golling complex. This unit is build up of a pre-Alpine basement showing pre-Alpine amphibolite facies metamorphic overprint, and a Permian to Triassic cover. The contact between the basement and the cover units is marked by a clear angular unconformity (Fig. 8). The basement is characterised by a well developed, pre-Alpine penetrative foliation with subhorizontal to slightly W-dipping layering (Fig. 8). In the field trip area, this basement mainly comprises highly variable paragneisses (quartz, plagioclase, muscovite, partly garnet, biotite), orthogneisses (quartz, K-feldspar, plagioclase, muscovite), and amphibolites (hornblende, plagioclase, quartz) that partly contain garnet. The garnets within these amphibolites usually show rims of chlorite and epidote (Fig. 9), indicating an Alpine metamorphic overprint at greenschist metamorphic conditions. The degree of retrogression during Alpine metamorphism increases towards the basement – cover contact. Close to this contact the amphibolites are strongly retrogressed as well, indicated by the formation of very fine grained symplectite (Fig. 9).

Figure 8 (previous page)**:** Exposure at 47°16'24,00"N; 13°35'13,20"E, showing the angular discordance between the pre-Alpine basement (right) and the Permian to Triassic cover (left). The basement at this site mainly comprises various paragneisses with distinct layers of amphibolite. The cover at the contact comprises quartzite and quartz phyllite. Due to the angular disconformity the penetrative foliation within the basement is assumed to be of pre-Alpine origin. This pre-Alpine foliation is subhorizontally layered in the area of exposure; the foliation within the cover is dipping towards southeast.

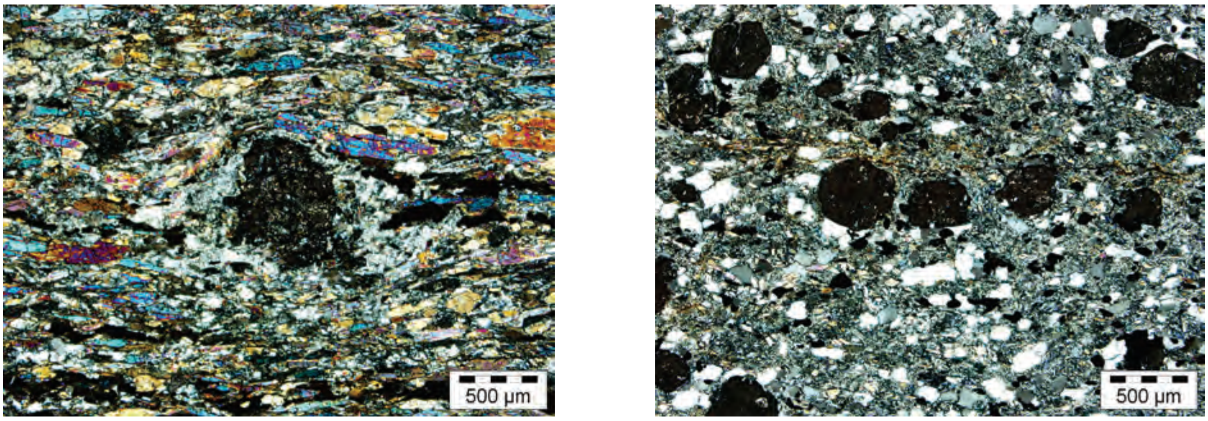

Figure 9: Microfabric and texture of retrogressed garnet amphibolite; garnets show rims of chlorite and epidote (left); retrogression of hornblende to fine-grained symplectite (right).

The Permian to Mesozoic cover, from base to top, consists of chlorite phyllites, partly with quartz pebbles (Fig. 11), meta-conglomerates, quartzites, cornule, dark schists to phyllites, and banded dark calcite marbles as well as dolomite marbles. The cornules, dark schists and marbles are assumed to be of Anisian stratigraphic age. In general, these sequences show low-grade Alpine metamorphic overprint and are incorporated into large-scale folding at a scale of several meters to kilometers. This results in a succession of gentle to tight antiforms and synforms, characterized by a sub-horizontal to slightly ESE-dipping fold axis (Fig. 10).

Figure 10: Equal area projections of penetrative foliation orientation data from pre-Alpine basement (right) and Permian to Triassic cover (left) at site 47°16'24,00"N; 13°35'13,20"E. The poles to the foliation data within the cover units are distributed along a girdle, indicating folding of the foliation around a ESE- plunging fold axis.

Strikingly the trend of the Alpine penetrative foliation as well as the trend of stretching lineations and fold axes is orthogonal or highly oblique between the higher (domain 2) and the lower unit of domain 3 (east-west in the lower unit, north-south in the higher unit). Hence, beside the angular unconformity within the lower unit around the Obersee, there is an additional structural discontinuity between the two nappes within the Golling Complex.

The basement – cover contact along the angular unconformity is tectonically overprinted by penetrative shearing. Pebble-bearing, micaceous quartzites and quartz phyllites were transformed to phyllonites with a very prominent penetrative foliation, and a well develop, E-plunging stretching lineation. The penetrative foliation is moderately to steeply dipping towards southeast. As these pyllonitic shear zones are overprinting the Alpine foliation and subsequent folding, this localized shearing is assumed to be related to post-stacking, E-W extension.

Figure 11: Quartzphyllite with quartz pebbles (Permian?) close to the angular conformity at the basement cover contact.

On the way back to Ursprungalm we cross again the unexposed boundary between domains 2 and 3 southwest of Brotrinnl (2088m) (47°17'9,56''N; 13°36'4,7"E) and proceed within the sedimentary cover suite (phyllite, quartzite) of the Schladming basement.

Summary of the tectonic evolution

1) Arguably the inverted metasedimentary suite exposed at Steirische and Lungauer Kalkspitze transgressively overlays basement rocks of the Silvretta-Schladming-Seckau Nappe system and thus are considered as part of a coherent nappe system.
2) The structural inventory and geometric relations suggest existence of two distinct nappes. The upper nappe of the Golling Complex in this area constitutes domains 1 and 2 that were assembled during an early phase of Eo-Alpine deformation. West-to northwest directed folding is considered to be responsible for the inverted stratigraphic succession of domain 2.
3) Stacking structures were overprinted by SE- vergent extensional structures that likely evolved during late Eo-Alpine (Gosauic) extension. During this phase previously buried rocks of domain 2 where exhumed along SE- dipping normal faults.
4) Rocks of domain 3 represent a deeper nappe of the Golling Complex, tectonically below domains 1 and 2. This unit preserves an angular unconformity between the Schladming basement and its cover. Variscan metamorphism and deformation is recorded within the basement. Tight folding of basement and cover units is related to Eo-Alpine shortening followed by late Eo-Alpine strike-slip shearing.

Field Trip A3: Triassic to Early Cretaceous shallow-water carbonates in the central Northern Calcareous Alps (Northwestern Tethyan realm)

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Abstract

The Triassic to Early Cretaceous sedimentary evolution in the northwestern Tethyan realm, very well preserved in the central Northern Calcareous Alps (Salzburg and Berchtesgaden Calcareous Alps, Salzkammergut region), is characterized by a complete Wilson cycle. After siliciclastic dominated Early Triassic sedimentation intense shallow-water carbonate production started around the Early/Middle Triassic boundary. Early/Middle Anisian shallow-water carbonates were deposited first under restricted (Gutenstein carbonate ramp) and later under more open marine conditions (Steinalm carbonate ramp). Late Anisian break-up of the Neotethys Ocean led to the drowning of this shallow-water ramp deposits. In the Ladinian again shallow-water carbonates start to form, and results in the complex Ladinian to early Carnian platform - basin pattern (Wetterstein Carbonate Platform). After the partial drowning of this platform by siliciclastic input in the Middle Carnian again shallow-water carbonate production starts and resulted in the huge Norian Hauptdolomit/Dachstein Limestone Carbonate Platform, with its classical lagoonal sediments - restricted lagoon (Hauptdolomit), open lagoon (Dachstein Limestone with Lofer cycles) - the reefs belt and its transition to the open shelf area (Hallstatt facies). In the Rhaetian the carbonate factories were again influenced by siliciclastic input, and resulted in the formation of a deepened lagoon (Kössen Basin).

In the Jurassic deep-water sediments are dominant: The Jurassic sedimentation in this realm is controlled by the palaeogeographic position of the depositional area between two oceans: the Neotethys Ocean to the east resp. southeast and the Alpine Atlantic to the west resp. northwest. The opening of the Central Atlantic Ocean with its continuation into the Alpine Atlantic (= Ligurian-Penninic Ocean) leads to a new Mediterranean plate configuration. The “Apulian” plate is formed. Successive spreading of the Alpine Atlantic is mirrored by the closure of parts of the Neotethys Ocean resulting in an early deformation of a former Triassic carbonate shelf since late Early Jurassic time. The former Triassic to Early Jurassic passive continental margin with its huge Triassic carbonate platforms came in a lower plate position and a thin-skinned orogen was formed. In the Late Jurassic to Earliest Cretaceous this mountain building process is sealed by the onset of shallow-water carbonate platforms (Plassen Carbonate Platform). Shallow-water platform carbonates were formed on top of the nappe stack.

1 Introduction

For an outline of the whole Permian/Triassic to Early Cretaceous sedimentary and geodynamic evolution of the northwestern Neotethys realm (e.g., Eastern and Southern Alps, Western Carpathians, Pannonian realm, Dinarides) see Gawlick et al. (2012).

During this field trip you will see (Fig. 1):

- Different Anisian shallow-water carbonates (restricted and open lagoon): Gutenstein and Steinalm carbonate ramps.
- Late Ladinian to Early Carnian Wetterstein Carbonate Platform sediments.
- The lagoonal facies belts of the Late Triassic carbonate platform: restricted Hauptdolomit facies belt with it's stromatolithes and the open lagoonal Dachstein Limestone facies belt with the classical Lofer cycles as well as the reefal framework.
- Formation of a palaeotopography in the latest Triassic due to siliciclastic influence and the response of the carbonate factories. Formation of a deep lagoon (Kössen Basin).
- Onset of shallow-water carbonate platforms on an uplifted nappe stack, progradation of shallow-water carbonates over older deep-water basins: different facies belts of the Plassen Carbonate Platform: lagoon, reef belts, reworked platform sediments in basinal *Calpionella* limestones.

To visit the classical Triassic and Jurassic shallow-water carbonate platforms of the tethys-side margin in their type region. This area is a geological highlight in one of the most classical geological areas of the world including classical, historical and more recent foraminifera and algae type-localities, e.g. the Anisian Clessinsperre section (Pia´s locality) and Mount Plassen (Kimmeridgian to Berriasian).

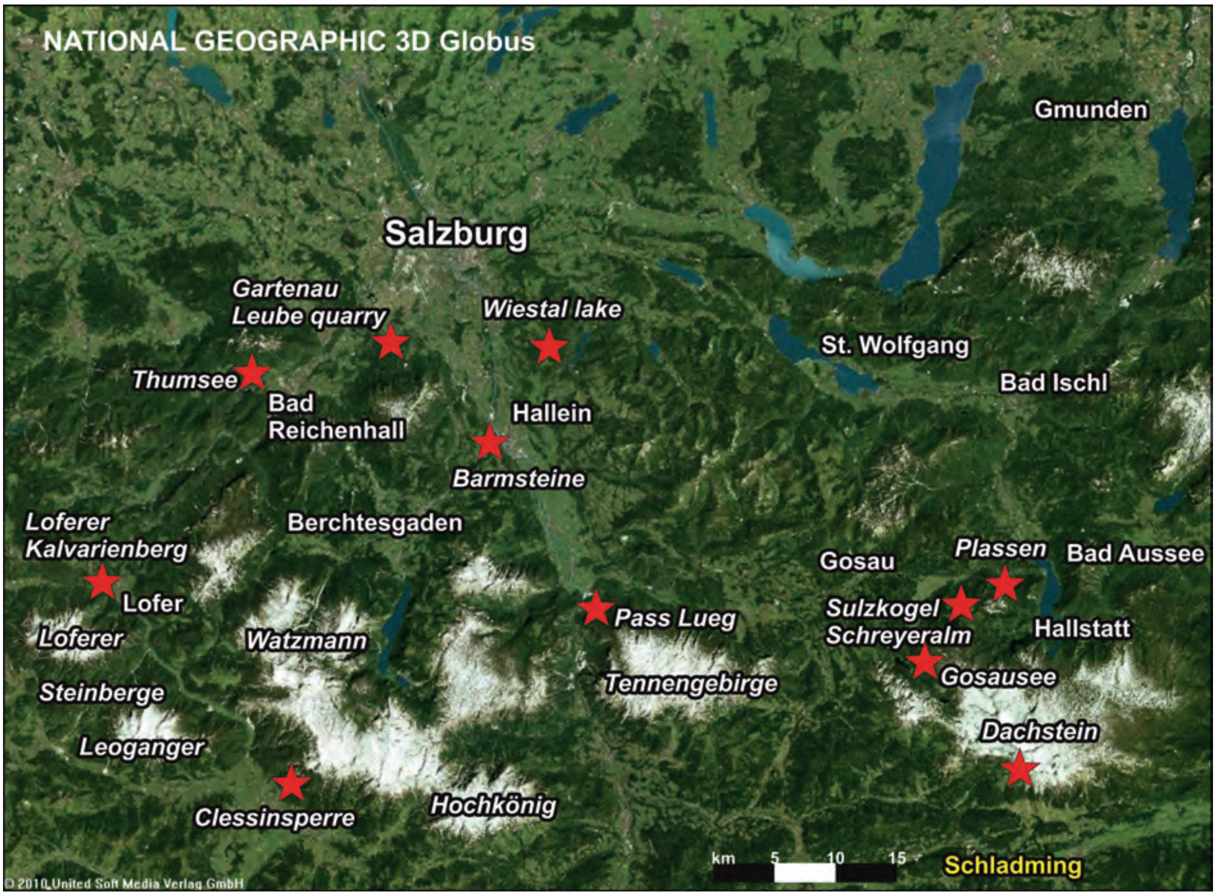

Figure 1: Satellite image of the central Northern Calcareous Alps, showing the localities which will be visited during this field trip (red stars). Sulzkogel/Schreyeralm and: Middle Anisian shallow-water carbonates, Late Anisian drowning. Clessinsperre: Early - Middle Anisian shallow-water carbonates, Late Anisian drowning, Late-Anisian to Late Ladinian deep-water sediments, Late Ladinian - Early Carnian Wetterstein Carbonate Platform. Thumsee and Wiestal lake: Norian Hauptdolomit. Dachstein and Pass Lueg: Norian Lofer cycles. Pass Lueg: Rhaetian Kössen Basin and Rhaetian lagoonal Dachstein Limestone. Gosausee: Late Norian/Rhaetian Dachstein reefal margin. Loferer Kalvarienberg: Lärchberg Carbonate Platform (Tithonian to ?Berriasian). Plassen: Plassen Carbonate Platform, reef and lagoon (Kimmeridgian - Tithonian). Mounts Barmsteine, Leube quarry: Late Tithonian - Berriasian resediments of the Plassen Carbonate Platform.

2 The Field Trip

To avoid confusion, the stop descriptions were sorted according to the different topics and not in strict chronological order according to the way of walking or driving.

2.1 Middle Triassic

Topics: Gutenstein and Steinalm carbonate ramp evolution (Early-Middle Anisian), Schreyeralm and Reifling Limestones (late Middle Anisian to Ladinian), Wetterstein Carbonate Platform (Late Ladinian to Early Carnian).

For a modern description of the Gutenstein and Steinalm Formations see LEIN et al. (2012). LEIN et al. (2012) discussed also the lithostratigraphic nomenclature of the Anisian, specially of the Gutenstein and Steinalm ramp evolution.

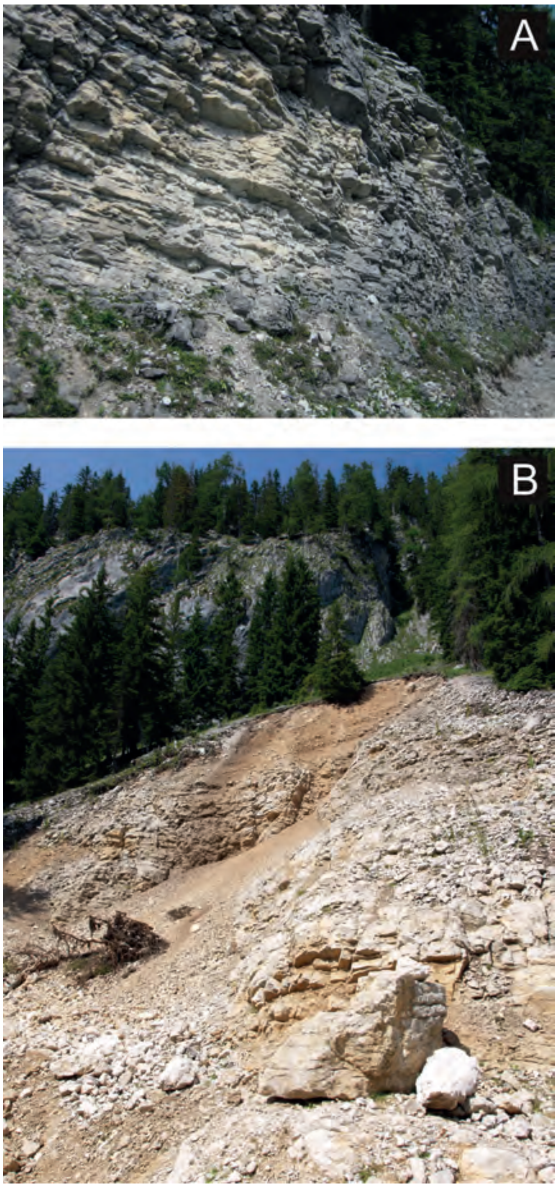

Figure 2: A) Bedded limestone succession of the Sulzkogel Member. B) The limestones of the Sulzkogel Member were first overlain by thin bedded dolomites and later by thick bedded dolomites of the Steinalm Formation.

Section Sulzkogel (Pelsonian)

The section Sulzkogel is located southsoutheast of the township Gosau (central Salzkammergut area) west of Mount Plassen (Fig. 2).

On top the Early Anisian Gutenstein Formation a more open marine facies evolved linked to a continuing thinning of the continental crust (LEIN, 1987). The latter (Annaberg Formation) is characterized by bedded algal-rich limestones with shallow-water debris (Fig. 3) intercalated by hemipelagic influenced filament-bearing limestones with conodonts: e.g. *Nicoraella germanica, Nicoraella kockeli, Gondolella bulgarica*. Most probably the age of this level (Sulzkogel Member of the Annaberg Formation - LEIN et al., 2010) is early Pelsonian.

Upsection first thin bedded dolomites and later thick bedded dolomites and massive limestones of the Steinalm Formation occur. In this unit the microfacies characteristics is hardly visible due to intense dolomitization.

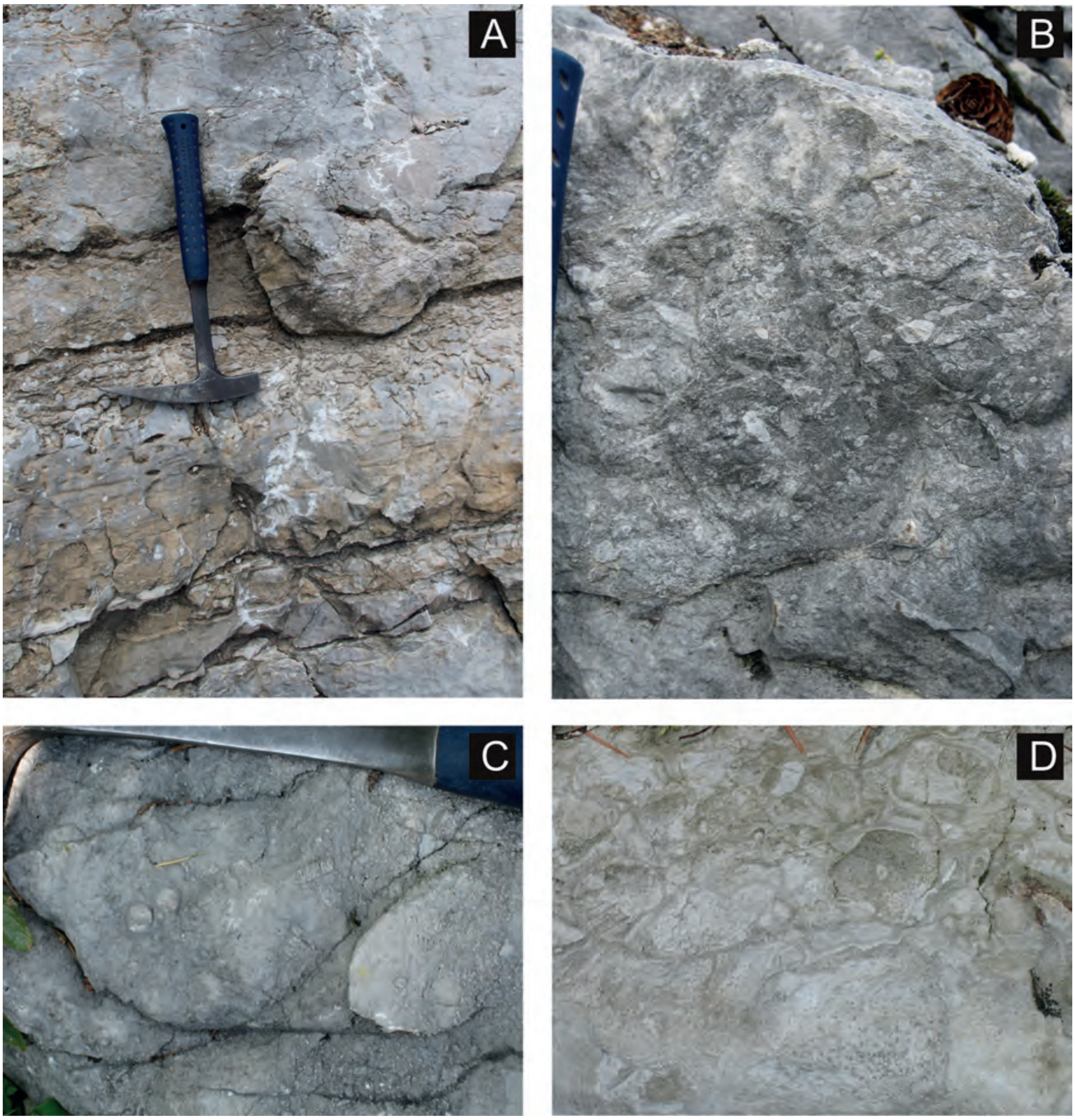

Figure 3: Lithological features of the coarse-grained bedded limestones with different shallow-water material (reworked microbial reefal framework) including calcareous algae.

Schreyeralm

Type-locality of the Schreyeralm Limestone.

The classical Schreyeralm section is located west of Mount Plassen north of the grassland area of the Schreyeralm. Red nodular limestones are exposed on the topmost part of the Steinalm Formation. The Schreyeralm Limestone represent the drowning sequence of the Steinalm carbonate ramp and is dated by ammonites and conodonts as Late Pelsonian (*binodosus*-Zone, e.g. ASSERETO, 1971; KRYSTYN & SCHÖLLNBERGER, 1972).

Both localities (Sulzkogel and Schreyeralm) combined show clearly, that the age of the Steinalm Formation (definition: PIA 1930; for algal-rich light coloured limestones) resp. the Steinalm carbonate ramp is restricted to the Pelsonian. These outcrops with the rich algal flora in the Steinalm Limestone in the area west of Mount Plassen provides for the first time the possibility to correlate the shallow-water fauna and flora with conodonts and cephalopods. The age of the Steinalm Formation can be restricted as Pelsonian.

Clessinsperre

Type-locality of the Steinalm Formation (PIA, 1930). Type-locality of several calcareous algae (OTT, 1972a, 1972b).

At the section Clessinsperre a continuous succession from the early Anisian Gutenstein Formation, deposited under restricted conditions, to the Ladinian - Early Carnian Wetterstein Carbonate Platform is exposed. The Steinalm Formation overlies the Gutenstein Formation directly. The Annaberg Formation is missing. The change from the restricted depositional environment of the Gutenstein Formation (dark grey micritic limestones with peloids and rare faunal elements, except few foraminifera) to the more open depositional environment of the lighter grey limestones of the Steinalm Formation is gradual. Also the floral and faunal content increases only slightly. The topmost part of the Steinalm Formation is characterized by in parts algal-rich beds with some filaments in the topmost part. These part of the succession (Fig. 4) is overlain by cherty limestones of the Reifling Formation (details in TOLLMANN 1976), dated by ammonites as *trinodosus*-Zone (early Illyrian). According to own investigations the uppermost part of the Steinalm Formation with the intercalations of the filament-bearing limestones contains Conodonts: e.g. *Gondolella bulgarica*, *Gondolella bifurcata*, and *Nicoraella.* sp. Therefore the drowning of the Steinalm ramp in the Clessinsperre section is contemporaneous with the drowning of the Schreyeralm section: Late Pelsonian.

Figure 4: Drowning unconformity: Late Anisian cherty limestones of the Reifling Formation on top of the Pelsonian Steinalm Formation. Section Clessinsperre.

The age of Reifling Formation is Late Anisian to Late Ladinian as dated by conodonts. In the Late Ladinian intercalations of volcanic ashes are characteristic. Upsection of these volcanic ash layers first shallow-water resediments of the prograding Wetterstein Carbonate Platform occur. Upsection we will see the here in this section dolomitized Wetterstein Carbonate Platform (Late Ladinian to Early Carnian). Due to intense dolomitization the microfacies characteristics of the Wetterstein Carbonate platform – typical are fore-reef carbonates, later reefal and back-reefal carbonates topped by lagoonal carbonates, are hardly visible. Dolomitization of the Wetterstein Carbonate Platform is a widespread phenomenon, especially in the Tirolic units of the Northern Calcareous Alps.

2.2 Late Triassic

Hauptdolomit (Norian), lagoonal Dachstein Limestone (Lofer cycles) (Norian-Rhaetian), reefal and fore-reefal Dachstein Limestone (Norian), Kössen Formation (Rhaetian): deep restricted lagoon.

The evolution of the Late Triassic (Norian-Rhaetian) Hauptdolomit-Dachstein Carbonate Platform is recently described in detail by RICHOZ et al. (2012) (compare ZANKL, 1971). For a detailed description of the different facies belts see also GAWLICK et al. (2012). The Hauptdolomit facies belt represents the restricted lagoonal environment of this platform, the lagoonal Dachstein Limestone represents the open lagoonal environment of the platform. The transition between these two facies belts is not preserved in the Northern Calcareous Alps.

<u>Thumsee (Bad Reichenhall)</u>

Hauptdolomit, rich in organic matter. Restricted lagoon. We will visit Hauptdolomit sections north of Bad Reichenhall (Thumsee). Here the Hauptdolomit is contemporaneous a source and a reservoir rock. Characteristic are beside the classical stromatolithes grainstone intercalations with foraminifera and algae (Fig. 5). The thickness of the Hauptdolomit in this area is around 1000 metres.

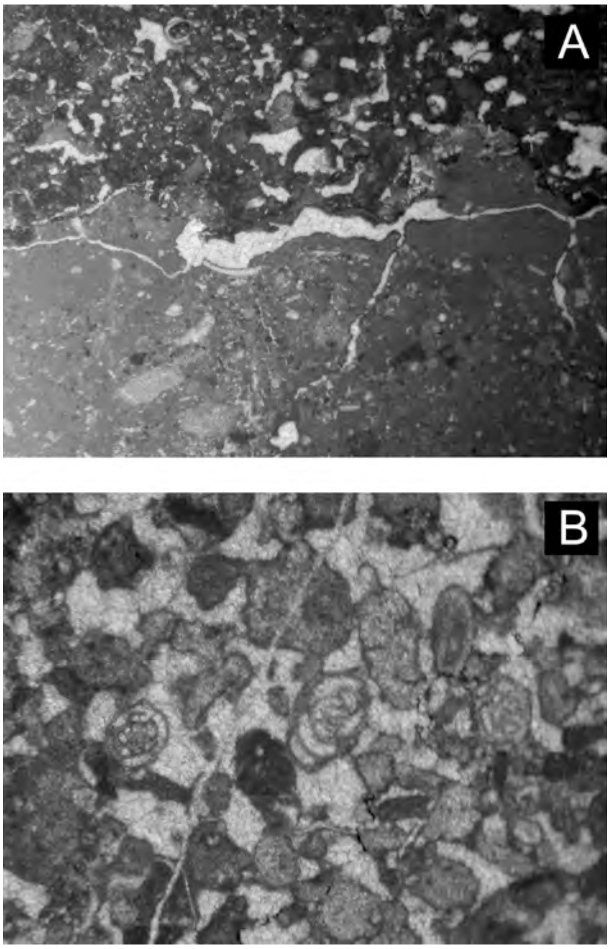

Figure 5: Microfacies characteristics of the Hauptdolomit around the Thumsee. A) Fenestral fabric made of microbial dolomite overlying a wackestone to packstone layer. B) Grainstone with e.g. foraminifera.

Wiestal lake (optional)

North of the Wiestal lake organic rich small scale basin intercalations in the Hauptdolomit are preserved (Fig. 6). The microfacies and the molecular indicators were recently investigated by BECHTEL et al. (2007).

Phytoplankton and photosynthetic bacteria are considered to be the major primary producers of the organic matter in these immature (~0.5% equivalent vitrinite reflectance), carbonate-rich rocks. Contributions from vascular plants are suggested from the n-alkane distribution pattern and high content of C_{29} steranes. Enhanced microbial activity in the depositional environment is proposed on the basis of the hopanoid content. The occurrence of aryl isoprenoids, probably derived from carotenoids of the photosynthetic green sulfur bacteria (Chlorobiaceae) indicates the presence of free H_2S in the bottom water. Mesohaline conditions in the upper part of the water column are deduced from the presence of dimethylated and trimethylated 2-methyl-2-(tridecylchromans) (MTTCs). Co-variation in the distribution of MTTCs and pristane/phytane ratio and the concentration of a C_{16} aryl isoprenoid argue for photic zone anoxia due to salinity stratification. The biomarker composition points to a high productivity marine environment with limited water exchange and a stratified water column confirmed by microfacies analysis.

Sedimentological and geochemical features provide evidence for the establishment of small-scale anoxic basins through erosion by currents or from the remnants of channels, which were possibly isolated periodically by small-scale sea level changes.

Figure 6: Wiestal lake section: the lower part of the section is characterized by dark-grey laminated and organic-rich dolomites. The upper part consists of “typical” light-grey Hauptdolomit.

Mount Dachstein (optional)

Type locality of the Norian lagoonal Dachstein limestone. The characteristic features of the lagoonal Dachstein Limestone were recently summarized by RICHOZ et al. (2012). This outcrop is optional and will be probably visited during the symposium Field trip.

The area around the Dachstein glacier provides excellent outcrops of the lagoonal Dachstein Limestone (Lofer cycles) (Fig. 7). Especially the Member C consists of different Pack- to Grainstone types with a rich fauna and flora, including microbial carbonates and calcareous algae.

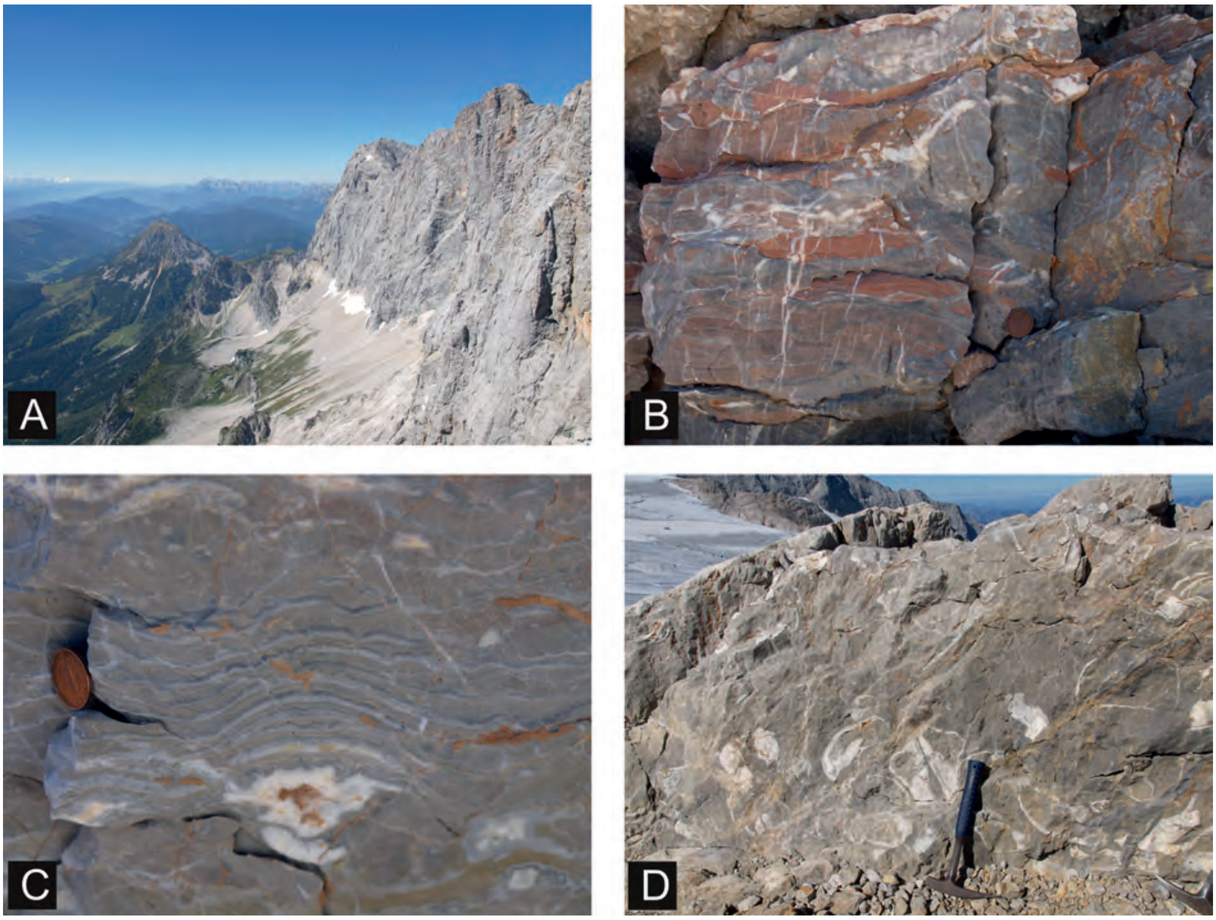

Figure 7: A) Southern Wall of the Dachstein massif with the bedded lagoonal Dachstein (Lofer cycles). Left: Mount Rettenstein (Kimmeridgian reef). B) Member A of the Lofer cycle sensu FISCHER (1964). C) Member B of the Lofer cycle sensu FISCHER (1964). C) Member C of the Lofer cycle sensu FISCHER (1964).

Pass Lueg (optional)

Norian lagoonal Dachstein Limestone, Rhaetian Kössen beds and Rhaetian lagoonal Dachstein Limestone.

This outcrop is described in detail in GAWLICK (2000), GAWLICK & MISSONI (2013), and RICHOZ et al. (2012). Around Pass Lueg a complete Late Norian to Jurassic sedimentary succession is preserved. The Late Norian is characterized by a Lofer cycle succession similar to that of Mount Dachstein. On top of the Norian Dachstein Limestone a siliciclastic input led to the deposition of a marly sequence (Early Rhaetian). Upsection the carbonate increases rapidly and a 1-2 metre-thick succession of marly limestones with corals ("Lithodendron Limestone") represents the most important lithofacies marker of the Kössen Basin. Whereas near the southern rim of this basin (this outcrop) this level is overlain by shallow-water lagoonal Dachstein Limestone this level marks in the central basin a deepening below the wave base (GOLEBIOWSKI, 1990, 1991; RICHOZ et al., 2012) and a transition phase between a deep, open marine lagoon and the intraplatform basin deposition milieu of the Eiberg Member.

The lagoonal Rhaetian Dachstein Limestone consists mainly of pack- to grainstones with rare megalodons and few corals, The Members A and B of the classical Lofer cycle are widespread missing.

Typical for this outcrop is *Coptocampylodon*? *rhaeticus* SCHLAGINTWEIT, MISSONI & GAWLICK. The type locality of *Coptocampylodon*? *rhaeticus* is located 3 kilometres west of Pass Lueg on Mount Kehlstein.

Gosau lake (optional)

Dachstein reef margin (Late Norian to Early Rhaetian).

This outcrop respectively the transect is described by RICHOZ et al. (2012). The succession around Gosausee (lake) provides insights in an intact microbial-sponge-coral barrier reef. We will visit the fore-slope facies as well as the reefal framework along and northeast of the Gosaussee, following the excursion route described by RICHOZ et al. (2012). This outcrop is optional and will be probably visited during the symposium Field trip.

2.3 Late Jurassic to Early Cretaceous

Plassen Carbonate Platform evolution (Late Oxfordian to Berriasian).

In the Early and Middle Jurassic no shallow-water carbonates were deposited in the northwestern Neotethyan realm. After the drowning of the Hauptdolomit/Dachstein Carbonate Platform red nodular or grey cherty limestones are the characteristic sediments in this realm.

After the Middle Jurassic to Oxfordian orogenesis a new shallow-water cycle starts in the latest Oxfordian (AUER et al., 2009). Since that time the Plassen Carbonate Platform, which consists of several - at least three- independent platforms evolved on the rising nappe fronts (for details see GAWLICK et al., 2009, 2012). These platforms differ in parts in their geometries, sedimentological evolution, subsidence history and faunal and floral content. As a consequence of this, the distribution of e.g. dasycladalean algae within the Plassen Carbonate Platform is not homogenous but shows several peculiarities (details in SCHLAGINTWEIT, 2011).

Mount Plassen

Plassen Carbonate Platform *s. str.* Slope and platform facies (Kimmeridgian), open and closed lagoon (Tithonian).

Mount Plassen is the type-locality of several species descriptions ("stromatoporids", gastropods, foraminifera, coproliths, chaetitide) (details in SCHLAGINTWEIT et al., 2005). The different facies belts preserved on Mount Plassen provide an opportunity to visit the maximum a faunal and floral inventory of the whole Plassen Carbonate Platform evolution (GAWLICK & SCHLAGINTWEIT, 2006).

We will visit the southwestern respectively the southern wall of Mount Plassen where the complete Kimmeridgian to Tithonian sequence is preserved (Fig. 8). The stratigraphically oldest part of the sequence consists of Kimmeridgian slope to reefal sediments, followed by Tithonian open and closed lagoonal limestones.

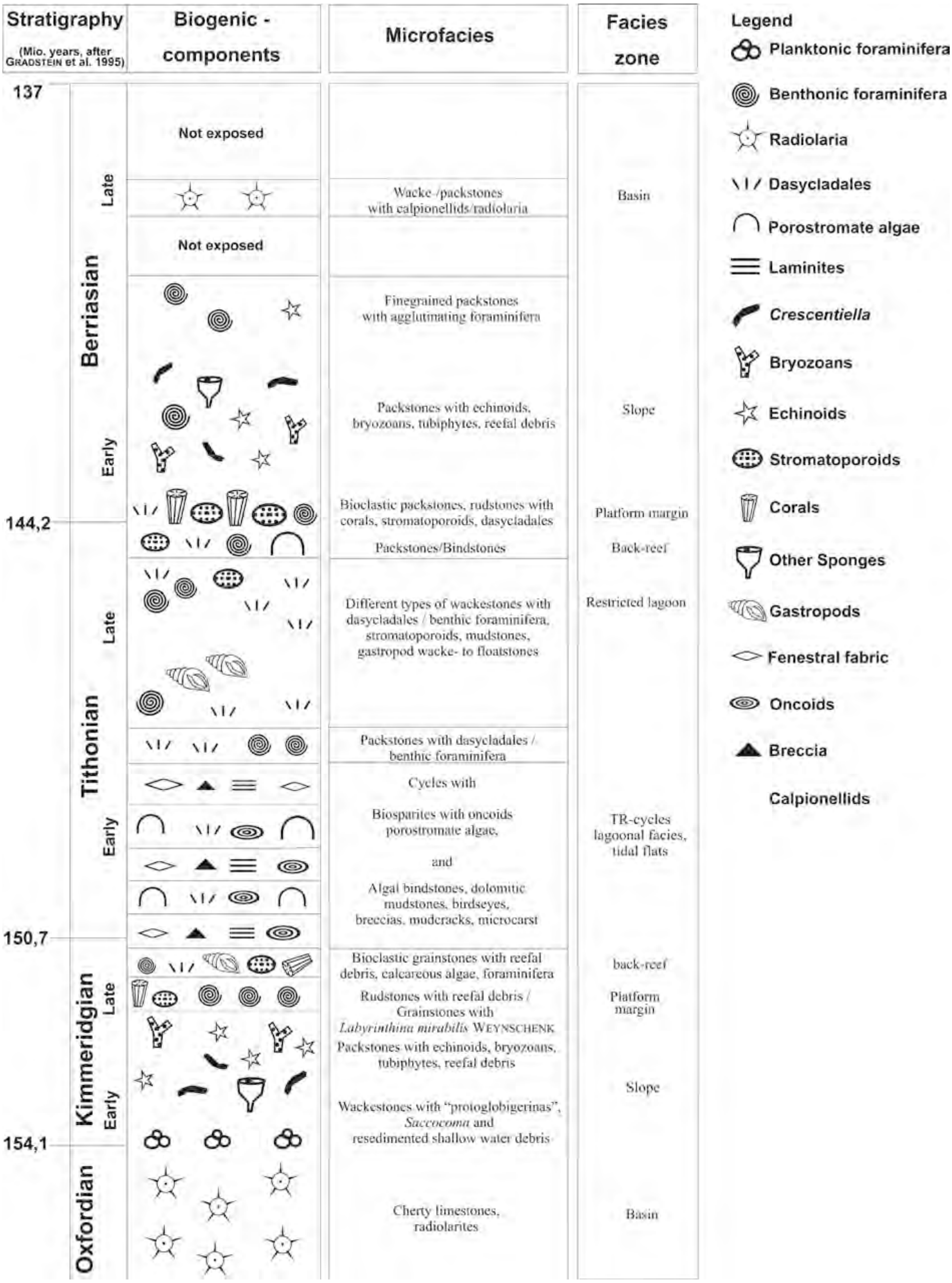

Figure 8: Sedimentary sequence of the Mount Plassen area (Oxfordian to Berriasian) after GAWLICK & SCHLAGINTWEIT (2006).

Loferer Kalvarienberg

Lärchberg Carbonate Platform. Tithonian to ?earliest Berriasian shallowing-upward cycle with final emersion.

As outstanding characteristic of the Lärchberg Carbonate Platform, in contrast to the Plassen Carbonate Platform *s. str.*, an overall terrigenous input can be stated. This and the occurrence of brackish-water influence in the latest platform stadium, pointing to a final emersion, are assumed as reasons for the discrete inventory of dasycladalean algae including 10 taxa not known from the Plassen Carbonate Platform *s. str.* (SCHLAGINTWEIT, 2011). A characteristic larger benthic foraminifer of the final series exhibiting increasing terrigeneous influx is represented by *Anchispirocyclina lusitanica* (EGGER). This foraminifer was already recognized by HAHN (1910) who described and illustrated the foraminifer as "Hydrocorallinen (?)stöckchen", meaning a stromatoporoid sponge. These strata are referred to as Lofer Beds, originally believed to represent basal, transgressive clastics sediments. In contrast, nowadays this succession is interpreted as deposit of a final coarsening- and shallowing-upward phase that finally led to platform emersion.

Mounts Barmsteine

Type-Locality: Resediments of the Plassen Carbonate Platform *s. str.* (Late Tithonian to Early Berriasian) intercalated in *Calpionella* Limestone.

Detailed description of the type locality in GAWLICK et al. (2005). The Barmstein Limestones (Fig. 9) represent various single mass-flow deposits, each with little varying component spectrum. These flows, partly containing clasts of radiolarites or *Saccocoma* Limestone probably deriving from the channel flanks, show minor variations only with respect to grain size and component spectrum. No other – older – clasts as Triassic Hallstatt Limestone clasts or clasts of the Permian Alpine Haselgebirge mélange were found at the type locality. In addition, turbiditic grainstone layers occur intercalated in the *Calpionella* Limestone (Oberalm Formation). For the genesis of the Barmstein Limestones, tectonic control mechanisms as well as possible sequence stratigraphic cyclicity are discussed (GAWLICK et al., 2005, 2009).

Figure 9: The Barmstein Limestone type-locality west of the township Hallein.

Gartenau: old Leube quarry

Barmstein Limestone with exotic clasts of the Permian Alpine Haselgebirge mélange (Late Tithonian)

In the old Leube quarry a series of coarse-grained Barmstein Limestones with components from the Plassen Carbonate Platform *s. str.* and the Alpine Haselgebirge melange and intercalated wackestones with radiolarians and Calpionellids will be visited (details in GAWLICK et al., 2005; Fig. 10)). The age of the series is Late Tithonian. This type of Barmstein Limestone represents the second type of Barmstein Limestones indicating a tectonic event in the Late Tithonian.

Figure 10: Mass-flow deposit (Barmstein Limestone) with shallow-water clasts from the Plassen Carbonate Platform *s. str.* and the Permian Alpine Haselgebirge mélange.

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Excursion B1: Cross section from the Austroalpine nappes to the Penninic and Subpenninic nappes of the Tauern Window

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The topic of this field trip is to visit and understand the structure of the Austroalpine nappes east of the Tauern Window, and the structure of Penninic and Subpenninic nappes within the Tauern Window. The Tauern Window exposes exhumed parts of Europe-derived crust that were accreted to the base of an Adria-derived upper plate, represented today by the Austroalpine nappes.This excursion will provide a cross section from the Austroalpine nappes east of the Tauern Window across the Eastern margin of the Tauern Window (Katschberg fault) into the central parts of the eastern Tauern Window.

The excursion will start and end in Schladming. Accomdation will be in Gmünd (travel time from Schladming approximately 45 minutes).

Day 1

Guided by: Walter Kurz, Harald Fritz & Kurt Krenn

Day one will cover the Austroalpine nappe system east of the Tauern Window. At good weather conditions a walking tour with a complete cross section from the Bundschuh Complex to the Gurktal nappe system is planned. Alternative exposures can be visited by bus travel along the road across the Nockberge.

Figure 1: Pre-Alpine basement of the Bundschuh Complex (left), overlain by Triassic low-grade metamorphic dolomites (Stangalm Mesozoic unit) (right).

The Austroalpine nappes in the field trip area comprise from bottom to top (Fig. 2):

1) The Bundschuh nappe system: pre-Alpine metamorphic basement (paragneisses, orthogneisses, metapelites) (Bundschuh Complex), overlain by a Permian to Triassic cover (meta-conglomerates, quartzites, dolomites) (Stangalm Meszoic unit). The sedimentary contact is tectonically reactivated by a low-angle normal fault (Fig.2).
2) The Gurktal nappe system:

a. The Phyllonite Zone: strongly retrogressed phyllites, overlain by Paleozoic carbonates. This unit was interpreted Tollmann as the base of the Upper Austroalpine nappe system. The phyllonites, however, now mark a low-angle detachment, related to Late Cretaceous extension.
b. The Pfannock slice: this unit comprises a pre-Alpine basement of orthogneisses (Pfannock Gneiss), covered by a partly inverted sequence of Carboniferous and Permian conglomerates, Permian to Triassic sandstones (Werfen Formation), and Triassic (Anisian to Carnian) carbonates.
c. The Gurktal nappe s.str. (including a lower Murau Nappe and a higher Stolzalpe Nappe): in the field trip area, this unit consists of Palaeozoic phyllites, greenschists and dolomites.

This cross section provides an overview of the structure of the upper part of the Bundschuh nappe, and the structure of the Gurktal nappe system. This section is a key area for the understanding of the Eo-Alpine history of the Austroalpine unit. It is under discussion for a long time and was one major argument for the subdivision of the Austroalpine by TOLLMANN (1977).

The **Bundschuh Complex** is overlying the Radenthein Complex with an Eo-Alpine thrust contact (SCHUSTER & FRANK, 2000). Its lower part consists of fine-grained paragneisses with some intercalations of felsic biotite-free orthogneisses and amphibolites (Priedröf paragneisses, Bundschuh orthogneisses). Micaschists and interlayered amphibolites are restricted to the uppermost part of the unit in the center of a large scale gentle syncline structure. The Priedröf paragneisses contain a mineral assemblage of garnet + biotite + plagioclase (albite and oligoclase) + muscovite + quartz. In the micaschists additional staurolite and pseudomorphs after staurolite (rarely containing chloritoid) may be present. Garnets are very characteristic in the whole unit. In the paragneisses they have an average grain-size of less than 0.5 mm, whereas in the micaschists they are up to 2 cm in diameter. Optically an inclusion-rich, often idiomorphic core can clearly be distinguished from an inclusion-free rim. The cores are compositionally homogenous with low CaO contents of 3-5 wt%. Their age is presumed to be Variscan, because Variscan Rb-Sr ages (c. 350 Ma) were determined on muscovites of orthogneisses from the uppermost part of the unit (FRIMMEL, 1986). In the rim the CaO content is much higher (6-8 wt%), FeO, MgO and also XMg is lower. Based on the regional metamorphic history this garnet generation is eo-Alpine in age. Eo-Alpine metamorphic conditions reached up to 600 °C and 10 kbar in the lowermost parts in the south and greenschist facies conditions below the transgressive Mesozoic unit.

The Bundschuh Complex is overlain by a Permian to Triassic metasedimentary sequence, known as the Stangalm Mesozoic. The **Mesozoic Stangalm Unit** is unconformalbly transgressing onto the pre-Alpine syncline structure. The lowermost part consists of Permian to Early Triassic quarzites. Above Anisian carbonates and Carnian phyllitic schists are preserved (TOLLMANN, 1977). A phyllonite horizon (Phyllonite Zone), composed of highly sheared Paleozoic and Mesozoic rocks marks the border to the overlying Pfannock slice. The Pfannock orthogneiss, which is very similar to the Bundschuh orthogneisses (FRIMMEL, 1988) forms the stratigraphically deepest part. It is transgressed by Permian to Carboniferous clastic sediments. Continuing Mesozoic carbonates and schists reach up to the Rhaetian Kössen Formation. The sediments show a lower greenschist facies metamorphic imprint.

The uppermost tectonic unit is the **Gurktal nappe system**. The latter comprises clastic metasediments with some intercalations of carbonates and metatuffitic layers, which were deposited in Lower Palaezoic times. During the Variscan tectonothermal event they experienced a greenschist facies metamorphic imprint. After that Carboniferous sediments of an intramontane basin (KRAINER, 1993) and Permo-Mesozoic sediment were deposited on top. During the eo-Alpine event the whole sequence suffered anchizonal to lower greenschist facies metamorphic conditions.

A tectonostratigraphic section including the Bundschuh Complex, the Stangalm Mesozoic, the Phyllonite zone, the Pfannock slice and the base of the Gurktal nappe is exposed in the area around the Erlacher Hütte (1636 m) (46°52'10"N; 13°44'55"E) (Figs. 2, 3).

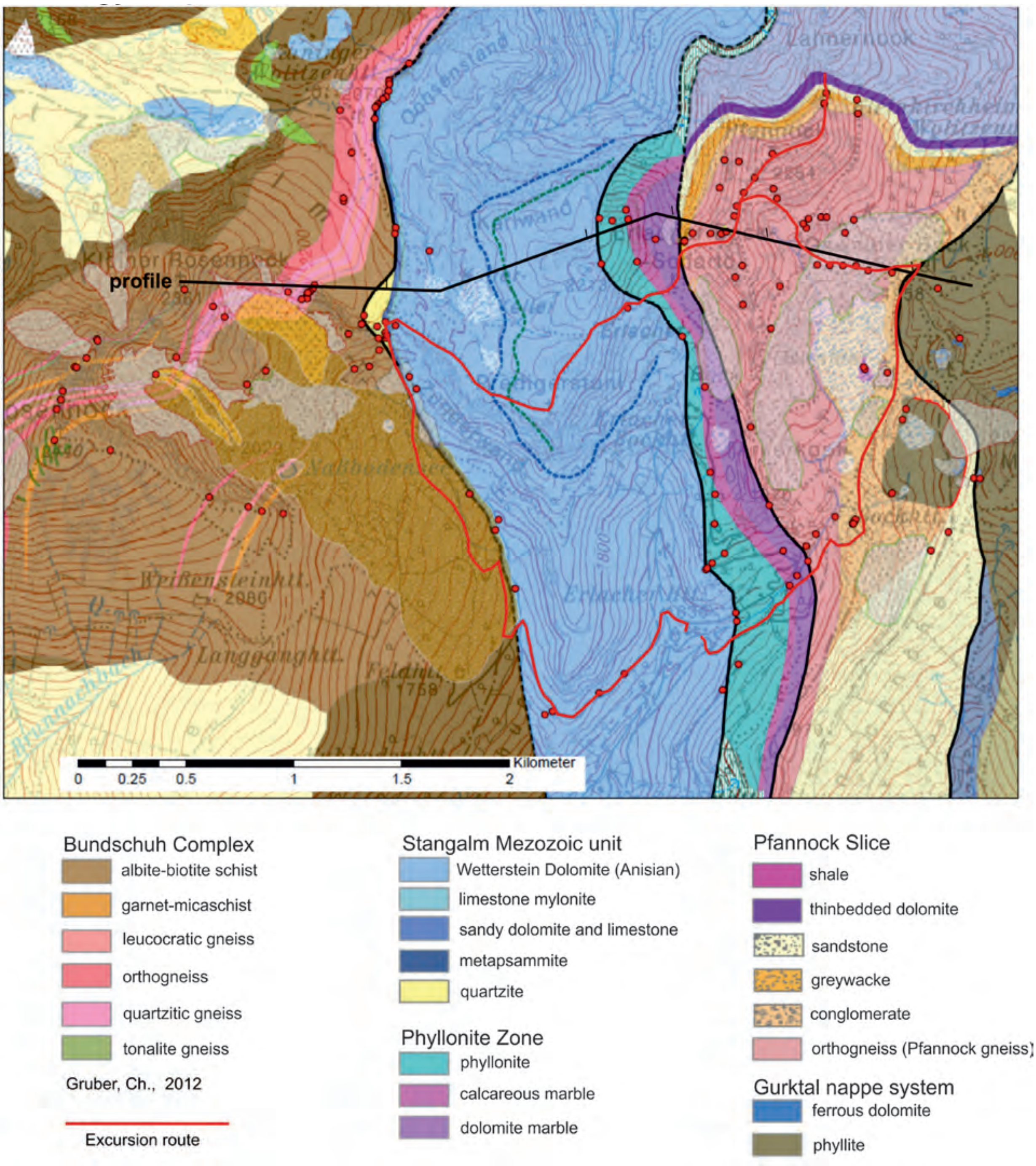


Figure 2: Geological map of the Nockberge area around the Erlacher Hütte. B1 field trip (day 1) is indicated.

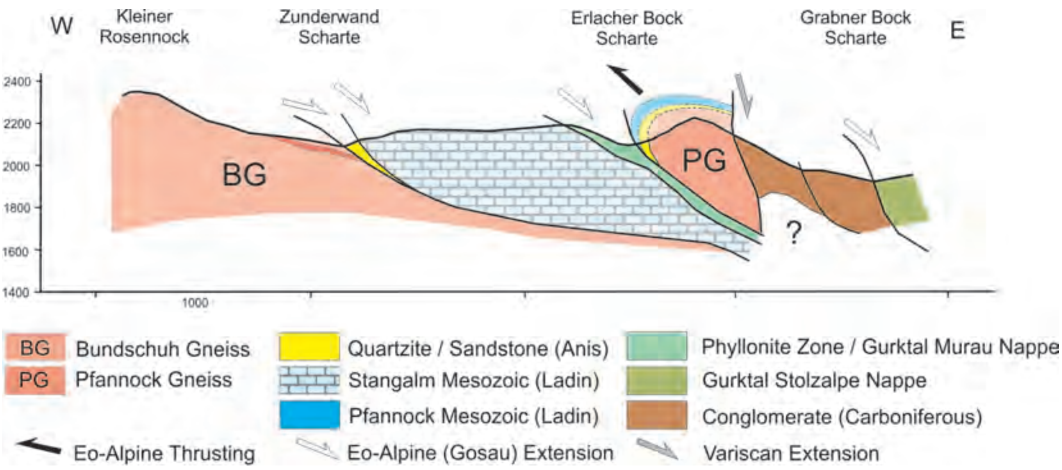


Figure 3: Geological and tectonic sketch profile of the Nockberge area around the Erlacher Hütte. For profile section see Fig. 2.

Stop 1 – Contact between the Bundschuh Complex basement and the Stangalm Mesozoic unit

The contact between the Bundschuh Complex basement and the Stangalm Mesozoic unit (Fig. 1) is exposed along the Zunderwand northwest of the Erlacher Hütte, and in the col between the Kleiner Rosennock (2361 m) and the Predigerstuhl (46°52'54"N; 13°43'53"E). The Bundschuh basement at this site mainly consists of dark micaschist and micaschists with albite blasts with a well developed penetrative foliation dipping towards the southeast (Fig. 4). This foliation is crosscut by multiple sets of shear bands, partly forming an extensional crenulation cleavage, indicating a top-to-the-east sense of shear.

The Stangalm Mesozoic unit comprises coarse-grained metaconglomerates and quartzites at the base, overlain by medium grey to dark, bedded dolomites with detritic flakes of white mica, and light grey to pink dolomite marbles, representing an equivalent of the Anisian Wetterstein Formation (Fig. 5). The metaconglomerate pebbles are highly elongated parallel to the stretching lineation, which is plunging towards the ESE. Generally, sense of shear is top-to-the-east and strain within the metaconglomerates shows a flattening geometry.

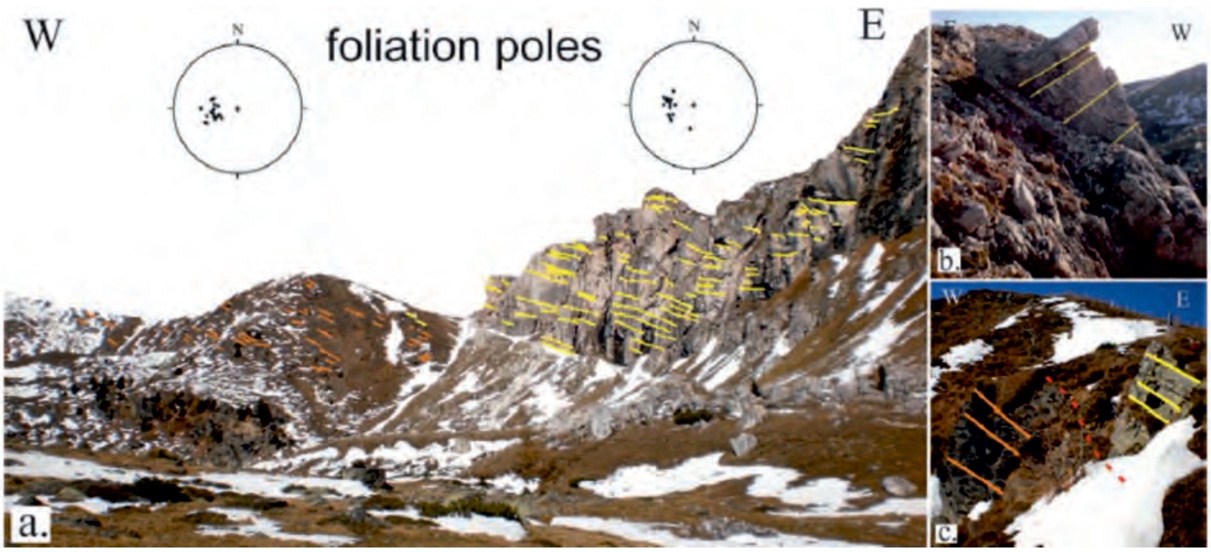


Figure 4: a - Panoramic view of the site exposing the contact between the lower Bundschuh complex basement (left) and the Stangalm Meszoic unit (right). b – Detailed view of the bedding within the Stangalm Mesozoic unit. c – Eastward dipping foliation within the Bundschuh complex basement.

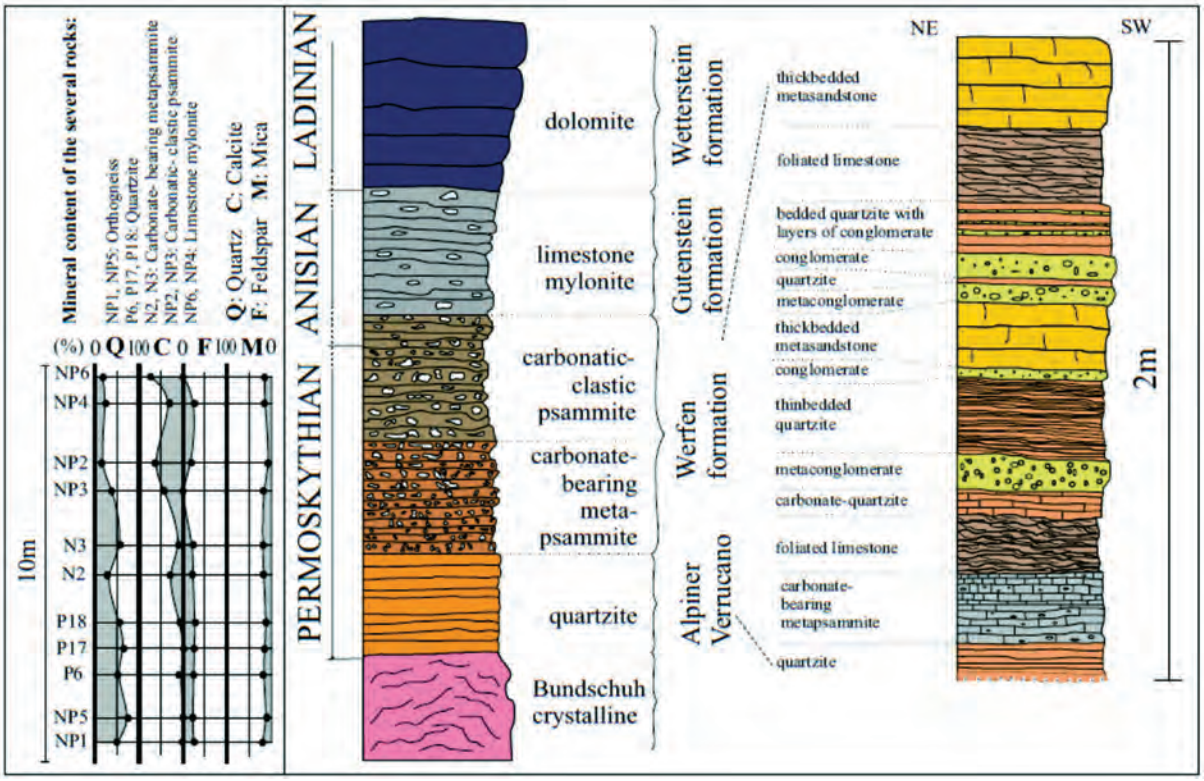


Figure 5: Columnar lithostratigraphic section of the upper part of the Bundschuh complex basement and its sedimentary cover.

Stop 2 – Phyllonite Zone and base of Pfannock Gneiss

Erlacher Bockscharte (46°52'58"N; 13°44'54"E)

The Stangalm Mesozoic unit is bound from the Pfannock slice above by the Phyllonite Zone. According to VON GOSEN et al. (1987), the Phyllonite Zone represents the basement of the Murau Nappe as part of the Gurktal nappe system, which is mostly built up by lower- and upper Palaeozoic meta-sediments.

The matrix of the phyllites is mainly built up by quartz. In some domains plagioclase (albite) is also very dominant and defines an important component of the middle- to fine-grained matrix. In most cases the amount of quartz reaches more than 70 percent. Muscovite and subordinate chlorite are the secondary components. The Phyllonite Zone shows indication for very strong tectonic as well as metamorphic overprint at greenschist facies metamorphic conditions. Macroscopic quartz layers of several decimeter thickness are not rare and a penetrative foliation as well as isoclinal folds are very charactertistic features for this unit, too. The penetrative foliation dips with a mean angle of 78° to the east (Fig. 6). The penetrative foliation is crosscut by single sets shear bands dipping towards ESE, which indicate a top-to-the ESE sense of shear. Locally, multiple sets of these shear bands form an extensional crenulation cleavage.The phyllonites are overlain by a sequence of carbonates, mainly lower Paleozoic (Devonian) cherty calcite marbles and radiolarian bearing calcite marbles.

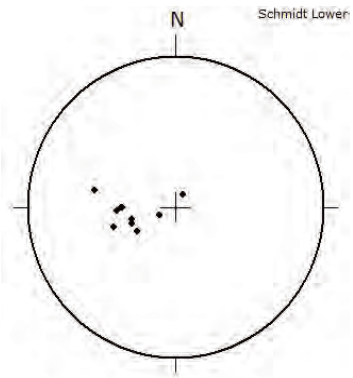


Figure 6: Equal area projections of penetrative foliation orientation data within the Phyllonite Zone.

Stop 3 – Pfannock Gneiss and Carboniferous to Triassic cover

Pfannock (2254 m) (46°53’16”N; 13°45’14”E)

ridge from Pfannock towards northeast; Lahnernock (46°53’31”N; 13°45’28”E).

This site exposes the lithostratigraphic sequence of the Pfannock slice, with the Pfannock gneiss basement, and a Carboniferous to Triassic cover sequence. According to FRIMMEL (1988), the Pfannock gneiss and the orthogneisses within the Bundschuh complex are quite similar. The protolith is classified as granite. The geochemical signatures give evidence for a S-type-granite without a trend of differentiation. Actually these granites are interpreted syn- to postcollision granites, but could also part of a volcanic arc part setting.

At its base the Pfannock gneiss is strongly overprinted by cataclastic deformation. This makes it, in some exposures, hard to distinguish from the Carboniferous metaconglomerates forming the base of the cover sequences.

The metaconglomerates of the Pfannock slice have a red Fe-rich matrix, which includes quartz and feldspar, as well as mica flakes. Quartz is poly- as well as monocrystalline. The clasts are poorly rounded, implying a short distance of transportation. In some domains the red matrix gets relieved by a sericite-quartz-matrix. According to KRAINER (1984) these conglomerates are deposited in a fluviatile environment. Clasts derived mainly from the nearby Pfannock gneiss (Fig. 7) but include also components from the Gurktal Nappe System.

Figure 7: Fabric variation of Carboniferous clastic sediments. Sediments formed by progressive disintegration of Pfannock gneiss and nearby deposition.

Along the ridge from the Pfannock to the Lahnernock an almost complete lithostratigraphic section from the Upper Carboniferous to the Lower Triassic is exposed (Fig. 8). The complete section is inverted due to recumbent folding related to the emplacement of the Pfannock slice during Alpine nappe stacking (Fig. 3). Beside the Carboniferous conglomerates, this succession comprises red clastics, mainly build up of coarse grained breccias to conglomerates. Along this section the thickness of these beds makes up approximately 50 meters. These clastics are generally assumed to be of Permian age. These clastics grade into the Werfen Formation (Skythian), mainly consisting of red sandstones. Beds thickness vary from a few meters to about 20 meters. Thin bedded dolomites and dolomite schists build up the Pfannock beds. At its base, the dark, thin bedded dolomites may contain sandy layers of quartz and detrital white mica. The dolomite schists may also contain calcitic layers. The Pfannock beds are generally assumed to be of Lower Anisian age. These are stratigraphically overlain by massive, light grey dolomites (Wetterstein formation; Anisian to Ladinian), building of the slope towards the Lahnernock.

Farther towards north, this iverted sequence additionally comprises sandy schists as equivalent to the Raibl formation (Carnian), cherty dolomites (Upper Carnian), Norian dolomites (Hauptdolomit formation) and Plattenkalk, as well as Rhaetian limestones and marls (Kössen Formation).

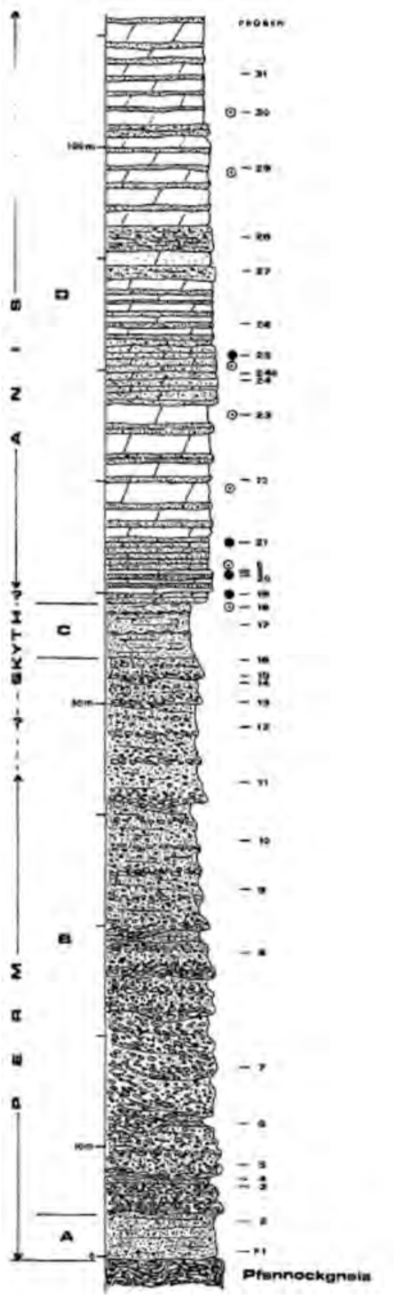


Figure 8: Columnar lithostratigraphic section of the Permian to Lower Triassic sequence at the ridge from the Pfannock to Lahnernock (after KRAINER, 1984).

The history of the **Gurktal nappe system** indicates that it was part of the eo-Alpine tectonic upper plate (SCHMID et al., 2004). It shows an upward decrease of the eo-Alpine metamorphic grade until reaching diagenetic conditions in the Permo-Mesozoic sediments at the top, indicating that it has not been buried since Permian times. It was affected by W-directed thrusting in the Lower Cretaceous (FRITZ, 1988; DALLMEYER et al., 1998), whereas in the Upper Cretaceous it was affected by ductile extensional deformation and normal faulting (NEUBAUER et al., 1995), as for the upper part of the Koralpe-Wölz nappe system. The extensional deformation led to the formation of basins (Kainach, Krappfeld, St. Paul) and the deposition of the Gosau Group sediments, which are Santonian to Paleogene in age (e.g. EBNER & RANTITSCH, 2000). The formation of these sedimentary basins is also linked to the rapid exhumation of the eclogite bearing unit (KURZ & FRITZ, 2003).

The tectonometamorphic evolution of the Austroalpine nappes along this section comprises pre-Alpine high grade metamorphism at upper greenschist to amphibolite facies condition within the Bundschuh Complex. The penetrative foliation is assumed to have formed during a pre-Alpine deformation event, as the foliation and folds within the Bundschuh Complex are discordantly overlain by the low-grade metamorphic sedimentary sequences of the Stangalm Mesozoic unit. The primary contact, however, was strongly overprinted during Alpine nappe stacking (early Cretaceous) and subsequent late Cretaceous extension. Nappe stacking related structures are strongly overprinted by extensional fabrics, especially along former thrusts. Extensional structures are mainly related to top-to-the SE to ESE shearing at low-grade metamorphic conditions and mainly affect the Phyllonite horizon and the base of the Gurktal nappe system.

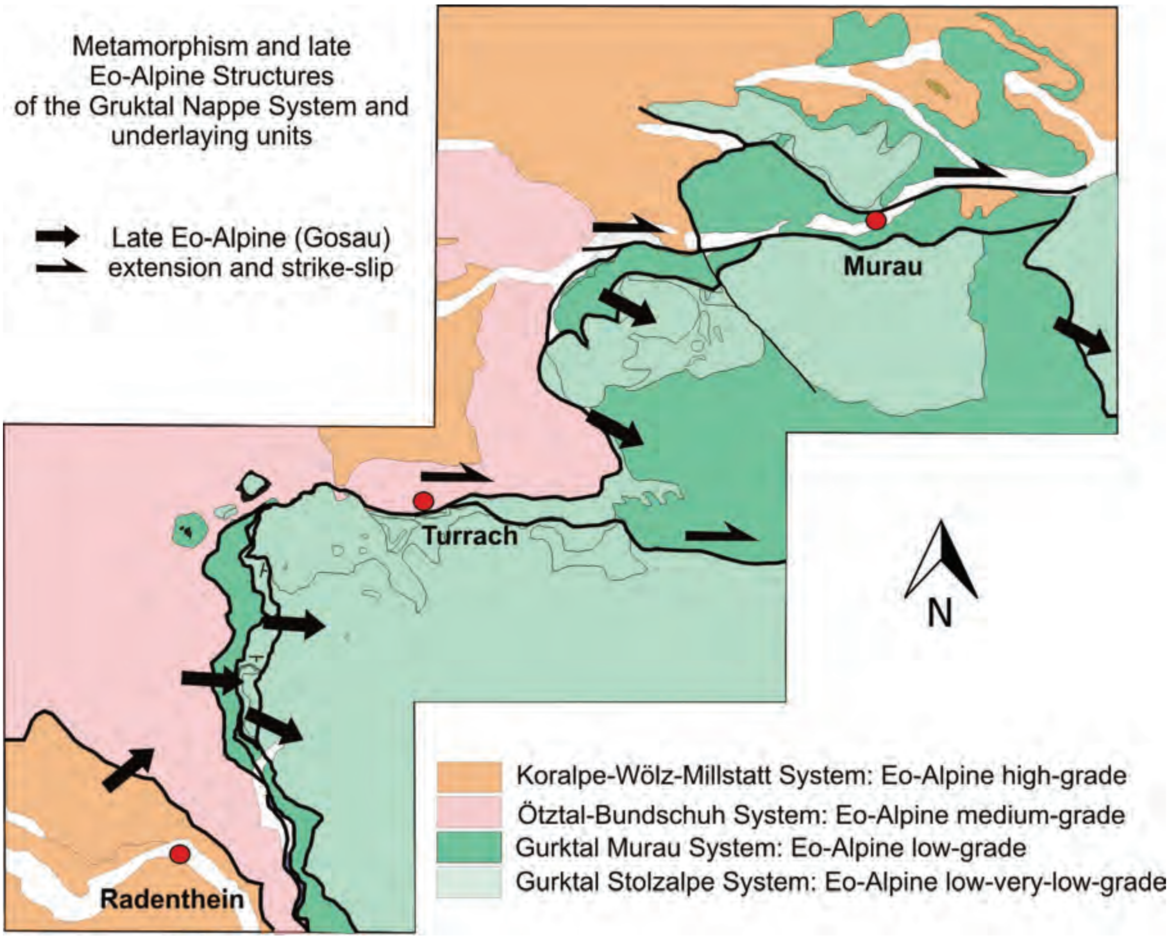


Figure 9: Overall geometry of late Eo-Alpine (Gosauic) strike-slip and extensional structures at the base of the Gurktal nappe system. Mention staircase geometry as result of extensional bridges linking strike-slip domains.

Recumbent, isoclinal folding within the Pfannock slice is interpreted to be related to the detachment of the main part of the Permian to Triassic sequence along the contact to the coarse grained Carboniferous metaconglomerates. This resulted in thickening of the stratigraphic succession in the fold hinge and the inverted limb of the recumbent fold.

In general, structural studies along the tectonic boundaries boundary display a complex Alpine tectonic evolution (Figs. 3, 9). (1) The contact between the Pfannock Gneiss and the Carboniferous conglomerates is interpreted as late-Carboniferous cataclastic fault zone that formed in the course of exhumation of the basement and coeval deposition of Carboniferous sediments. Cataclastic pebbles are present within the Carboniferous sediments and suggest exhumation prior to deposition of rocks. The pre-Carboniferous fault can be traced all along the eastern and southern margin oft he Pfannock Gneiss. (2) The Pfannock slice includes an inverted suite of Permian to Mesozoic sediments. It is interpreted as a tectonic sliver with the Pfannock Gneiss in the core of a northwest vergent fold. Shearing and folding is correlated with Cretaceous northwestward nappe stacking. (3) The actual geometry of the boundary is result of bulk extension during the late Cretaceous. Extensional structures with E- to SE displacement dominate N-S trending segments, dextral strike-slip zone the W-E trending segments. The overall geometry can be described by eastward spreading units with normal faults forming extensional bridges between strike-slip domains (Fig. 1.9).

Day 2

Guided by: Mark R. Handy, Silvia Favaro & Andreas Scharf

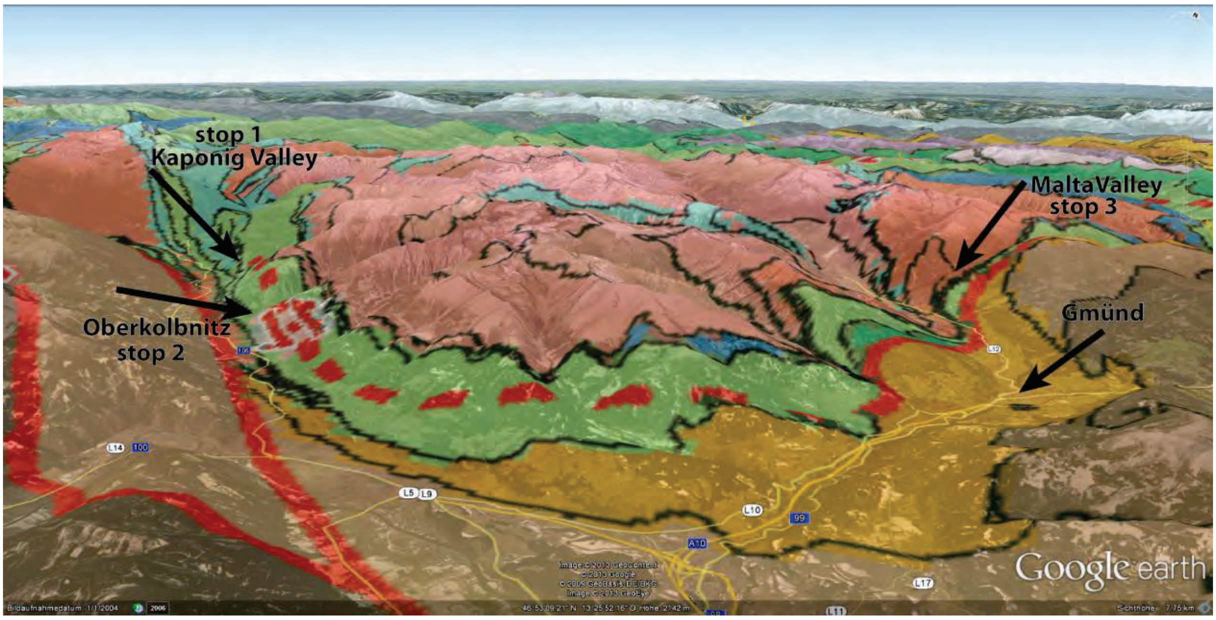


Figure 10: Google Earth image with superposed tectonic map of the southeastern end of the Tauern Window as viewed to the NNW. Black arrows indicate the stops described below and show the town of Gmünd, where we will spend a night. Symbols as in the tectonic map of the Tauern Window (Fig. 11, 27).

Introduction

The Tauern Window and adjacent areas in the Eastern Alps (Fig. 11a) expose a nappe stack that formed during the convergence of the Adriatic and European plates in Late Cretaceous to Cenozoic time (e.g., TRÜMPY, 1980; SCHMID et al., 2004). From top to bottom, this nappe stack comprises Adria- derived (Austroalpine), oceanic (Penninic units = Matrei Zone, Glockner Nappe System) and Europe- derived (Modereck Nappe System, Venediger Nappe System with its Subpenninic units) crustal slices that were sheared, multiply folded and exhumed in Oligocene to Miocene time (Fig. 11; e.g., KURZ et al., 2008; SCHMID et al., 2013). In contrast, the Austroalpine units were affected by Late Cretaceous deformation and metamorphism (e.g., HOINKES et al., 1999; FROITZHEIM et al., 1994; VILLA et al., 2000; SCHUSTER, 2003) before being thrust onto the Penninic units. Crustal accretion (D1) leading to nappe stacking (D2) below the Austroalpine units occurred primarily in Palaeogene to Eocene time and culminated in high-pressure metamorphism and later folding (D3) of

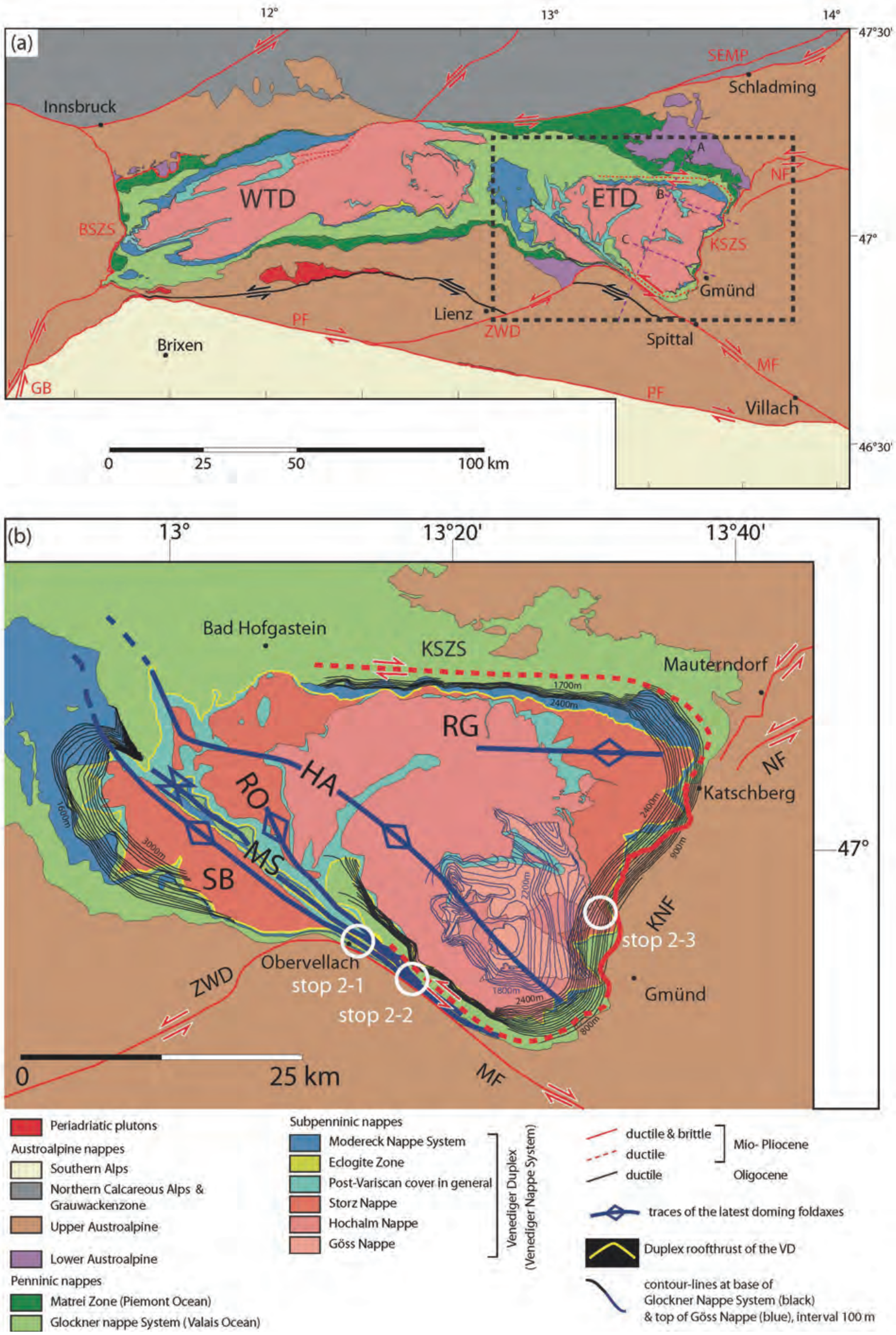

(a)
12°
13°
14°
47°30'
47°
46°30'
Innsbruck
Schladming
SEMP
WTD
ETD
A
B
C
NF
BSZS
KSZS
Gmünd
Lienz
ZWD
PF
Spittal
Brixen
MF
GB
Villach
0
25
50
100 km
(b)
13°
13°20'
13°40'
47°
Bad Hofgastein
KSZS
Mauterndorf
1700m
2400m
RG
NF
Katschberg
HA
RO
MS
SB
KNF
stop 2-3
Obervellach
stop 2-1
stop 2-2
Gmünd
ZWD
MF
0
25 km
Periadriatic plutons
Austroalpine nappes
Southern Alps
Northern Calcareous Alps & Grauwackenzone
Upper Austroalpine
Lower Austroalpine
Penninic nappes
Matrei Zone (Piemont Ocean)
Glockner nappe System (Valais Ocean)
Subpenninic nappes
Modereck Nappe System
Eclogite Zone
Post-Variscan cover in general
Storz Nappe
Hochalm Nappe
Göss Nappe
Venediger Duplex (Venediger Nappe System)
ductile & brittle
ductile
ductile
Mio- Pliocene
Oligocene
traces of the latest doming foldaxes
Duplex roofthrust of the VD
contour-lines at base of Glockner Nappe System (black) & top of Göss Nappe (blue), interval 100 m

Figure 11 (previous page)**:**
(a) Tectonic map of the Tauern Window; dotted box shows location of Fig. 11b. BSZS – Brenner Shear Zone System; GB – Guidicarie Belt; KSZS – Katschberg Shear Zone System including the Katschberg Normal Fault (KNF) along its central part; MF – Mölltal Fault; NF – Niedere Tauern Southern Fault; PF – Periadriatic Fault; SEMP – Salzach-Ennstal-Mariazell-Puchberg Fault; ZWD – Zwischenbergen-Wöllatratten-Drau Fault. ETD Eastern Tauern Subdome; WTD – Western Tauern Subdome. Purple dotted lines (A-C) mark the trace of cross-sections in Fig. 2.3.
(b) Tectonic map of the eastern Tauern Window showing location of the three stops. White lines delimit the upper and lower limit of Katschberg-related shearing (maps from SCHARF et al., 2013). Structure of the Eastern Tauern Subdome: (a) Contours: black - basal thrust of the Glockner Nappe System, blue - top of the Göss Nappe within the Venediger Nappe System; Post-nappe folds and dome axes: HA - Hochalm Dome; RG - Rotgülden Dome; RO - Romate Fold; SB - Sonnblick Dome; MS - Mallnitz Synform.

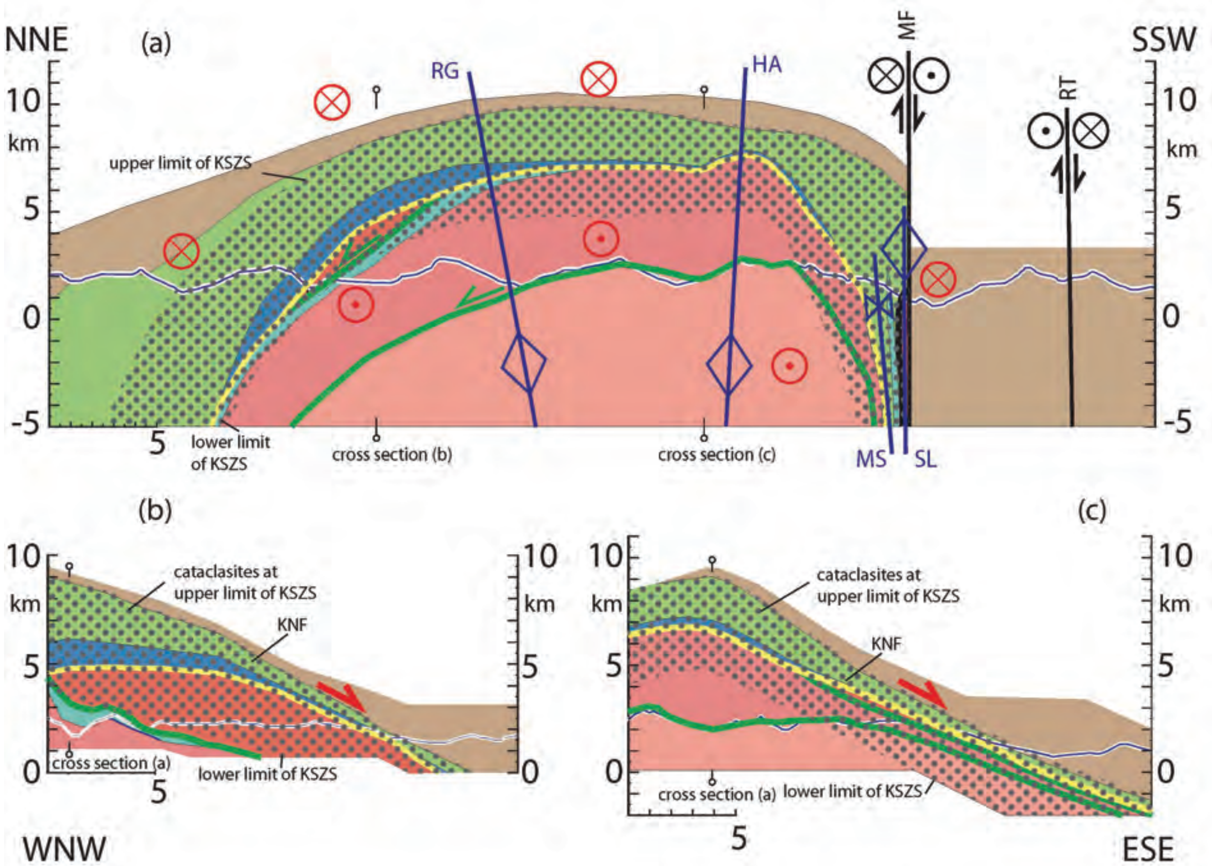


Figure 12: Cross sections across the easternmost Tauern Window corresponding to profile traces in Fig. 11a. Legend as in Fig. 11:
(a) Section perpendicular to the Katschberg transport direction and crossing the northern and southern branches of the KSZS that bound the Hochalm- (HA) and Rotgülden (RG) domes. These domes deformed the underlying Venediger Nappe System. Other structures include the Mallnitz Synform (MS), Sonnblick Gneiss Lamellae (SL), Mölltal Fault (MF) and the Ragga-Teuchl Fault (RT);
(b) and (c): Cross sections parallel to the ESE transport direction of the KSZS and perpendicular to the KNF, respectively. Grey stippled pattern indicates Katschberg mylonitic shearing; the mylonite belt along the KNF is capped by cataclasites. Green lines are nappe contacts within the Venediger Nappe System; yellow line marks the roof thrust. Major nappe contacts and fault boundaries were constructed with the aid of structural contour maps.

Penninic nappes exposed in the central part of the Tauern Window (e.g., KURZ et al., 2008). The age of this high-pressure metamorphism is controversial, with Eocene (RATSCHBACHER et al., 2004) and Oligocene ages (GLODNEY et al., 2005; NAGEL et al., 2013) proposed so far. The main accretion of Europe-derived nappes occurred in Late Eocene to

Oligocene time (D4) followed by Miocene folding, exhumation and orogen-parallel extension (D5, Figs. 12 & 13; e.g., SCHMID et al., 2013).

Exhumation is greatest at the western and eastern ends of the Tauern Window, where basement rocks with Barrow-type, greenschist- to amphibolite-facies rocks are exposed in the cores of upright D5 folds and domes (Eastern- and Western Tauern subdomes in Fig. 11a). This thermal peak metamorphism, termed the "Tauernkristallisation" (SANDER, 1911), is marked by widespread static recrystallization and overprints all nappe systems, including the D4 Venediger Duplex (LAMMERER & WEGER, 1998; SCHMID et al., 2013) but is itself overprinted by mylonitic fabrics of the D5.

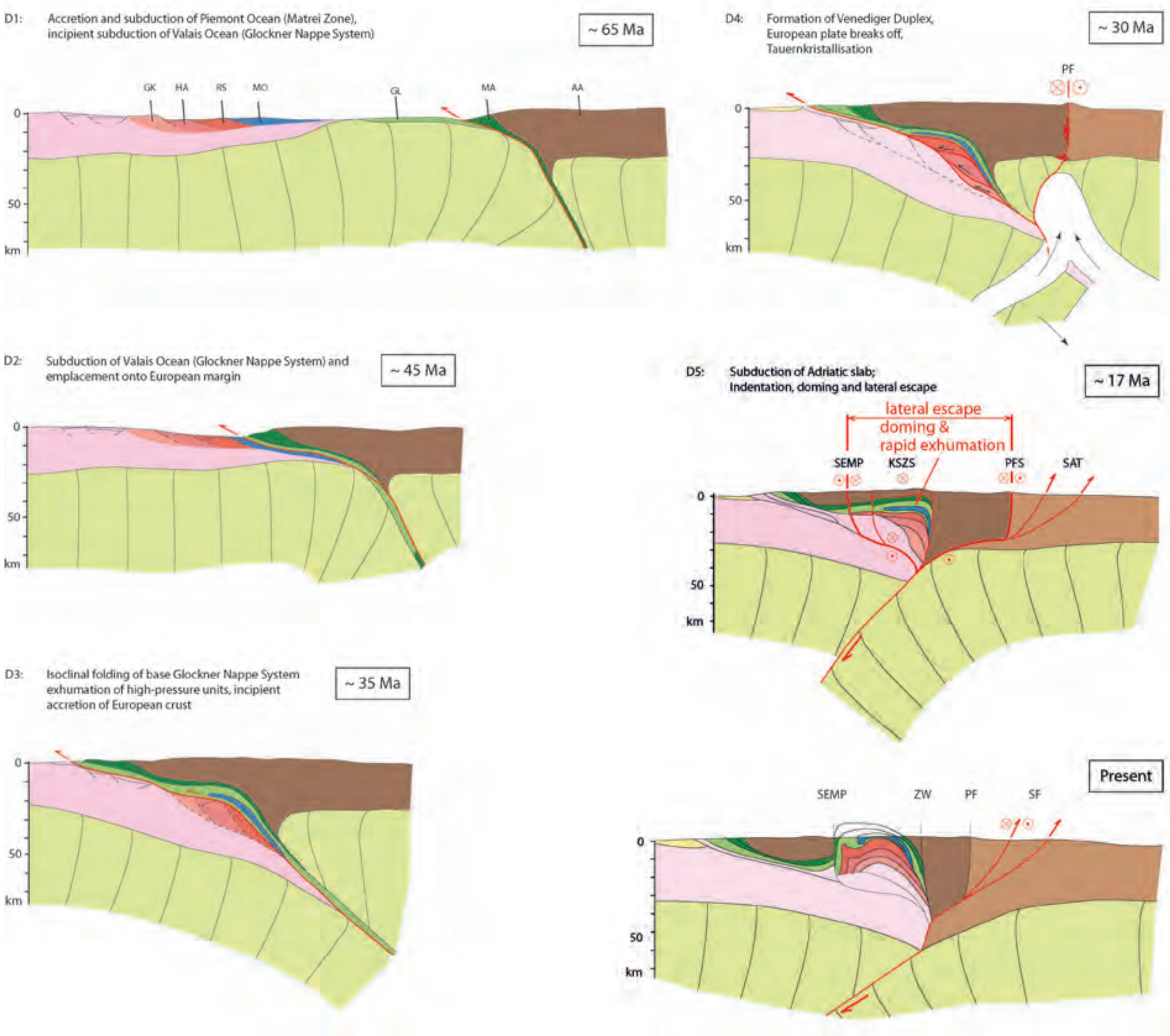


Figure 13: Sketches of illustrating the evolution in a north-south trending section through the eastern part of the Tauern Window (SCHMID et al., 2013). (a) D1 subduction of the Piemont-Liguria Ocean and accretion of oceanic relics in front of the Austroalpine nappe stack, ~ 65 Ma; (b) D2 subduction of the Valais Ocean and parts of the distal European margin, ~ 45 Ma; (c) D3 exhumation of the high-pressure units and incipient accretion of the European crust, ~ 35 Ma; (d) D4 formation of the Venediger Duplex and "Tauernkristallisation" at ~ 30 Ma. (e) D5 Indentation, doming and lateral extrusion, ~ 17 Ma; (f) Present-day section. Tectonic nappes: AA – Austroalpine units; GK – Göss Nappe; GL – Glockner Nappe System; HA – Hochalm Nappe; MA – Matrei Zone. MO – Modereck Nappe System; RS – Romate-Storz Nappe; SA – Southern Alps. Major Faults: KSZS – Katschberg Shear Zone System; PF – Periadriatic Fault; SEMP – Salzach-Ennstal-Mariazell-Puchberg Fault; SF – Sava Fault; ZW – Zwischenbergen-Wöllatratten Fault. Active faults are marking red and inactive faults are in black.

Brenner- and Katschberg shear zone systems at both ends of the Tauern Window. The age of the "Tauernkristallisation" is constrained to be somewhere in the range of 30-25 Ma (Rb/Sr on garnet- bearing assemblages, CHRISTENSEN et al., 1994; Rb/Sr white mica of VON BLANCKENBURG et al., 1989; KURZ et al., 2008; U-Pb allanite, CLIFF et al., 1998; INGER & CLIFF, 1994; Sm-Nd garnet isochron age of FAVARO et al., in prep.).

The Katschberg Shear Zone System (KSZS) at the eastern end of the Tauern Window is a belt of mylonites up to 5 km wide that separates the Penninic and Subpenninic units from the overlying Austroalpine nappes. The KSZS accommodated c. 26 km of east-directed orogen-parallel stretch in the Miocene (SCHARF et al., 2013; Fig. 11b). The central segment of the KSZS comprises the Katschberg Normal Fault (KNF, GENSER & NEUBAUER, 1989), whereas northern and southern branches are steeply dipping and accommodated dextral and sinistral strike-slip motion, respectively (Fig. 11b). These branches are interpreted as stretching faults in the sense of MEANS (1989) due to the decreasing amounts of displacement towards their western ends as inferred from the progressive weakening of their fabric toward the center of the Tauern Window (SCHARF et al., 2013).

Stop 1 – Kaponig Valley (N 46°56'33'' E 13°12'04'' Alt. 1100 m)

Directions: From Schladming follow the A10 to Spittal a. d. Drau. Few km before arriving at Spittal, turn west onto the A9. After 3 km the autobahns ends as the main road 106. Drive to Obervellach and turn right (north) to Mallnitz. After c. 1 km, turn right (first road after Obervellach), then follow this road until you reach the old train station, where we will park our cars (Fig. 14).

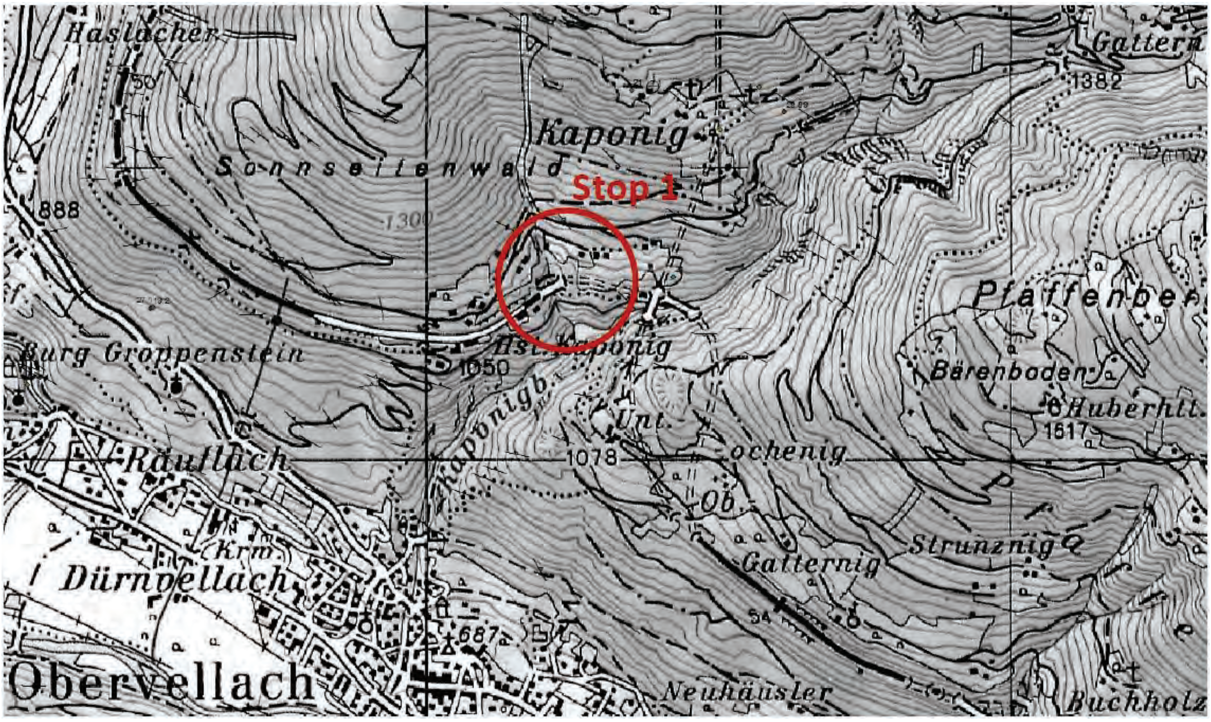


Figure 14: Location of Stop 1

In the Kaponig Valley, we observe the following sequence of folded nappes from left (south) to right (north) in Fig. 15: Sonnblick Nappe, Modereck Nappe System (MNS), Geißel Nappe belonging to the Glockner Nappe System, Modereck Nappe System, Kolm Nappe (also belonging to the Glockner Nappe System) and the Hochalm Nappe.

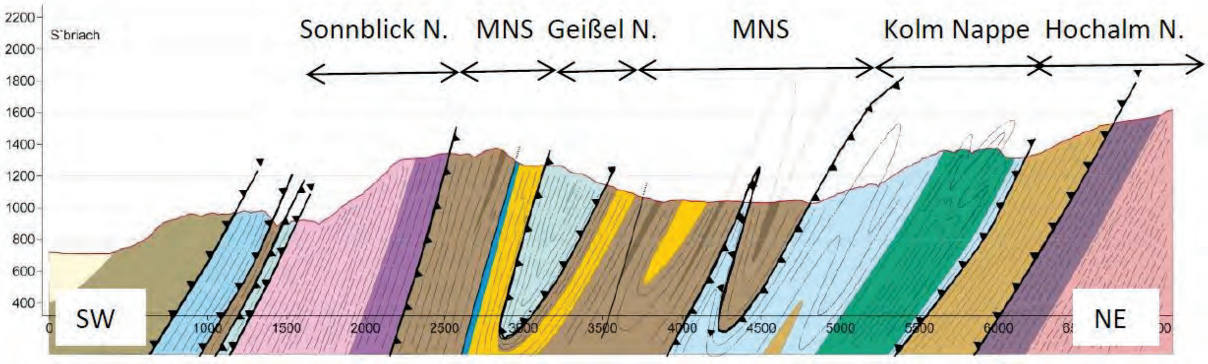


Figure 15: Profile 1 (trace and legend in Figure 26) near the Kaponig Valley: nappe sub-division

The Kolm Nappe is interpreted to be the lower subunits of the Glockner Nappe System. Its lithologies are gray - blue, thickly bedded, mica - bearing marble intercalated with dark, grayish to brownish calcareous mica schist of the "Bündnerschiefer Group" (PESTAL et al., 2009). Other large ophiolitic bodies contain prasinite, amphibolite and serpentinite. The Geißel Nappe is interpreted to be the upper unit of the Glockner Nappe System. It differs from the Kolm Nappe in nappe having no amphibolites and more stratified and finer-grained marbles.

The section in Fig. 16 crosses several D5 synforms and antiforms as well as the D3 antiform overlying the roof thrust of the Venediger Duplex. These structures were all highly sheared, mostly during D4 (in the east) and D5 (in the west) events. The internal part of the Mallnitz Synform is made up of Geißel Nappe in its core surrounded by the Modereck Nappe System on its limbs (Fig. 16).

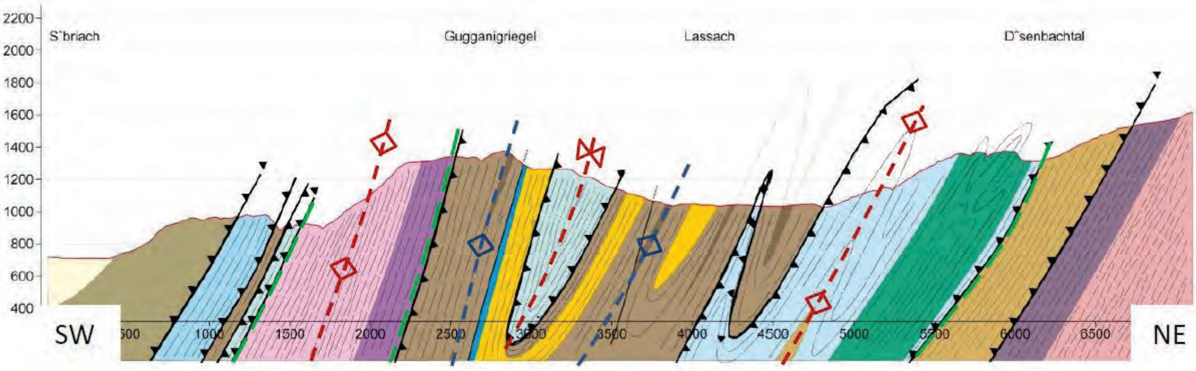


Figure 16: Profile 1 (trace and legend in Figure 26) near the Kaponig Valley: D5 folds marked in red, axial traces of D3 in blue, D4 roof thrust of the Venediger Duplex in green dashed lines.

A second D5 synform is developed at Auernig, near Mallnitz. This fold is open, with its hinge in the Kolm Nappe and its axial plane dipping parallel to that of the Mallintz Synform. The roof thrust of the Venediger Nappe System (Fig. 17) is a thin D5 shear zone at the base of the Kolm Nappe that also affects garnet and chloritoid-bearing schists of the Romate Nappe and schist of the Brennkogel Formation derived from the underlying Hochalm-Ankogel Nappe. A small D5 antiform located between the two synforms is located just west of Mallnitz (Fig. 17).

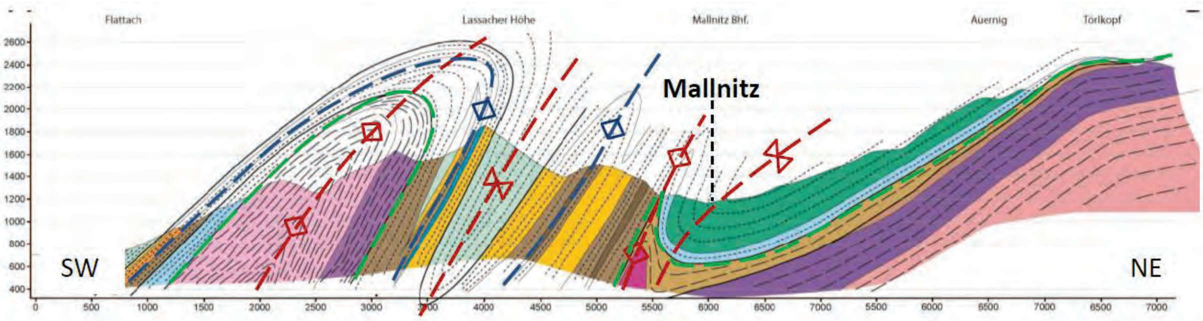


Figure 17: Profile 2 (trace and legend in Figure 26) near Mallnitz. D5 folds marked in red, axial traces of D3 (blue), D4 roof thrust of the Venediger Duplex (green).

Stop 2 (A) – Danielsberg (N 46°53'18'' E 13°16'51'' Alt. 966 m)

Directions: From Obervellach, head southeast on the main road 106. Then turn left onto a road just before Penk that leads to Preisdorf and follow it for a kilometer until you reach a little road on the right that leads to Danielsberg (Fig. 18).

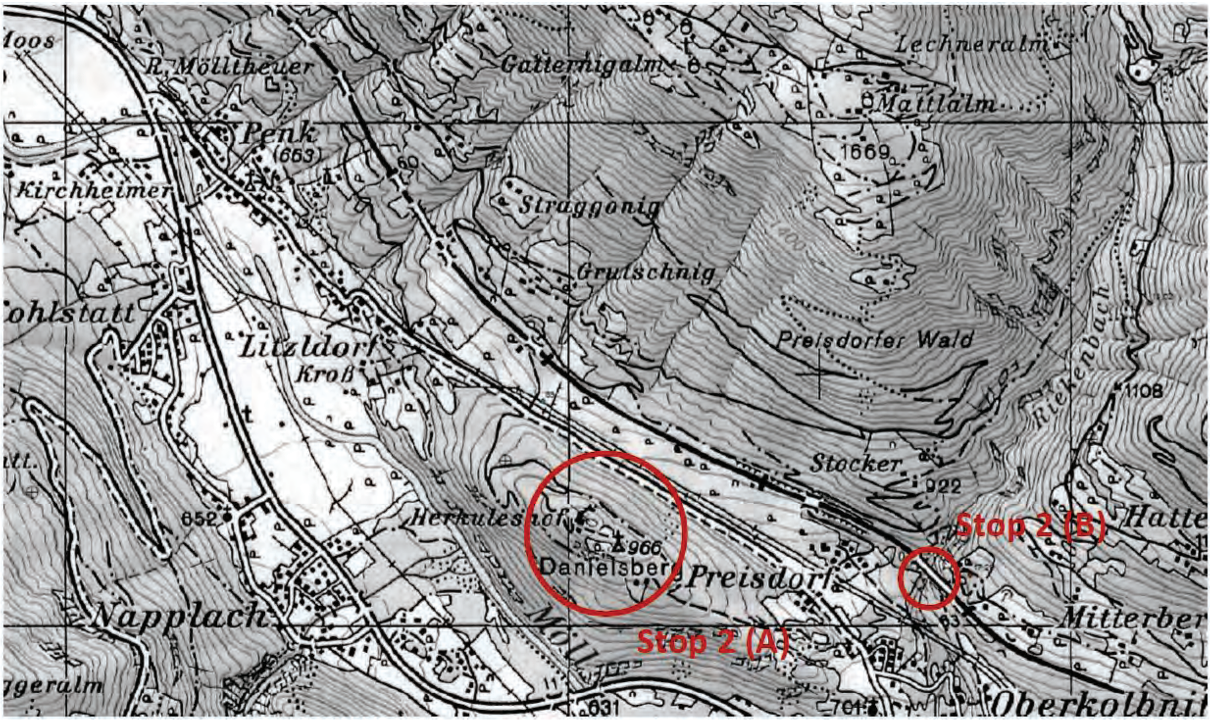


Figure 18: Location of Stops 2 (A) and 2 (B)

Danielsberg is located in the middle of the Mölltal Valley within the Austroalpine nappes. It is bounded to the northeast by the Mölltal Fault and to the southwest by a minor fault within the Austroalpine units. This hill is attributed to tectonics, as it coincides with a positive flower structure.

On top of Danielsberg, a little gothic-style church built in 1127 offers a nice panorama of the Möll Valley and the geology, including the next stop (Fig. 19).

Figure 19: View from Danielsberg to the southeast along the Möll Valley (Tauern Window with Penninic and Subpenninic nappes on the left, Austroalpine nappes on the right).

Stop 2 (B) – Oberkolbnitz (N 46°52'49'' E 13°19'10'' Alt. 775 m)

Directions: This outcrop is located in the Rieckengraben between the villages of Oberkolbnitz and Preisdorf. After leaving the cars along the road that leads up to the Rieckengraben (exactly under the railway bridge), take a small forest path that leads down to the streambed outcrop (Fig. 18).

In Fig. 20: The most competent lithologies in the outcrop shown in Fig. 20 are strongly sheared Augengneiss of the Sonnblick Lamellae (Abb. 27). All lithologies in this outcrop are affected by sinistral Katschberg mylonitic shearing and were later truncated by brittle faults planes associated with the Mölltal Fault.

In the Oberkolbnitz area, the Mölltal Fault is a NW-trending, subvertical zone of fractured rock and cataclasites some 10 m wide that delimits the southeastern Tauern Window from the Austroalpine nappes of the Eastern Alps. This fault overprints mylonites of the KSZS and is interpreted to have accommodated dextral strike-slip motion along the northeaster side of a triangular-shaped block of Austroalpine crust that indented the warm Penninic nappes in the eastern part of the Tauern Window (Figs 11a & b, 21; SCHARF et al., 2013).

Between Obervellach and Oberkolbnitz, the Mallnitz Synform changes its dip direction from steeply SW to steeply-to-moderately NE dipping (c. 040/30). The thickness of the Sonnblick Nappe decreases drastically going from NW to SE as the dome thins to become a narrow lamellae with a main S5 foliation that dips to the NE in the Möll Valley (Fig. 22). Along the NE slopes of this valley, the Sonnblick Lamellae as well as the adjacent Glockner- and Modereck nappe systems have narrowly spaced sinistral shear bands. These bands mark a c. 1 km wide zone of sinistral mylonitic shear that bends into continuity with the SE-dipping Katschberg Normal Fault (KNF) along the eastern margin of the Tauern Window (Fig. 11).

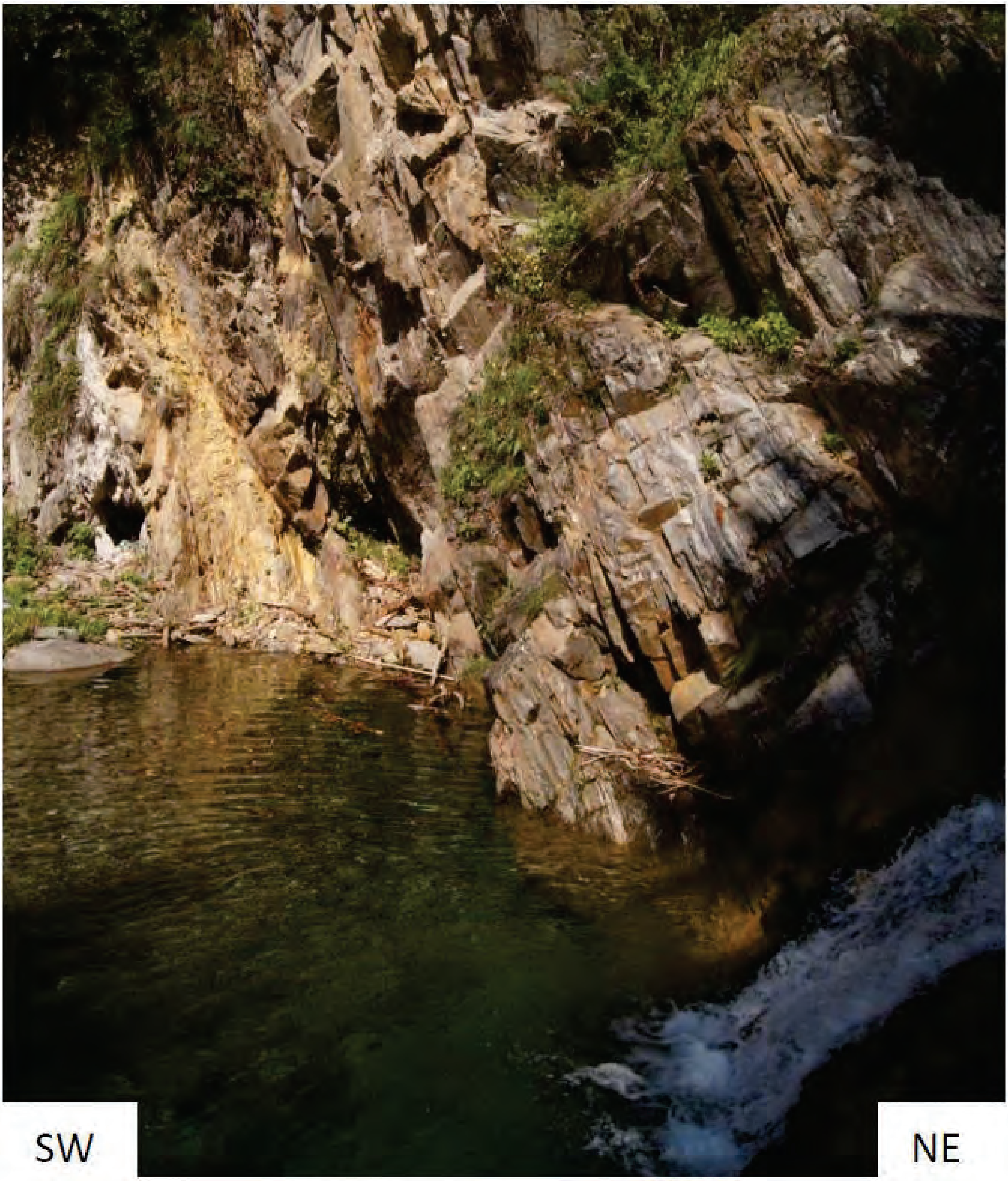


Figure 20: Outcrop at Oberkolbnitz. The mylonitic foliation dips to the NE. South of the Sonnblick Lamellae (right), yellowish layers of dolomitic marble intercalated with dark schist, grayish marble and calcareous mica schist of oceanic unit are exposed (left). All these lithologies are affected by sinistral Katschberg mylonitic shearing and are cut by later brittle fault related to the Mölltal Fault.

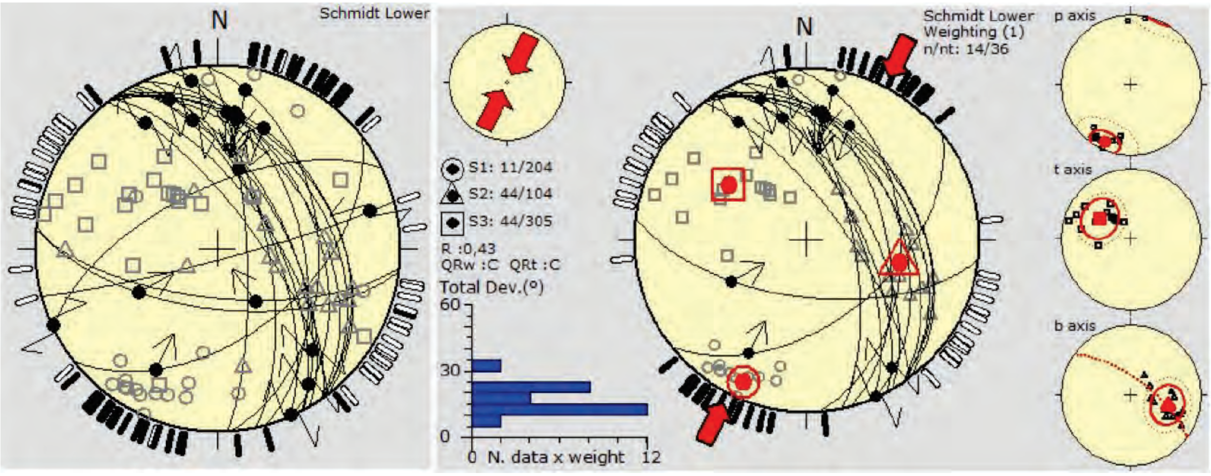


Figure 21: Fault analysis at Oberkolbnitz: (a) Equal area plot of brittle structures; (b) palaeostrain analysis.

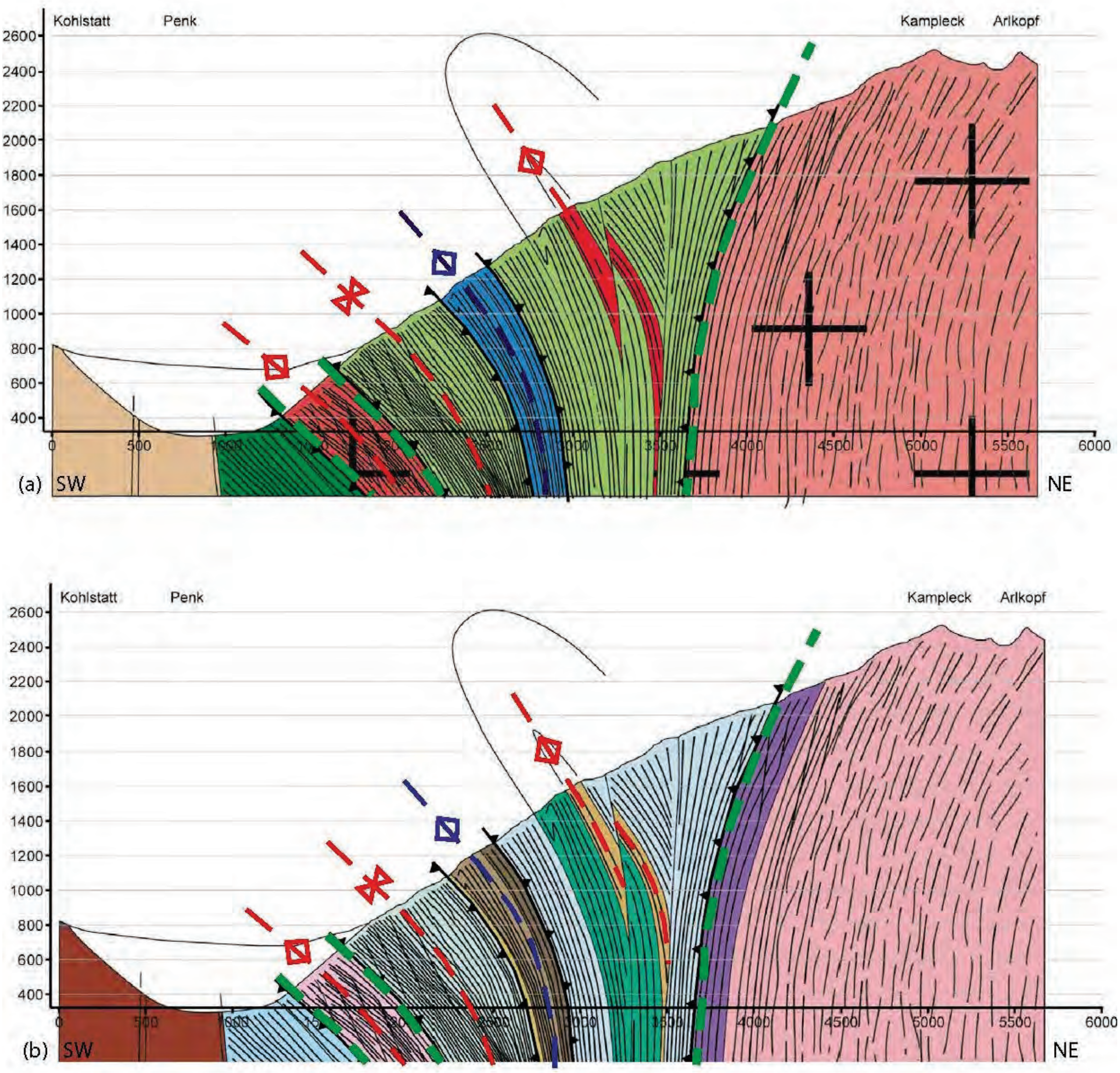


Figure 22: Profiles 3 (trace and legend in Figure 26) near Oberkolbnitz: (a) tectonic units, (b) lithology. D5 folds marked in red, axial traces of D3 (blue), D4 roof thrust of the Venediger Duplex (green).

Stop 3 – The Katschberg Normal Fault in the Malta Valley

Directions: From Gmünd, follow the road L12 into the Malta Valley and turn right (north) at the village of Malta. Drive up to the Maltaberg (the end of the road) and park at the Almhütte there at c. 1600 m (they serve cakes, coffee and Almdudler). From there, walk back to a forestry road branching off at an elevation of c. 1500 m (i.e., before the first U-bend). Follow this forestry road to the southwest into the "Ballonwald".

This stop consists of two sections of several small outcrops along a forestry road. It involves about 3 hours of easy walking and ends with a beautiful view of the Katschberg Normal Fault and the Hochalm Dome. The outcrops are of structures related to Miocene E to SE-directed shearing of Subpenninic and Penninic units in the footwall of the Katschberg Normal Fault (KNF). The entire stop is described in the explanations sheet of Map 182 "Spittal a. d. Drau", scale 1:50.000 (SCHUSTER et al., 2006).

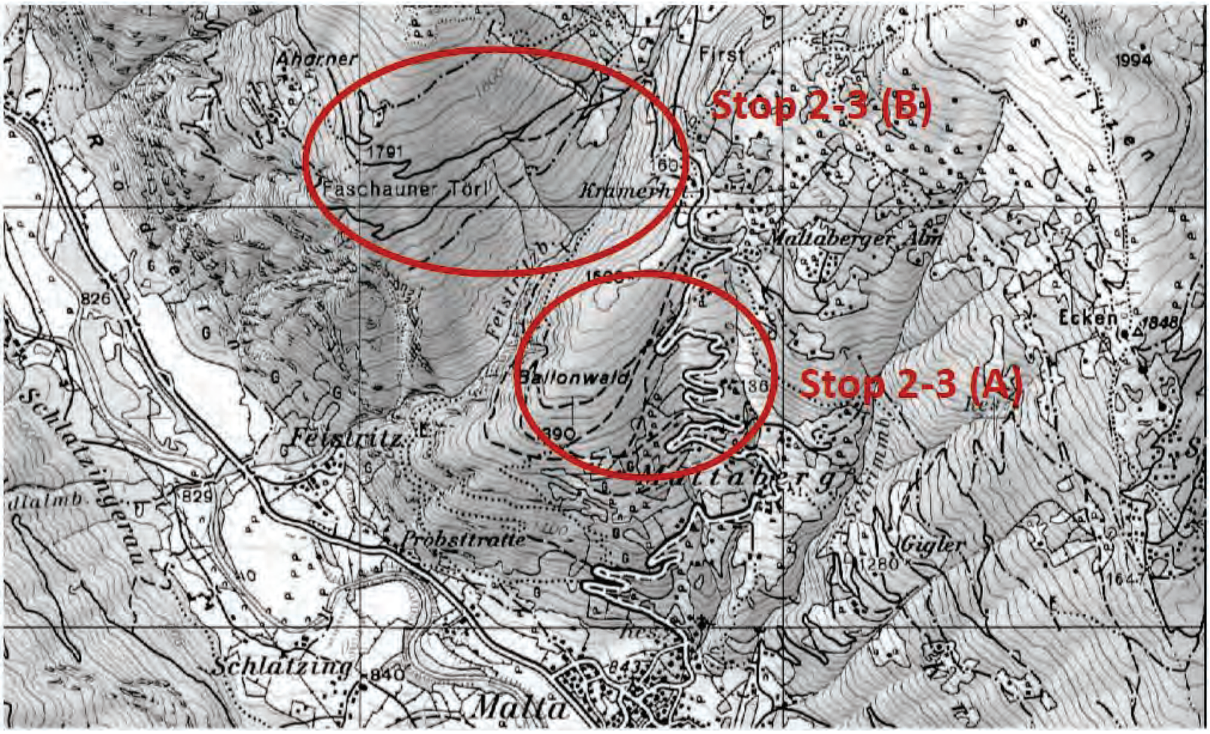


Figure 23: Location of Stops 3 (A) and 3 (B)

Section one, stop 3 (A) ("Ballonwald") (N 46°58'05'' E 13°29'56'' Alt. 1500 m) (Fig. 23)

Several small outcrops along the forestry road (1.5 km) oriented perpendicular to the strike of the Katschberg Normal Fault (KNF) reveal the lithologies in the footwall of the KNF: Penninic rocks (calc- schist and so-called "prasinite" of the Glockner Nappe System) and Subpenninic rocks (siliciclastic albite-bearing gneiss of the Modereck Nappe System, pre-Variscan paragneisses of the Storz Nappe).

The contact of the Modereck Nappe System with the underlying Storz Nappe marks the roof thrust of the Venediger Duplex (Figs. 11 & 12). All units dip moderately to the ESE and preserve top-ESE kinematic indicators. Peak temperature estimates obtained from Raman microspectroscopy on carbonaceous material (RSCM) in the metasediments above the aforementioned roof thrust yield temperatures of 515 ± 10° C in the structural lowest units and 460 ± 8° C in the structurally highest units (Fig. 24; Scharf et al., in press). This enormous decrease in peak temperature (field-gradient of 70° km-1; Fig. 25) corresponds with the zone of greatest tectonic omission in the footwall of the KNF.

Section two, stop 3 (B) (“Faschauer Törl”) (N 46°58’38’’ E 13°29’24’’ Alt. 1791 m)

Directions: Return to the cars parked at the Almhütte and follow the path crossing the Feistritz Valley to the west.

This path (2 km long with an altitude difference of 200 m) has exposures of the Variscan granitic intrusions that intruded the pre-Variscan paragneisses seen along the path in the “Ballonwald”. All these rocks belong to the Storz Nappe below the roof thrust of the Venediger Duplex (Figs. 11 & 12). The asymmetry of the feldspar augen in the intrusive rocks indicates top-ESE sense of shear. The end of this path provides a beautiful view of the “Faschauer Törl” (1791 m), where one can see the large-scale culmination of the Hochalm Dome, as well as the moderate eastward dip of all thinned Penninic- and Subpenninic units in the footwall of the KNF (Figs. 11 & 12).

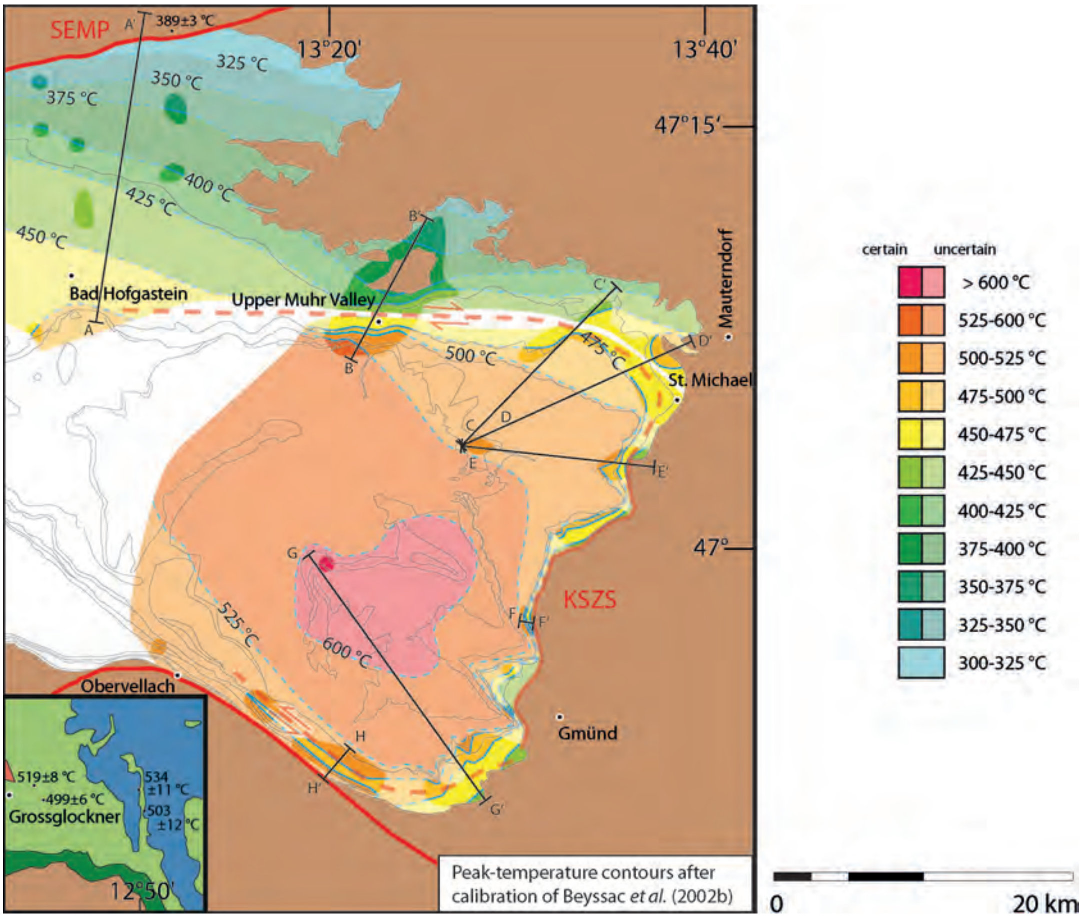
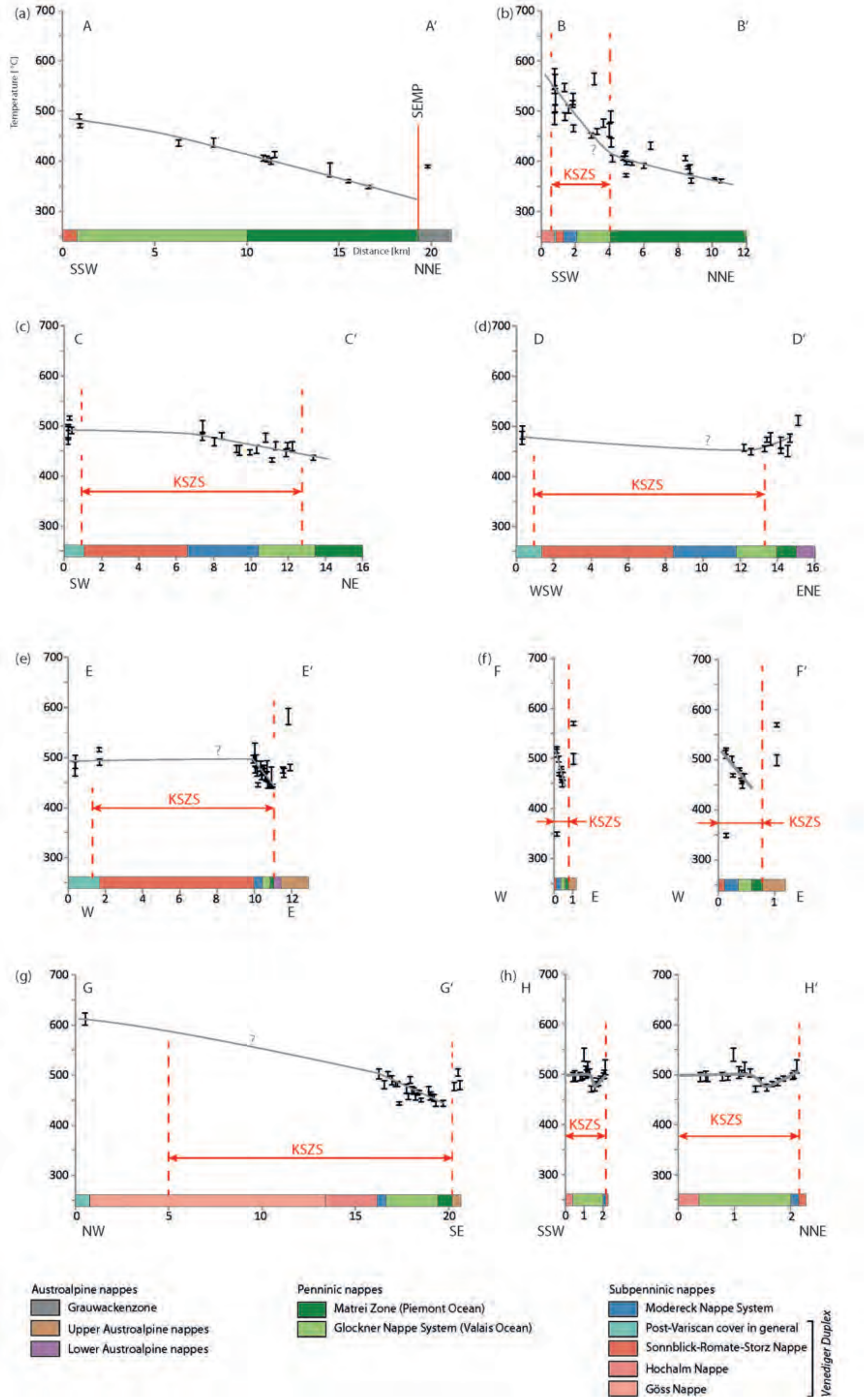


Figure 24: Peak-temperature contours based on the calibration of BEYSSAC et al. (2002) for CM. Transparent colours and dashed lines indicate areas and contours where the sample density is low. Brown = Austroalpine units. Grey lines = tectonic contacts separating units of the Tauern Window (after SCHMID et al., 2013). The peak-temperature contours are marked in blue. Inset shows estimated peak temperatures of 4 samples in the only area of high-pressure metamorphism. Trace of cross sections which are shown in Fig. 25. Profile “Ballonwald” is located along the cross section F-F’.

Figure 25 (next page)**:** Cross sections a-h of peak temperature along traces shown in Fig. 24. Calibration of BEYSSAC et al. (2002) with individual confidence interval bars (CI 95%). Colours along the horizontal axes indicate the tectonic units from the tectonic map of the Tauern Window (Fig. 11). The boundaries of the KSZS (Katschberg Shear Zone System, SCHARF et al., 2013) are marked in cross sections b-h by red dotted lines. Note that the horizontal axes in sections f and h are expanded by a factor of 3 for easier viewing. Peak-temperature points are projected into the sections from as much as 2.5 km on either side of the section planes, except in Fig. 25a where the projection is up to 5 km from the plane. Profile “Ballonwald” is located along the cross section F-F’.


(a)
A
A′
Temperature [°C]
SEMP
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SSW
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B′
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SSW
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C′
KSZS
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NE
(d)
D
D′
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WSW
ENE
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NW
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SSW
NNE
Austroalpine nappes
Grauwackenzone
Upper Austroalpine nappes
Lower Austroalpine nappes
Penninic nappes
Matrei Zone (Piemont Ocean)
Glockner Nappe System (Valais Ocean)
Subpenninic nappes
Modereck Nappe System
Post-Variscan cover in general
Sonnblick-Romate-Storz Nappe
Hochalm Nappe
Göss Nappe
Venediger Duplex

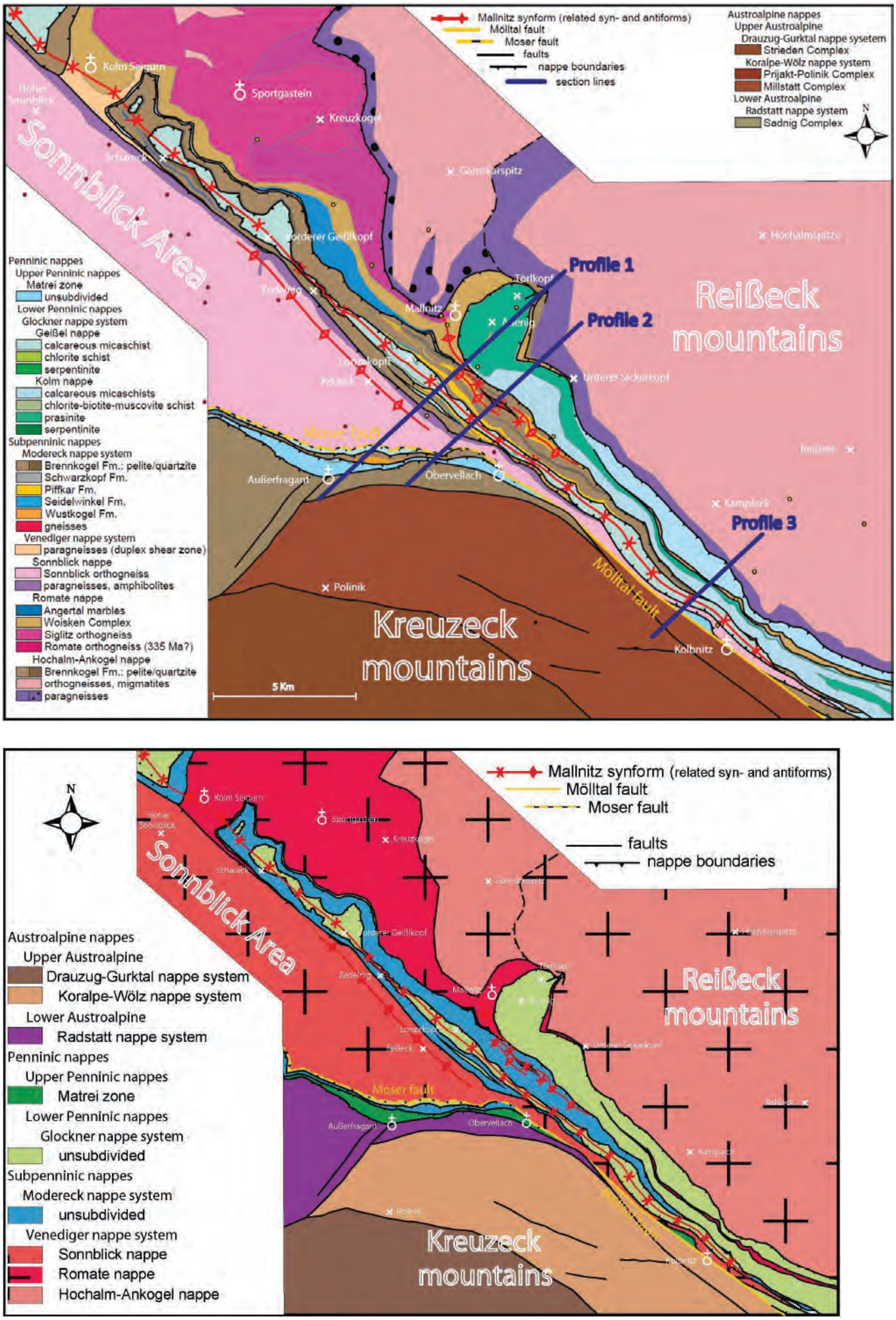

Figure 26: Maps derived from the filed work of Favaro S. and Schuster R. according with Schmid et al. (2013) and Pestal et al. (2009).

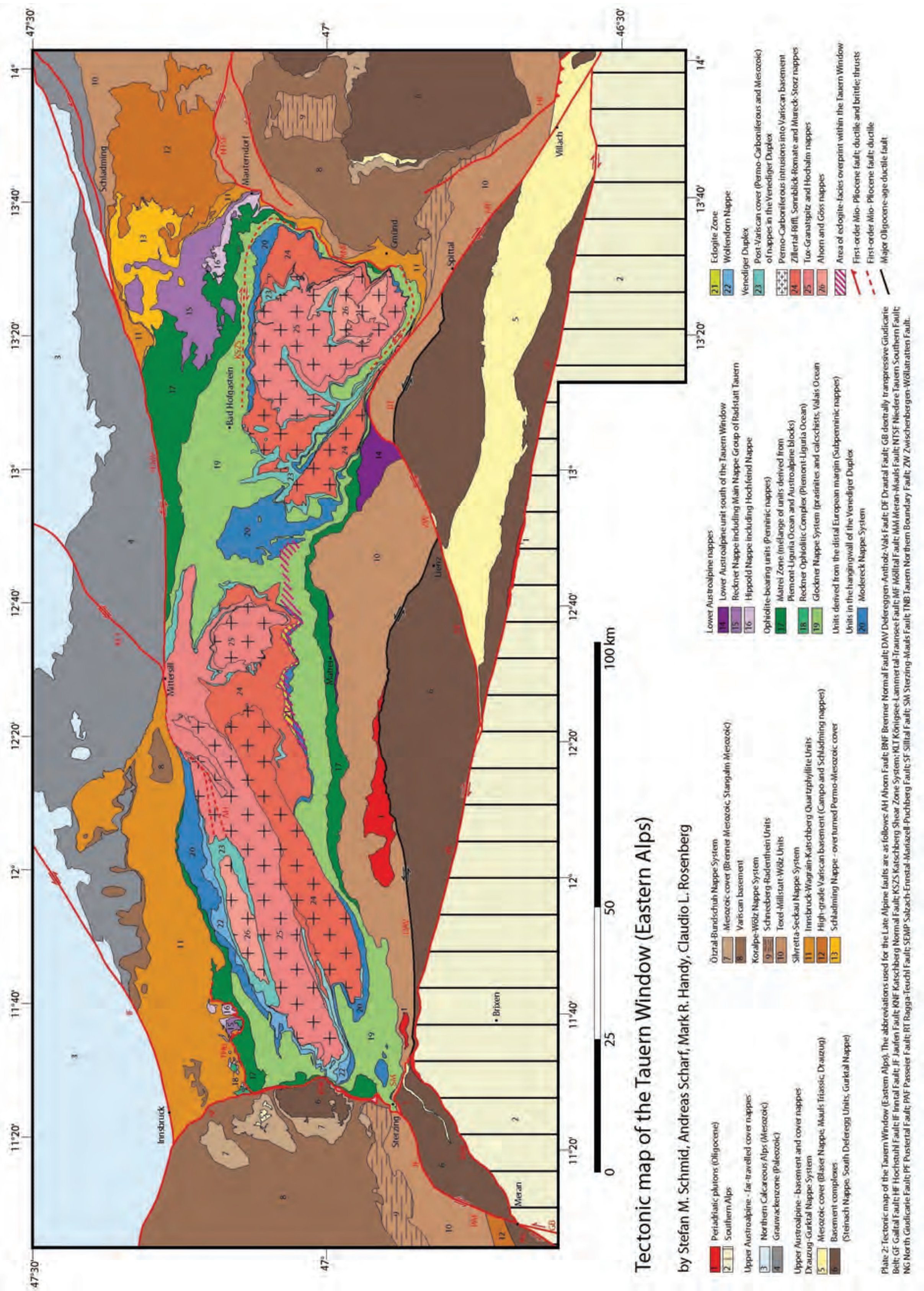

Figure 27: Tectonic map of the Tauern Window (SCHMID et al., 2013).

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Field Trip B2: Triassic to Early Cretaceous geodynamic history of the central Northern Calcareous Alps (Northwestern Tethyan realm)

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Content

Abstract

The topic of this field trip is to get to know and understand the sedimentation of Austria's Northern Calcareous Alps and its tectonic circumstances from Triassic rifting/drifting to Jurassic collision/accretion, and the Early Cretaceous "post-tectonic" sedimentary history. The Northern Calcareous Alps as part of the Eastern Alps is one of the most prominent Alpine areas. Together with the Carpathians, the Southern Alps and the Dinarides, they constituted an up to 700 km wide and approximately 2000 km long shelf strip of the northwestern Tethys margin.

The Triassic sedimentation was controlled by Early to early Middle Triassic extension, the break-up of the Neotethys in the early Middle Triassic and the formation of huge carbonate platforms in the late Middle to Late Triassic. The Jurassic sedimentation in this realm was controlled by the palaeogeographic position of the depositional area between two oceans and their evolution, respectively: the Neotethys Ocean to the east resp. southeast and the Alpine Atlantic to the west resp. northwest. The opening of the Central Atlantic Ocean with its continuation into the Alpine Atlantic (= Ligurian-Penninic Ocean) leads to a new Mediterranean plate configuration. The "Apulian" plate was formed. Successive spreading of the Alpine Atlantic is mirrored by the closure of parts of the Neotethys Ocean resulting in an early deformation of a former Triassic carbonate shelf since late Early Jurassic time. Nappe thrusting was sealed by Late Jurassic carbonate platforms. Uplift of the orogen since latest Jurassic was followed by the filling-up of the remaining foreland basin in Early Cretaceous times.

Deformation and accretion started in the Neotethys Ocean with intra-oceanic thrusting in the late Early Jurassic. This thrusting process resulted in the obduction of the accreted ophiolites onto the outer shelf in Middle Jurassic times as demonstrated for example in the Dinarides. The former Triassic to Early Jurassic passive continental margin with its huge Triassic carbonate platforms took a lower plate position in this developing thin-skinned

orogen. Thrusting started in the outer shelf region and successively propagated towards the inner shelf. In the late Middle Jurassic contractional tectonics reached the inner parts of the shelf and affected the Triassic carbonate platforms. Deep-water trench-like basins formed in sequence in front of advancing nappes: Thus the initial first trench-like basins formed in the south. Later, in the early Late Jurassic, further trench-like basins formed farer to the north. The trench-like basins accumulated thick successions of gravitatively redeposited sediments deriving from the accreted older sedimentary sequences. In the Late Jurassic to Earliest Cretaceous this mountain building process is sealed by the onset of shallow-water carbonate platforms. Shallow-water platform carbonates were formed on top of the nappe stack whereas hemipelagic limestones or radiolarites were deposited in the former radiolaritic trench-like basins. Latest Jurassic uplift of the orogen led to the destruction of this platform/basin pattern and resulted in a diachronous drowning of the platform (central and northern part) resp. uplift and erosion of the platform in the more southern areas. In the Early Cretaceous the remaining basins were filled up by the erosional products of the older nappe stack including material from the obducted ophiolites.

This Triassic to Early Cretaceous evolution of the Northern Calcareous Alps is best preserved in their central region. During the field trip we will visit some of the finest outcrops documenting this earliest phase of Alpine mountain building and degradation.

1 Introduction

As introduction a short outline of the whole Permian/Triassic to Early Cretaceous sedimentary and geodynamic evolution of the northwestern Neotethys realm (e.g., Eastern and Southern Alps, Western Carpathians, Pannonian realm, Dinarides) is provided in order to better understand the topics of the field trip (Fig. 1). We will see Late Permian to Middle Jurassic rocks from different provenance areas as reworked, differently sized (millimetre to square kilometre) components in the late Middle to early Late Jurassic deep-water basin successions. Beside age dating of the matrix sediments, unravelling the derivation of these components is of great importance for the reconstruction of basin formation during that time span. The overall geodynamic evolution is crucial for the initiation of the large-scaled mass movements into these deep-water basins and the time-equivalent to subsequent formation of carbonate platforms. The Eastern Alps, especially the Northern Calcareous Alps (Fig. 2) as part of this northwestern Neotethyan realm, provide an excellent opportunity to study this story. More than 150 years of geological investigations form a solid data base with many topics still controversially discussed and remaining open questions. Not only the geodynamic models are controversial but there is also still no consensus on the palaeogeographic configuration of today's mountain puzzle in this region (details in MISSONI & GAWLICK, 2011a).

There is a large number of contrasting palaeogeographic reconstructions of the Alpine Belt and adjacent regions for the Late Triassic to Jurassic period (e.g., FRISCH, 1979; HAAS et al., 1995; GAWLICK et al., 1999a, 2008; STAMPFLI & BOREL, 2002; SCHMID et al., 2004, 2008; STAMPFLI & KOZUR, 2006, and many others; compare ZACHER & LUPU, 1999). Our reconstruction of the Austroalpine domain´s tectonostratigraphic evolution follows a causal approach. It is based on the tectonic events steering the depositional areas´ development and the deposition of the different sedimentary successions (= formations and lithostratigraphic names), respectively. The formations are classified in respect of their event-related deposition within a palaeogeographic domain. The subordinate control of the history of the Austroalpine domain was the situation of the latter as part of a continent between two oceanic domains: the Alpine Atlantic Ocean (= South Penninic/Piemont/Ligurian Ocean) to the west/northwest related to the Central Atlantic Ocean (e.g., FRISCH, 1979; LEMOINE & TRÜMPY, 1987 - the term "Alpine Tethys" should not be used in order to avoid confusion: e.g., DAL PIAZ, 1999; STAMPFLI & BOREL, 2002; SCHMID et al., 2004, 2008; STAMPFLI & KOZUR, 2006) and the Neotethys Ocean to the south/southeast (not Meliata Ocean - compare KRYSTYN et al., 2008) (Figs. 3, 6).

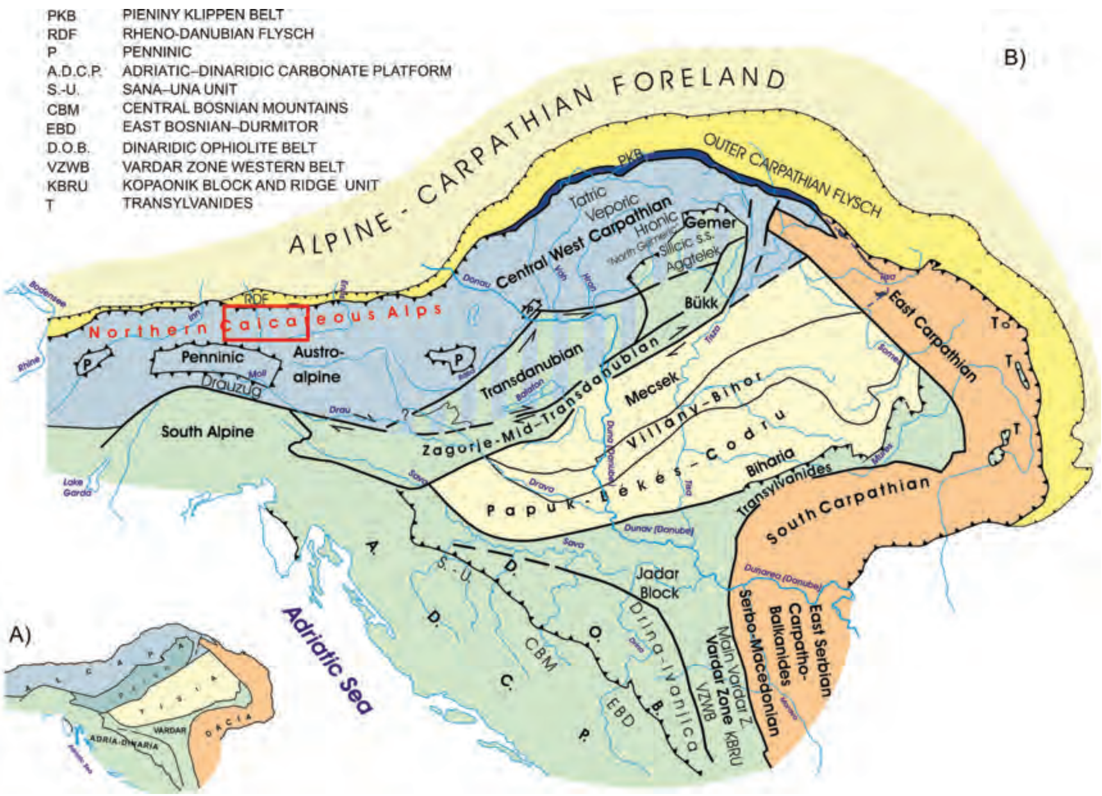


Figure 1: **A**) Mega-units and mountain belts in the Alpine-Carpathian-Dinaride-Pannonian realm. **B**) Most important tectonic mega-units/nappe systems in the Alpine-Carpathian-Dinaride-Pannonian realm with more detailed names of the different units and the area of the field trip indicated (after KOVACS et al., 2010, 2011). For the Austroalpine mega-unit and the exact geographic position of the Northern Calcareous Alps see Fig. 2.

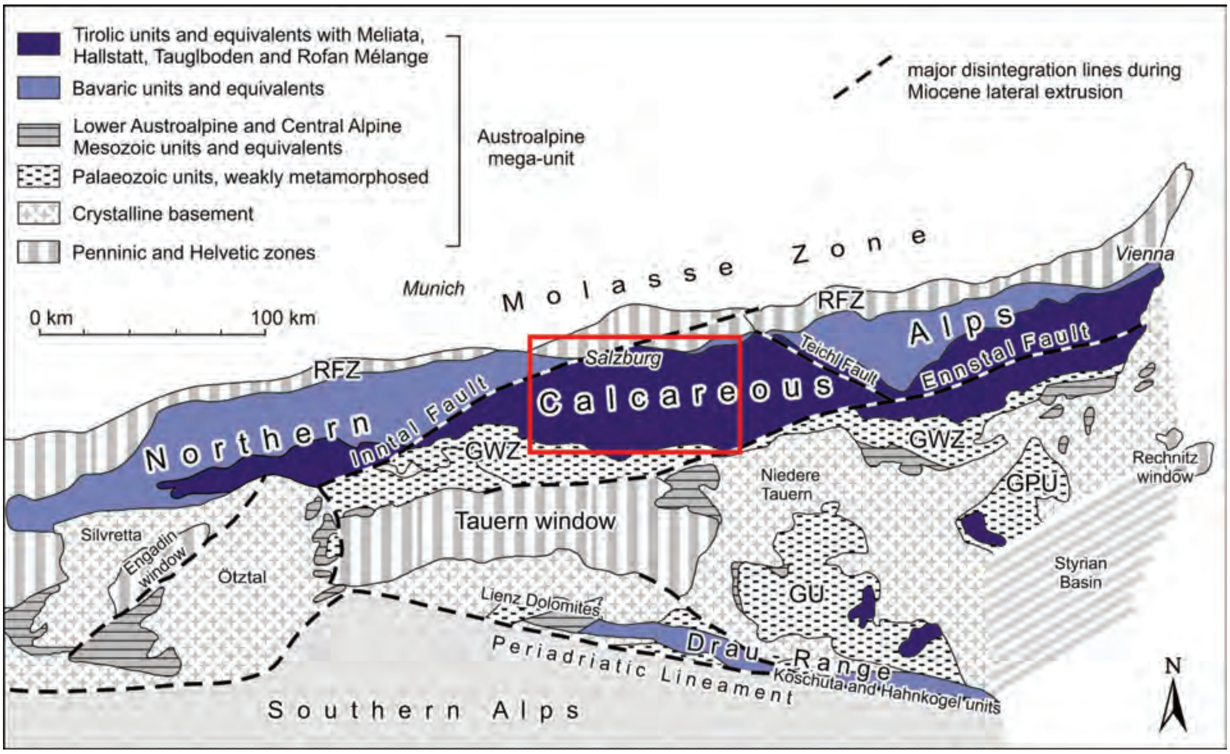


Figure 2: Tectonic sketch map of the Eastern Alps and field trip area (compare Fig. 8; after TOLLMANN, 1977; FRISCH & GAWLICK, 2003). *GPU* Graz Palaeozoic Unit; *GU* Gurktal Unit; *GWZ* Greywacke Zone; *RFZ* Rhenodanubian Flysch Zone.

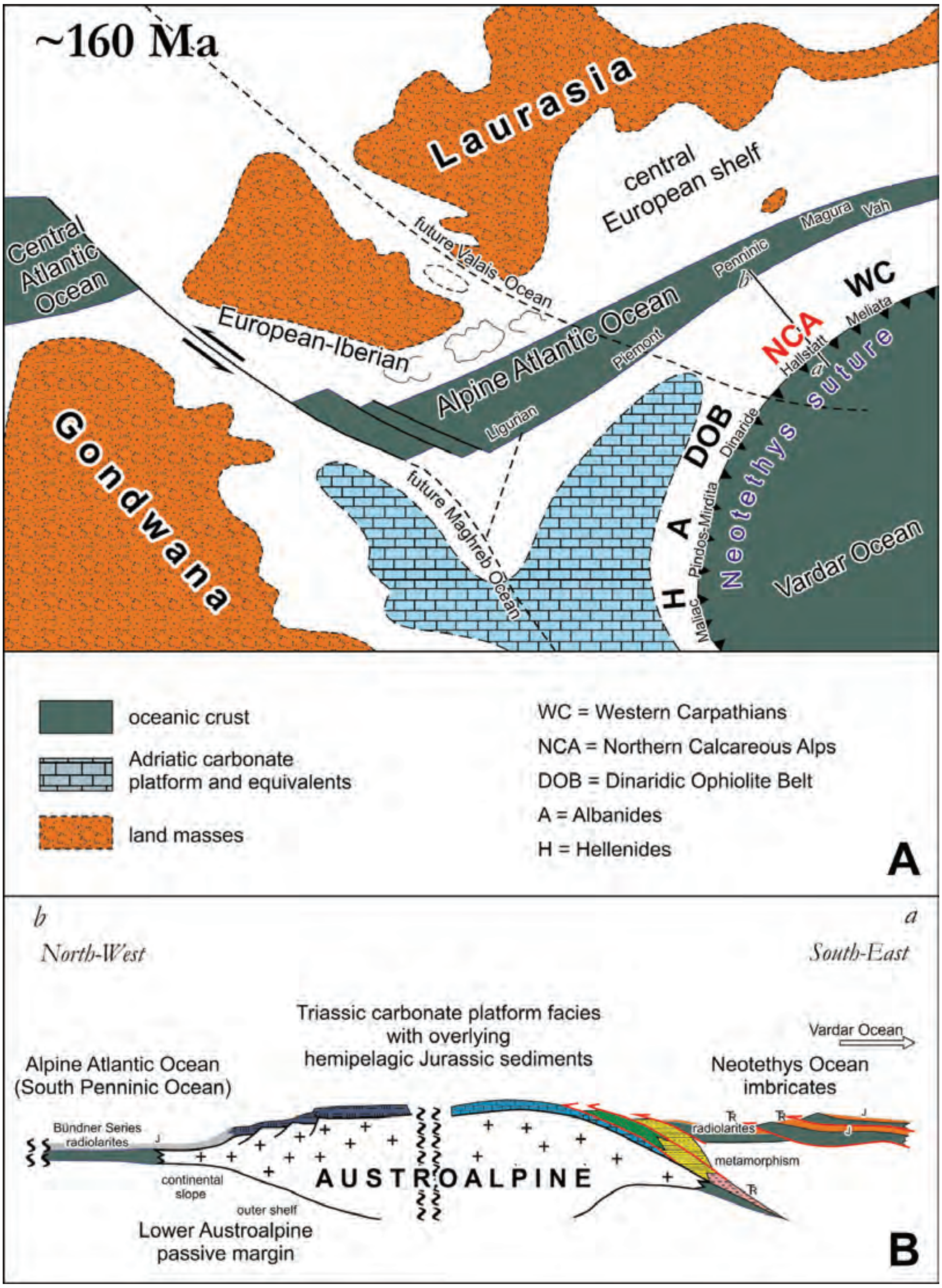


Figure 3: A) Palaeogeographic position of the Northern Calcareous Alps as part of the Austroalpine domain in Late Jurassic time (after FRISCH, 1979; GAWLICK et al., 2008). In this reconstruction the Northern Calcareous Alps are part of the Jurassic Neotethyan Belt (orogen) striking from the Carpathians to the Hellenides. The Neotethys suture is equivalent to the obducted West-Vardar ophiolite complex (e.g., Dinaridic Ophiolite Belt) in the sense of SCHMID et al. (2008) = far-travelled ophiolite nappes of the western Neotethys Ocean in the sense of GAWLICK et al. (2008) (see ROBERTSON, 2012 for discussion). The eastern part of the Neotethys Ocean remained open = Vardar Ocean (compare Figs. 16–22). Toarcian to Early Cretaceous Adria-Apulia carbonate platform and equivalents according to GOLONKA (2002), VLAHOVIC et al. (2005), and BERNOULLI & JENKYNS (2009). **B**) Schematic cross section reconstructed for Middle to Late Jurassic times. It shows the passive continental margin of the Lower Austroalpine domain facing the Penninic Ocean to the northwest (e.g., TOLLMANN, 1985; FAUPL & WAGREICH, 2000) and the lower plate position and imbrication of the Austroalpine domain in relation to the obducted Neotethys oceanic crust (after GAWLICK et al., 2008). Compare FRISCH (1979, 1980a, b).

In Triassic to Early Cretaceous times the Northern Calcareous Alps, together with the Western Carpathians, the Dinarides, the Albanides, the Hellenides and other regions, formed a continuous NNE-SSW trending belt facing the north-western margin of the Neotethys Ocean (Fig. 3) and undergoing the same history: Formation of oceanic crust since Late Anisian, onset of inneroceanic thrusting in late Early Jurassic, ophiolite obduction in Middle-Late Jurassic, followed by the formation of shallow-water platforms, extensional collapse due to tectonic thickening and mountain uplift before the Jurassic/Cretaceous boundary, and infilling of the foreland basins with the erosional products of this orogen in the Early Cretaceous. The detailed documentation of the geodynamic evolution as synthesized in MISSONI & GAWLICK (2011a, b) clearly demonstrates that a prominent orogenic event with oceanic accretion, fold thrust belt formation and foreland basin creation has taken place in that period. The regional importance of this event affected the complete western margin of the Neotethys margin; therefore the name Neotethyan Belt for this Jurassic orogen was introduced by MISSONI & GAWLICK (2011b).

What you will see:

- the Late Triassic shallow-water carbonate platform: restricted lagoon, open lagoon, reef to open shelf sedimentary rocks,
- formation of a palaeotopography in the latest Triassic due to siliciclastic influence and the response of the carbonate factories. Formation of a deep lagoon,
- Early Jurassic open marine sediments sealing the Late Triassic palaeotopography (pelagic platform),
- formation of Middle to early Late Jurassic deep-water radiolaritic trench-like basins due to out-of-sequence thrusting with the deposition of fine-grained organic rich sediments intercalated by olistostromes and huge slides,
- large scale mass movements from an accretionary wedge in adjacent trench-like basins; each basin fill is characterized by a coarsening-upward cycle,
- onset of shallow-water carbonate platforms on an uplifted nappe stack, progradation of shallow-water carbonates over older deep-water basins,
- formation of starved basins in between carbonate platforms as result of the interplay of tectonics and carbonate production,
- carbonate platform collapse due mountain uplift associated with extensional tectonics,
- Early Cretaceous drowning of carbonate platforms due to siliciclastic input.

To see the complete, very complex passive to active continental margin evolution from Late Triassic to Early Cretaceous in the central Northern Calcareous Alps (Salzburg and Berchtesgaden Calcareous Alps). This area is a geological highlight in one of the most classical geological areas of the world.

Classical concept and historical alternatives

The classic tectonic subdivision of the Northern Calcareous Alps (compare Fig. 2) (in its fundamentals established by HAUG, 1906, later modifications by, e.g., HAHN, 1913; KOBER, 1923; SPENGLER, 1951; PLÖCHINGER, 1980; TOLLMANN, 1985) defined three nappe groups. These are, from bottom to top: Bavaric, Tirolic, and Juvavic nappe group (in the central Northern Calcareous Alps today only preserved in the Hallstatt Mélange). This tectonic concept, established in the Berchtesgaden Alps and in the Salzkammergut area, was widely accepted. Later, a subdivision into three tectonic units ("Stockwerke" *sensu* LEBLING et al., 1935) was proposed: the Tirolic unit ("Tirolische Einheit" *sensu* HAHN, 1913) at the base, overlain by the Lower Juvavic unit ("Tiefjuvavische Einheit": Hallstatt nappes), and the Upper Juvavic unit ("Hochjuvavische Einheit": Berchtesgaden and Dachstein nappes). Subsequently, in the salt-mine of Hallein MEDWENITSCH (1962) subdivided the Lower Juvavic nappe into a Lower ("Untere Hallstätter Decke": Zlambach nappe - grey Hallstatt facies rocks) and an Upper Hallstatt nappe ("Obere Hallstätter Decke": Sandling nappe - variously coloured Hallstatt Limestone nappe). In this concept fragmentary blocks of Lower Juvavic

Hallstatt Limestones (TOLLMANN, 1976b) framed the Upper Juvavic nappes (TOLLMANN, 1985 for details and figures).

In an alternative concept, evaporites, subsumed as Alpine Haselgebirge (Permian salt-claystone succession; Haselgebirge Mélange according to SPÖTL et al., 1998), acted as a ductile paste and motor of gravitational tectonics. Gravitational tectonics in the Juvavic units should have started in the Oxfordian (e.g., TOLLMANN, 1981, 1987; MANDL, 1982; LEIN, 1985; 1987a) or Late Tithonian (PLÖCHINGER, 1974, 1976, 1984), leading to Late Jurassic to Early Cretaceous sliding of Alpine Haselgebirge and Hallstatt Limestone successions towards the north. According to these models (summarized in, e.g., TOLLMANN, 1987; LEIN, 1987b), sliding began in a phase of enhanced radiolarite sedimentation when troughs with marine sedimentation were arranged along the median longitudinal axis of the Northern Calcareous Alps (DIERSCHE, 1980). Mainly based on ammonite stratigraphy (summarized in DIERSCHE, 1980), the onset of radiolarite sedimentation was estimated as Oxfordian. Hence, the radiolarite basins were filled up by deep-water cherty limestones to radiolarites with intercalated breccias and turbidites. Slump folds are characteristic features in these sediments (e.g., GARRISON & FISCHER, 1969; SCHLAGER & SCHLAGER, 1973; DIERSCHE, 1980; TOLLMANN, 1987).

The formation of the generally asymmetric radiolarite basins was attributed to extensional tectonics (e.g., SCHLAGER & SCHLAGER, 1973; DIERSCHE, 1980; VECSEI et al., 1989). Another group of authors attributed basin formation and breccia mobilization to strike-slip tectonics (e.g., FISCHER, 1965; WÄCHTER, 1987; FRANK & SCHLAGER, 2006; ORTNER et al., 2008).

Current concept

In the current concept, based on new results, we follow:

1) The tectonic subdivision of the Eastern Alps of TOLLMANN (1977) with some modern modifications (FRISCH & GAWLICK, 2003; compare SCHMID et al., 2004) (Fig. 2),
2) The palaeogeographic reconstructions of KRYSTYN & LEIN in HAAS et al., (1995) with some modifications (Fig. 6), and
3) The concept that the Jurassic geodynamic history of the Austroalpine domain mirrors its palaeogeographic position between two oceanic domains (Fig. 3):
   I. To the west (northwest) the newly formed Penninic Ocean as part of the Alpine Atlantic, where continental extension started around the Triassic/Jurassic boundary or in the Hettangian, with the first oceanic crust formed in the late Early Jurassic (Toarcian), and
   II. to the east (southeast) the Neotethys Ocean, in which closure started before the Early/Middle Jurassic boundary.

The Juvavic nappe stack represented the Jurassic accreted wedge of the Northern Calcareous Alps (FRISCH & GAWLICK, 2003). It became completely eroded in the sector of the central Northern Calcareous Alps with remnants of this nappe complex only preserved in the Middle to Late Jurassic radiolaritic trench-like (wildflysch) basin fills (GAWLICK & FRISCH, 2003). Most probably the huge blocks on top of the basin fills represent remnants of the overthrusting nappes. These basins were situated in front of the propagating thrust belt or on top of them and were later overthrusted. In these radiolaritic basins all sedimentary rocks of the Meliata facies zone, the Hallstatt facies belt and from the reefal belt of the Triassic carbonate platform occur as redeposits. Some blocks show the effect of transported metamorphism (GAWLICK & HÖPFER, 1999; MISSONI & GAWLICK, 2011a; compare FRANK & SCHLAGER, 2006).

In the Bajocian the sedimentary evolution in the southern (palaeogeographically southeastern - Fig. 3) part of the Tirolic realm as well as in the Hallstatt realm differed from that in the northern (palaeogeographically northwestern - Fig. 2) part. Deep-water trench-like basins formed in front of advancing nappes. The first basin group in the southern parts of the Northern Calcareous Alps received mass-flow deposits and large, up to nappe sized slides which derived from the Hallstatt Zone (= Hallstatt Mélange). The thickness of the basin fills may reach up to 2.000 metres. The nappe stack carrying the Hallstatt Mélange is defined as Upper Tirolic nappe (group) (Fig. 7).

The second basin group, the Tauglboden and the Rofan trench-like basins in the north were subjected to high subsidence and sedimentation rates in the Oxfordian to earliest Kimmeridgian. The Trattberg Rise was eroded and supplied the Tauglboden Basin to its north with mass-flow deposits and slides. The nappe carrying the Tauglboden Mélange is defined as lower Tirolic nappe. On the other hand, the Rofan Basin was carried by the lowermost Tirolic nappe. It formed later than the Tauglboden Basin and received the material from the Hauptdolomit facies zone (Brunnwinkl Rise).

2 Overall geodynamic and sedimentary evolution

Following a major post-Variscan regression and Permian crustal extension (e.g., SCHUSTER & STÜWE, 2008), sedimentation in the northwestern Tethyan realm started in the Middle/Late Permian with coarse-grained siliciclastic sediments in the northwest (Alpine Verrucano - compare TOLLMANN, 1976a, 1985) and evaporites to the southeast (Alpine Haselgebirge: TOLLMANN, 1976a, 1985) due to early Neotethyan crustal extension (SCHUSTER et al., 2001). In the Early Triassic, siliciclastic sedimentation continued with the deposition of the Alpine Buntsandstein in the northwest and with deposition of the marine Werfen Beds in the southeast (Fig. 4). Around the Early/Middle Triassic boundary, carbonate production started with the build-up of carbonate ramps (top Werfen Formation, Gutenstein and Steinalm Formations: Fig. 4). The opening event with open marine influence is manifested below the Middle Anisian Steinalm Formation (LEIN et al., 2010). Shallow-water carbonate sedimentation with overlying hemipelagic carbonates (GALLET et al., 1998) as the result of a partial drowning event due to the final break-up of the Neotethys Ocean in the late Pelsonian (LEIN & GAWLICK, 2008) dominated in the entire Eastern Alps in the Middle Triassic. In late Middle to early Late Triassic times, the Wetterstein Carbonate Platform was formed (Fig. 4). This platform was overlain by siliciclastic sediments of the Lunz and Northalpine Raibl Formations or by the Reingraben Formation (*Halobia* Beds) in the Hallstatt realm (HORNUNG, 2007; KRYSTYN, 2008). After this siliciclastic event a new carbonate ramp built up in Tuvalian time (Opponitz and Waxeneck Formations). On top, the classic Late Triassic Hauptdolomit/Dachstein Carbonate Platform was formed during optimum climatic and geodynamic conditions in the Norian and Rhaetian.

At the Triassic/Jurassic boundary, the carbonate production rate significantly decreased. This occurred in connection with an environmental crisis that led to mass extinction and was accompanied by a sea-level drop (compare SEPKOSKI, 1996). Regardless of the causes of this mass extinction, which are intensively debated (summarized e.g., in PÁLFY, 2008), these environmental events left a signature in the Austroalpine domain (e.g., HILLEBRANDT & KRYSTYN, 2009; RICHOZ et al., 2012).

Earliest Jurassic sediments are missing on top of the morphologic highs (former Hauptdolomit/Dachstein Carbonate Platform). Only in basinal areas sedimentation was continuous (HILLEBRANDT & KRYSTYN, 2009). Lack of sufficient sediment supply led to drowning of the Hauptdolomit/Dachstein Carbonate Platform in Late Hettangian times due to a sea-level rise. The spread and morphology of the facies zones in the Early to early Middle Jurassic followed in general the Triassic inventory (Fig. 5) except in the lower Austroalpine units and equivalents.

Later on, a horst and graben morphology developed (BERNOULLI & JENKYNS, 1974; EBERLI, 1988; KRAINER et al., 1994) and triggered breccia formation along submarine slopes and escarpments, mainly in Late Pliensbachian to Early Toarcian times (BÖHM et al., 1995). An increasing pelagic influence was manifested in the Early to Middle Jurassic sediments (GARRISON & FISCHER, 1969; BÖHM, 1992). Breccia formation in late Early Jurassic time is mostly interpreted as a result of the opening of the Ligurian/Penninic (= Alpine Atlantic) Ocean (e.g., BERNOULLI & JENKYNS, 1974; EBERLI, 1988; KRAINER et al., 1994), named Penninic Ocean in the Eastern Alpine realm (compare Fig. 3). Whereas the older part of the Early Jurassic sequences near to the Penninic realm (Lower Austroalpine passive continental margin) shows the typical features of a rifted margin (e.g., EBERLI, 1988), the other areas of the Austroalpine were only slightly influenced by these rifting processes. In contrast, late Early Jurassic (Late Pliensbachian to Early Toarcian) tectonics affected mainly the Dachstein Limestone facies belt (Fig. 5) and resulted in a completely new palaeogeographic setting. Meanwhile the Lower Austroalpine passive margin was not or only mildly influenced by these tectonic processes.

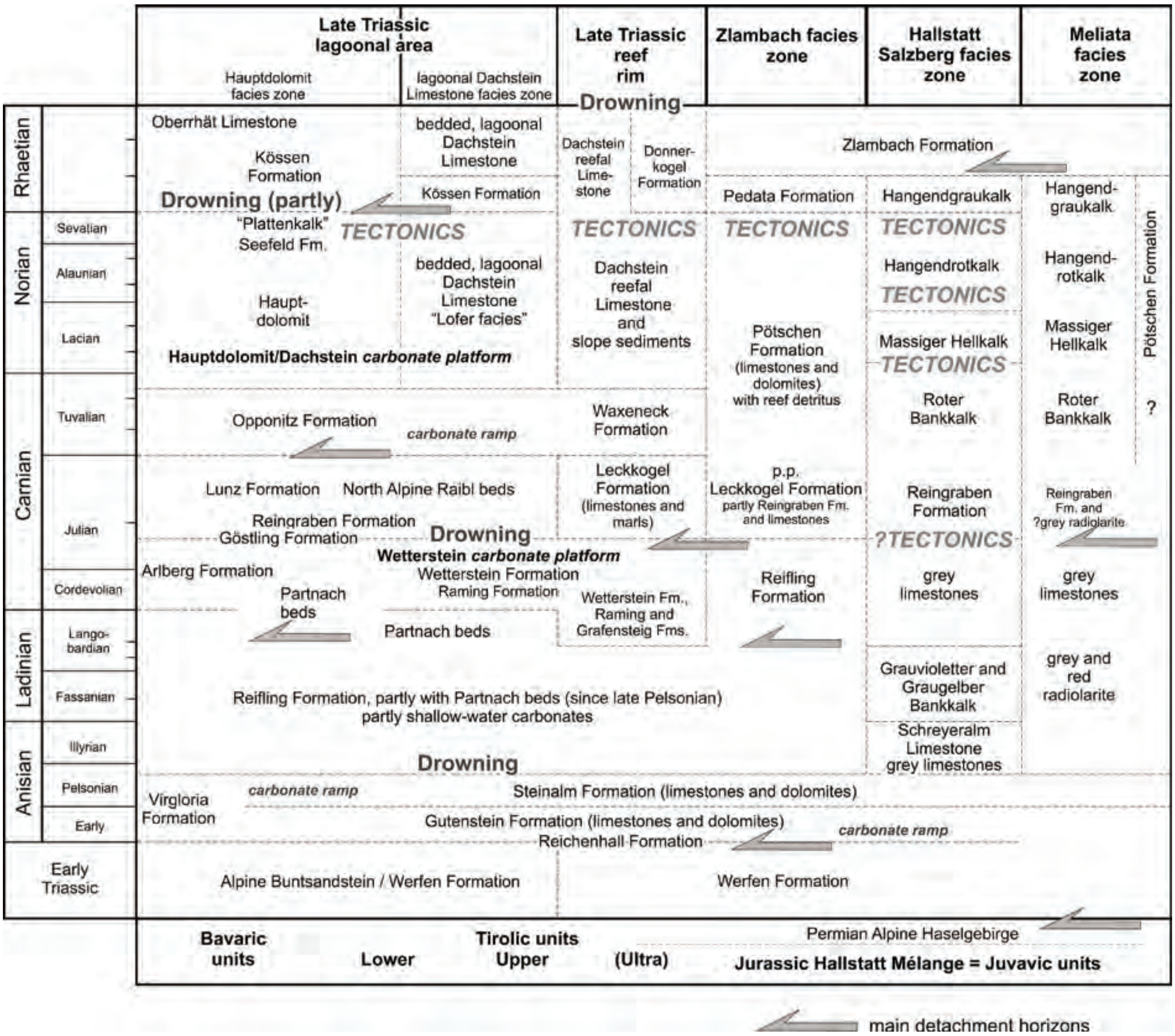
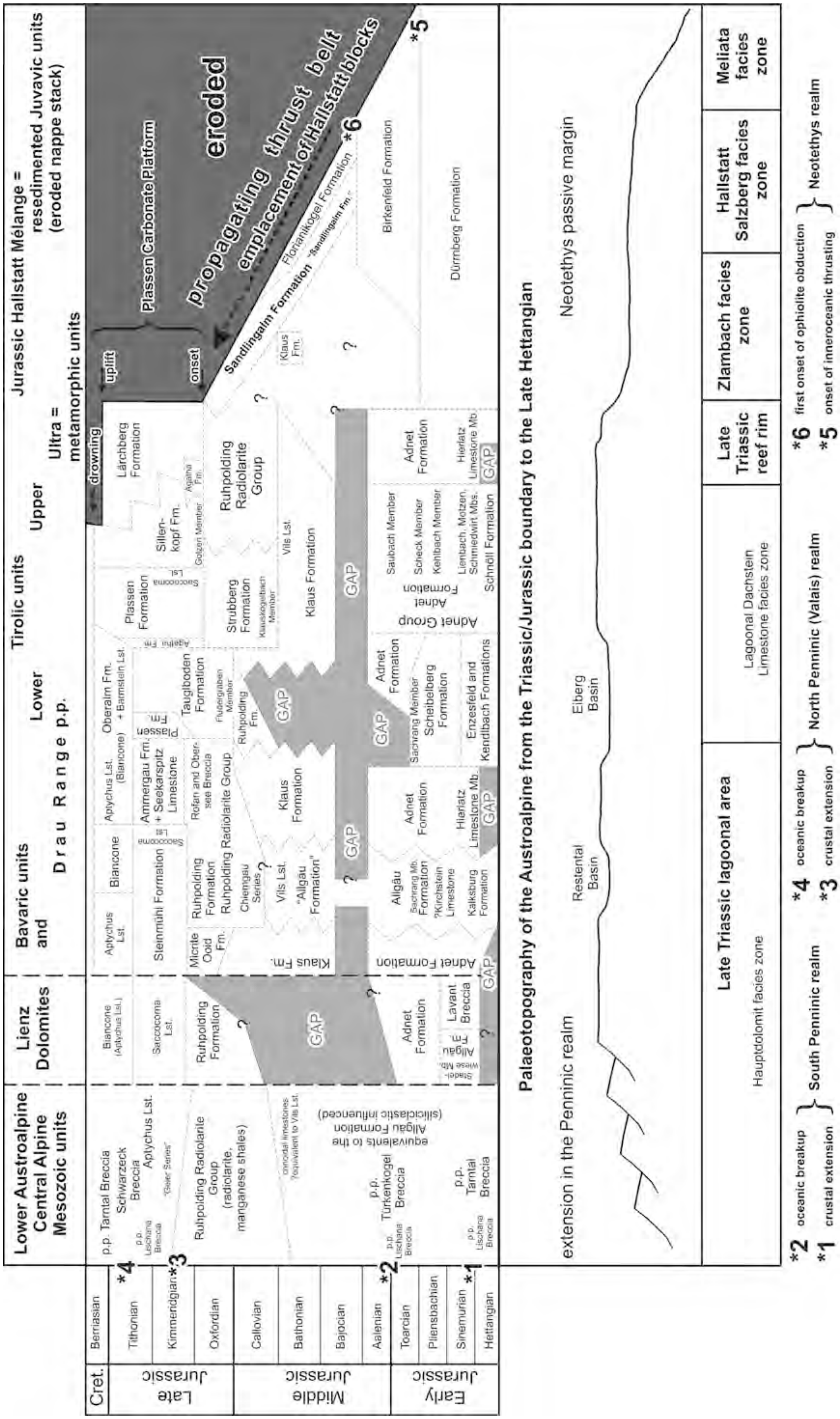


Figure 4: Lithostratigraphic table of Triassic formations and tectonic events in the central Northern Calcareous Alps (modified after TOLLMANN, 1985; GAWLICK & FRISCH, 2003; PILLER et al., 2004; MISSONI & GAWLICK, 2011a, b). The main detachment horizons are indicated because of their importance during Jurassic nappe stacking and disintegration of the sequence in the course of mélange formation. The colours of the different facies belts in this figure correspond to the colours in the other figures, clarifying the provenance of the different clasts and slides in the Jurassic basin successions (after MISSONI & GAWLICK, 2011a). Compare also Fig. 6.

Figure 5 (next page)**:** Stratigraphic table with lithostratigraphic names and main tectonic events of the Jurassic in the Austroalpine realm with their variations depending on the palaeogeographic position (after GAWLICK et al., 2009a; compare Fig. 4, Fig. 6). In red the sedimentary succession which will be visited during the field trip. Bavaric units, Tirolic units, Hallstatt Mélange = Northern Calcareous Alps.


Lower Austroalpine Central Alpine Mesozoic units
Lienz Dolomites
Bavaric units and Tirolic units Lower Upper
Drau Range p.p.
Ultra = metamorphic units
Jurassic Hallstatt Mélange = resedimented Juvavic units (eroded nappe stack)
eroded
propagating thrust belt
emplacement of Hallstatt blocks
Plassen Carbonate Platform
Sandlingalm Formation
Neotethys passive margin
extension in the Penninic realm
Palaeotopography of the Austroalpine from the Triassic/Jurassic boundary to the Late Hettangian
Late Triassic lagoonal area
Late Triassic reef rim
Zlambach facies zone
Hallstatt Salzberg facies zone
Meliata facies zone
*2 oceanic breakup
*1 crustal extension
South Penninic realm
*4 oceanic breakup
*3 crustal extension
North Penninic (Valais) realm
*6 first onset of ophiolite obduction
*5 onset of inneroceanic thrusting
Neotethys realm

Many authors interpreted the above described change in the late Early Jurassic as a result of the opening of the Penninic Ocean (e.g., EBERLI, 1988; KRAINER et al., 1994). In contrast, FRISCH & GAWLICK (2003), GAWLICK et al. (2009a) and MISSONI & GAWLICK (2011a, b) attributed this “event“ to the onset of subduction in the Neotethys Ocean realm.
In late Early to Middle Jurassic times the situation generally changed also in the former (Triassic) carbonate platform area due to the partial closure of the Neotethys Ocean (Fig. 3). Concerning the active margin, the Austroalpine domain attained the lower plate position (GAWLICK et al., 1999a). The tectonics of this time span were characterized by a propagating thrust belt in front of the overriding ophiolite nappe stack, as proven in the Albanides and Dinarides (GAWLICK et al., 2008, 2009b). In the Eastern Alps and the Northern Calcareous Alps, respectively, the obducted ophiolite nappe stack is not preserved. Here, only pebbles in the Late Jurassic to Early Cretaceous deep-water sedimentary successions prove this ophiolite obduction stage (summarized in GAWLICK et al., 2009a; KRISCHE et al., in press). The same story is visible in the southern Western Carpathians (FROITZHEIM et al., 2008; KOVACS et al., 2011; HAAS et al., 2011).

Middle Jurassic northwest-directed thrusting caused the formation of deep-water trench-like basins in front of the propagating nappes which obliquely cut through former facies belts. Tectonic shortening decreased in Late Jurassic time. In contrast to the Triassic evolution, shallow-water carbonates are generally missing in the Austroalpine domain during most time of the Jurassic until the Late Oxfordian, when new shallow-water carbonate ramps and platforms established (Fig. 3) and sealed the main tectonic shortening structures. They existed until the Early Cretaceous. Siliciclastic influenced sediments occurred in the southern Northern Calcareous Alps in the Kimmeridgian and in the more northward parts in the Early Cretaceous (Fig. 3).

NW-SE directions refer to Triassic-Jurassic palaeogeographic reconstructions. North-South geographic directions refer to the Present as a result of a complex rotation history of the Eastern Alps since Late Cretaceous (e.g., HAUBOLD et al., 1999; CSONTOS & VÖRÖS, 2004; THÖNY et al., 2006; PUEYO et al., 2007).

3 Palaeogeography, sedimentary successions and stratigraphy

The reconstruction of the Triassic palaeogeography, i.e., the facies zones of the shallow-water Hauptdolomit/Dachstein Carbonate Platform and its gradual transition to the hemipelagic Hallstatt Zone, has been arranged in a characteristic shore parallel fashion (Fig. 6) (LEIN, 1985; KRYSTYN & LEIN 1995 in HAAS et al., 1995; GAWLICK et al., 1999a). Their Late Anisian to Early Jurassic sedimentary succession represented an open marine, distal periplatform setting on the Triassic European continental margin facing the Neotethys Ocean (= Meliata Ocean or Meliata-Hallstatt Ocean according to, e.g., KOZUR, 1991; SCHWEIGL & NEUBAUER, 1997a; NEUBAUER et al., 2000; STAMPFLI et al., 2001; STAMPFLI & KOZUR, 2006).
The variegated Hallstatt Salzberg facies represents the oceanward belt on this margin, giving way to siliceous limestones and radiolarites towards the Neotethys Ocean (= Meliata facies; Fig. 6). In the sedimentary environment of the Hallstatt Salzberg facies with relatively stable hemipelagic conditions for at least 40 Ma, the existence of large intermediate shallow-water carbonate platforms is quite unrealistic (GAWLICK & BÖHM, 2000). Only the Zlambach facies zone received shallow-water debris from the large, flat-topped Triassic carbonate platforms.

3.1 Hauptdolomit facies zone

Triassic

The Hauptdolomit facies zone is preserved only in the lower structural units of the Northern Calcareous Alps (Bavaric and in parts Tirolic nappes). Permian and Early Triassic sediments are mostly missing in these profiles as a result of the usage of shallower detachment levels during younger tectonic movements (TOLLMANN, 1985). The thickness of the Middle and Late Triassic formations (Fig. 4) can only be roughly estimated due to the polyphase tectonic history, but could be around 4-5 km (BRANDNER, 1984).

Carbonate production started around the Early/Middle Triassic-boundary with carbonate ramp sediments above the Alpine Buntsandstein (STINGL, 1989) and the evaporitic Reichenhall Formation. The lower Gutenstein Formation was formed in a restricted, periodically hypersaline lagoonal area. The overlying Steinalm Formation (in case with the Annaberg Formation – LEIN et al. (2010) – between) represent sediments of more open marine conditions, partly forming small build-ups and reefal structures created particularly by calcareous algae and microbial mats. The Gutenstein and Steinalm Formations are named Virgloria Formation in the western Northern Calcareous Alps (PILLER et al., 2004). In Late Anisian time a large part of this (Steinalm) carbonate ramp was drowned and widespread basinal carbonate sedimentation took place (grey, cherty limestones of the Reifling Formation) (BECHSTÄDT & MOSTLER, 1974, 1976; KRYSTYN, 1991; KRYSTYN & LEIN, 1996). According to GAWLICK (2000a) and MISSONI & GAWLICK (2011a) the hemipelagic carbonatic basins were separated from the open shelf area by the growing Wetterstein carbonate platforms to the southeast in the Late Ladinian (Langobardian) (compare KRYSTYN & LEIN, 1996; LEIN et al., 2012). The Reifling sedimentation was replaced by fine-grained siliciclastic deposition of the Partnach Beds. During Early Carnian, after a regressive/transgressive cycle the Wetterstein Carbonate Platform (Arlberg and Wetterstein Formations) started to prograde into this facies belt (BRANDNER & RESCH, 1981; KRYSTYN & LEIN, 1996; LEIN et al., 2012). South of the rapidly southeastward (towards the Dachstein Limestone facies zone) prograding platform (Raming Formation as slope deposits: LEIN, 1989), a basinal area prevailed in Early Carnian (Cordevolian) time. The youngest sediments in these basinal areas were the organic-rich grey, cherty limestones of the Göstling Formation. As consequence of the Lunz/Reingraben event (SCHLAGER & SCHÖLLNBERGER, 1974; LEIN et al., 1997; recently renamed as Carnian Pluvial Event), the Wetterstein Carbonate Platform drowned nearly in the whole area in Julian time and deposition of siliciclastic sediments (Lunz and Northalpine Raibl Formations) took over (TOLLMANN, 1976a, 1985; KRAINER, 1985). These siliciclastic deposits filled the basinal areas between the Wetterstein Carbonate Platforms, with the result of a uniform topography at the end of this siliciclastic event. In the Late Carnian, the siliciclastic input decreased rapidly and a new carbonate ramp was established (Opponitz-Waxeneck carbonate ramp). The transition between the early Late Carnian "Northalpine Raibl Formation" and the more carbonatic sedimentation farer to the south is gradual. Around the Carnian/Norian-boundary this carbonate ramp passed in the Late Triassic Hauptdolomit/Dachstein Carbonate Platform (for details see TOLLMANN, 1976a, 1985; GAWLICK & BÖHM, 2000). The Hauptdolomit ranges from ?latest Carnian/earliest Norian to the Middle/Late Norian, with newly formed intraplatform basins in Middle to Late Norian times (e.g., Seefeld Formation) (TOLLMANN, 1976a; DONOFRIO et al., 2003; compare BECHTEL et al., 2007). In the Late Norian, opening of the restricted Hauptdolomit lagoon resulted in deposition of the "Plattenkalk". In Early Rhaetian the lagoon deepened and renewed siliciclastic input led to deposition of the mixed terrigenous-carbonatic Kössen Formation (stratigraphic details in GOLEBIOWSKI, 1990a, 1991). In Late Rhaetian, the Kössen Formation was in many places overlain by shallow-water carbonates including reefal build-ups in some areas (Oberrhät Limestone: FLÜGEL, 1981). Within the Hauptdolomit facies zone, these shallow-water carbonates prograded from north towards south.

Jurassic

In the earlier Early Jurassic, the sedimentation was mainly controlled by the Late Triassic topography (Fig. 5; BÖHM, 2003; GAWLICK & FRISCH, 2003; GAWLICK et al., 2009a). Only in the westernmost part of the Austroalpine domain extensional tectonics led to the formation of the southeastern (Lower Austroalpine and equivalents) passive continental margin of the (South) Penninic Ocean (FRISCH, 1979; EBERLI, 1988; HÄUSLER, 1988) as part of the Central Atlantic system (Fig. 3, details of the whole evolution in GAWLICK et al., 2009a). Near to the future oceanic realm (start of sea-floor spreading in Late Toarcian: RATSCHBACHER et al., 2004) asymmetric, breccia-filled basins are common features (e.g., EBERLI, 1988). The influence of this extensional process decreased in eastern direction towards the Dachstein Limestone facies zone. Therefore, in most areas block tilting was relatively mild in the Hauptdolomit facies zone in direction towards the Dachstein Limestone facies belt.

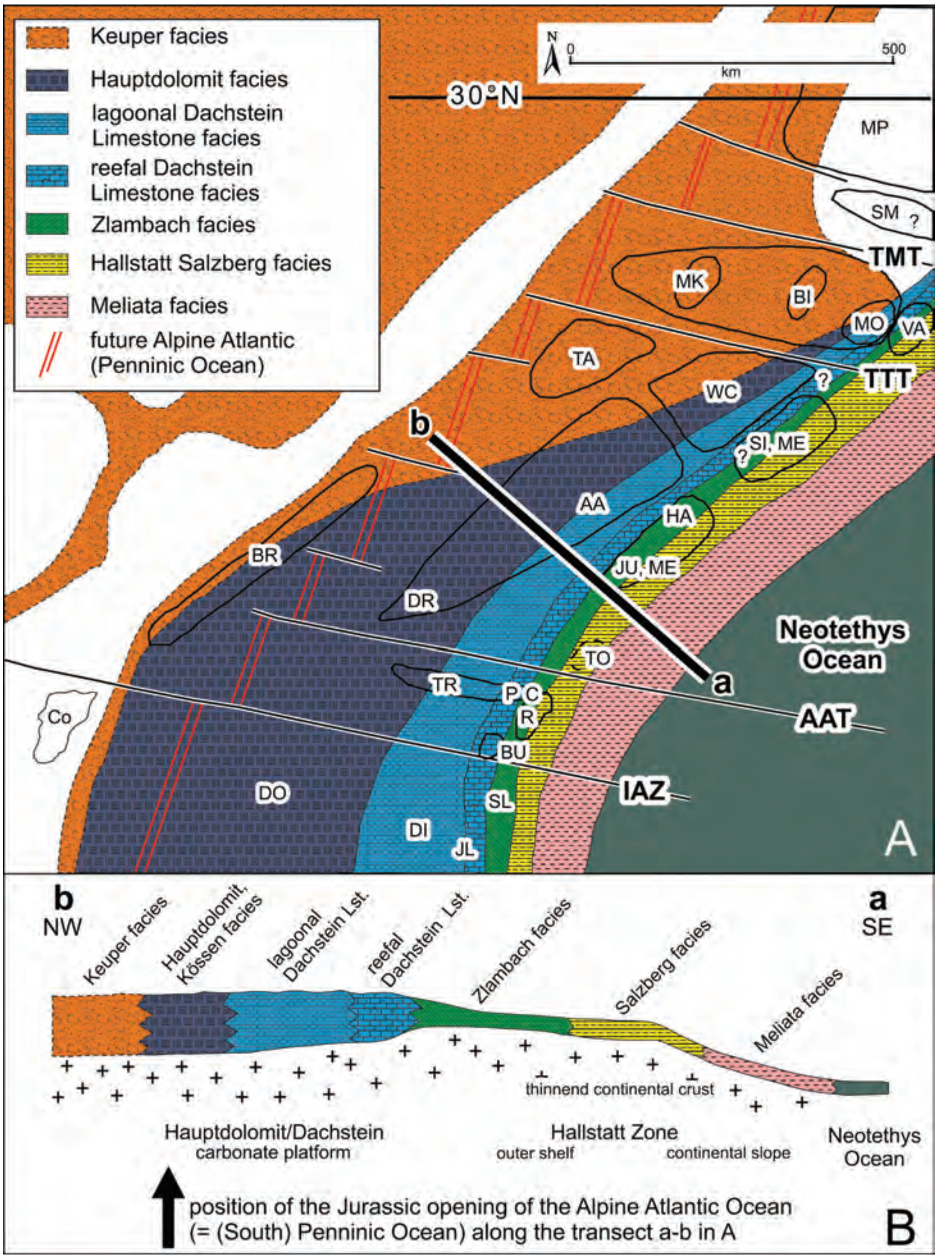


Figure 6: A) Late Triassic palaeogeographic position and facies zones of the Austroalpine domain as part of the northwestern Neotethys passive margin, modified after KRYSTYN & LEIN in HAAS et al. (1995) and GAWLICK et al. (1999a, 2008). **B**) Schematic cross section (for position, see line a-b in A) showing the typical passive continental margin facies distribution across the Austroalpine domain in Late Triassic time (after GAWLICK & FRISCH, 2003). Compare Fig. 3.
IAZ = Iberia-Adria Zone transform fault, AAT = future Austroalpine-Adria transform fault, TTT = future Tisza-Tatra transform fault, TMT = future Tisza-Moesia transform fault, AA = Austroalpine, BI = Bihor, BR = Briançonnais, BU = Bükk, C = Csovar, Co = Corsica, DI = Dinarids, DO = Dolomites, DR = Drau Range, HA = Hallstatt Zone, JU = Juvavicum, JL = Julian Alps, ME = Meliaticum, MK = Mecsek, MO = Moma unit, MP = Moesian platform, P = Pilis-Buda, R = Rudabanyaicum, SI = Silicicum, SL = Slovenian trough, SM = Serbo-Macedonian unit, TA = Tatricum, TO = Tornaicum, TR = Transdanubian Range, VA = Vascau unit, WC = central West Carpathians. For other reconstructions of the western Tethyan realm see, e.g., SENGÖR (1985a, b); CHANNELL et al. (1990, 1992); DERCOURT et al. (1986, 1993); MARCOUX & BAUD (1996); CHANNELL & KOZUR (1997); STAMPFLI & BOREL (2002); STAMPFLI & KOZUR (2006).

The Rhaetian shallow-water carbonates were overlain by red and grey crinoidal limestones in the Hettangian and Sinemurian, partly with a gap in the depositional record (EBLI, 1997). On top of the Rhaetian Kössen Formation cherty and marly bedded limestones were deposited (Kalksburg Formation and Kirchstein Limestone). These sediments progressed gradually into the hemipelagic Allgäu Formation (Sinemurian to ?Bathonian). In the depositional areas of the Adnet and Enzesfeld Formations, condensed sedimentation prevailed partly until the late Middle Jurassic. Red limestone deposition resumed in the form of the Steinmühl or Klaus Limestones (Bajocian to Tithonian; KRYSTYN, 1971, 1972). In the Callovian to Oxfordian there was a widespread deepening of the depositional environment, which resulted in the sedimentation of cherty limestones, cherty marls, and radiolarites. In basinal areas on top of the Allgäu Formation, dark grey cherty marls and cherty limestones were deposited. These were formerly interpreted as early to late Middle Jurassic Allgäu Formation (EBLI, 1997; PILLER et al., 2004), but are in fact time equivalents of the Ruhpolding Radiolarite Group (Chiemgau series) in the sense of GAWLICK & FRISCH (2003), followed by *Saccocoma* Limestone. On the Early to Middle Jurassic topographic highs, red condensed limestones or condensed radiolarites were deposited (Callovian to Kimmeridgian). In the Kimmeridgian the siliceous sedimentation passed gradually to a marlier and then limier one, which is characteristic for the Tithonian to Early Berriasian (Ammergau Formation, Aptychus beds, Biancone). Typical Aptychus beds beside Biancone were deposited in the Late Tithonian.

3.2 Dachstein Limestone facies zone

Triassic

In the Dachstein Limestone facies zone (mainly preserved in the Tirolic unit) the stratigraphic and facial evolution reflects the intermediate passive margin setting between the Hauptdolomit facies zone and the Hallstatt facies belt (Fig. 6). The thickness of the Middle and Late Triassic formations is slightly higher compared to that in the Hauptdolomit facies zone.

Carbonate production began in the Late Olenekian, slightly earlier than in the Hauptdolomit facies zone (MOSTLER & ROSSNER, 1984), followed by the evaporitic Reichenhall Formation around the Olenekian/Anisian-boundary. Increased carbonate productivity started also around the Early/Middle Triassic-boundary with carbonate ramp sediments (Gutenstein and Steinalm Formations) above the Alpine Buntsandstein/Werfen Formation and the evaporitic Reichenhall Formation. In Late Anisian time, large part of this carbonate ramp drowned and widespread basinal sedimentation took place, with dolomites predominating, (Reifling Formation) (e.g., MISSONI & GAWLICK, 2011a). The siliciclastic influenced Partnach Formation was deposited in the northern part of this facies belt, whereas in the more southeastern part of this facies belt the Wetterstein Carbonate Platform was formed since the Late Ladinian (KRYSTYN & LEIN, 1996). Transitional to the hemipelagic open shelf areas, the Raming and Grafensteig Formations (HOHENEGGER & LEIN, 1977) were formed. This platform drowned in Julian time nearly in the whole facies belt in the wake of the Lunz/Reingraben event (SCHLAGER & SCHÖLLNBERGER, 1974; recently renamed as Carnian Pluvial episode: SIMMS & RUFFEL, 1989). Siliciclastic (e.g., Lunz/Raibl Formation, Reingraben Formation) and carbonatic sediments (Cidaris Limestone) were deposited. As in the Hauptdolomit facies belt, these siliciclastic rocks filled the basinal areas between the Wetterstein Carbonate Platforms, leading to a nearly uniform topography at the end of the siliciclastic event. In the Late Carnian the siliciclastic input decreased rapidly and a new carbonate ramp was established. The Opponitz Formation was deposited under shallow-water, partly evaporitic conditions in the northern part of the Dachstein facies belt. Towards south, the environment passed gradually to a more open marine one, however, with the shallow-water Waxeneck Formation in the southern part of the Dachstein Limestone facies zone (KRYSTYN et al., 1990). Around the Carnian/Norian-boundary, this carbonate ramp passed into the lagoonal to reefal Dachstein Limestone platform. The Dachstein Limestone ranged from the lowermost Norian to the Late Norian, without recognised intraplatform basins in the Middle or Late Norian. In Early Rhaetian, the northern part of the Dachstein Limestone lagoon deepened by siliciclastic input and changed to the mixed terrigenous-carbonatic sedimentation of the Kössen Formation, intercalated by the "*Lithodendron*" reef limestone (GOLEBIOWSKI, 1990, 1991). In the Late Rhaetian, the Kössen Formation was occasionally overlain by shallow-water, partly reefal carbonates (Oberrhät Limestone or Rhaetian Dachstein Limestone). The Rhaetian Dachstein Carbonate Platform (FLÜGEL, 1981; SCHÄFER & SENOWBARI-DARYAN, 1981) prograded from south towards north.

The southern part of the Dachstein Limestone facies zone, i.e., the reef rim (Upper Tirolic nappe), represented the transitional area from the lagoonal area to the open marine shelf (reef rim and transitional zone to the Hallstatt facies zone). The early Middle Triassic sedimentary succession of this transitional area is similar to those of the other parts of this facies belt. An Early Ladinian transition of the Reifling Formation into the Hallstatt Limestone is partly preserved. The formation of the Wetterstein Carbonate Platform started in the Late Ladinian. It rapidly prograded towards southeast (Raming Formation: LEIN, 1989). The Lunz/Reingraben event affected these areas only peripheral with thin, fine-grained siliciclastic sediments (Reingraben Beds). In some areas, shallow-water organisms survived the event as recorded in the Julian Leckkogel Formation (DULLO & LEIN, 1982). The Leckkogel Formation passed gradually into the Late Carnian Waxeneck Formation (LEIN in KRYSTYN et al., 1990) and later into "Hallstatt Limestones" (eastern Northern Calcareous Alps, Mürzalpen nappe; LEIN, 1987b) or the Norian to earliest Rhaetian reefal Dachstein Limestone (ZANKL, 1969; FLÜGEL, 1981; KRYSTYN et al., 2009; RICHOZ et al., 2012) which drowned in Early Rhaetian time (KRYSTYN et al., 2009: Donnerkogel Formation). In fact, in this palaeogeographic area a vertical mixture of basinal sediments, fore reef to back reef sediments, and partly lagoonal sediments occurred, reflecting sea-level fluctuations and possibly ?extensional tectonic movements (LEIN, 1985; GAWLICK, 1998, 2000a; GAWLICK & BÖHM, 2000; compare MISSONI et al., 2008: strike-slip tectonics). In Late Norian time, in some areas of this facies belt hemipelagic sequences were deposited in newly formed basins (Mürztal facies, Aflenz facies: LEIN, 1982, 1985, 2000; TOLLMANN, 1985).

Jurassic

In the Early Liassic, the sedimentation was controlled by the topography of the Late Triassic Hauptdolomit/Dachstein Carbonate Platform (Fig. 5, BÖHM, 2003; GAWLICK & FRISCH, 2003). On top of the Rhaetian shallow-water carbonates red condensed limestones of the Adnet Group (Hettangian to Toarcian: BÖHM 1992, 2003) were sedimented, partly above a depositional gap. On top of the Rhaetian Kössen Formation cherty and marly bedded limestones (Scheibelberg Formation: Hettangian to Toarcian; Kendlbach Formation: Hettangian: BÖHM, 1992, 2003; EBLI, 1997; KRAINER & MOSTLER, 1997) were deposited in the transitional areas to the Rhaetian Kössen Basin crinoidal or sponge spicula rich limestones of the Enzesfeld Formation (Hettangian to Sinemurian: BÖHM, 1992). In the Late Pliensbachian and Early Toarcian, a horst and graben morphology developed (BERNOULLI & JENKYNS, 1974; KRAINER et al., 1994) and triggered breccia formation along submarine slopes and escarpments (BÖHM et al., 1995). On the horsts, the Toarcian and most of the Middle Jurassic (if deposited) are either characterized by starved sedimentation and ferro-manganese crusts or by a hiatus. In contrast, the grabens were filled with deep-water carbonates and breccias shed along fault scarps. Neptunian dykes developed in various places. In these newly formed basinal areas grey bedded limestones were deposited, whereas the topographic highs were covered by condensed red limestones of the Klaus Formation (e.g., KRYSTYN, 1972).

This sedimentation pattern diachronously changed dramatically in the late Middle Jurassic (GAWLICK & FRISCH, 2003) when deposition of radiolarian cherts, radiolarian-rich marls and limestones of the Ruhpolding Radiolarite Group commenced (DIERSCHE, 1980). For details see the description below.

3.3 Hallstatt facies zone (preserved in the reworked Jurassic Hallstatt Mélange)

The mostly condensed Triassic to Early Jurassic hemipelagic succession was deposited in an outer shelf depositional setting (Fig. 4, Fig. 6).
The Hallstatt facies zone (i.e., Hallstatt Zone) is subdivided into three facies zones:

a) Zlambach/Pötschen facies zone (grey Hallstatt facies, Zlambach/Pötschen facies with shallow-water allodapic limestone intercalations from the Dachstein reef rim).
b) Hallstatt Limestone facies zone (red or variously coloured Hallstatt facies or Hallstatt Salzberg facies) (for newest review see KRYSTYN, 2008).
c) Meliata facies zone (LEIN, 1987a; GAWLICK et al., 1999a); including the Pötschen Limestone *sensu stricto* (compare MOSTLER, 1978). Recently the depositional area of the Pötschen Limestone without shallow-water influx (Pötschen Formation *sensu stricto*) has been interpreted as transitional facies from the Meliata facies belt (continental slope) to the oceanic realm (MISSONI & GAWLICK, 2011a, b, compare GAWLICK et al., 2008).

Remnants of this facies belt are only present in the Middle to Late Jurassic radiolaritic trenches and on top of them, where all sedimentary rock types of the Hallstatt facies belt from the Triassic platform transitional area to the Meliata facies zone occur (for details: GAWLICK & FRISCH, 2003; GAWLICK et al., 2009a, 2012; MISSONI & GAWLICK, 2011a).

Zlambach facies zone (Gosausee facies)

Early Triassic as well as Early and Middle Anisian sediments of this facies belt are not preserved within continuous sections. Fine-grained siliciclastic sediments of the Werfen Formation only occur as components together with components of the Gutenstein and Steinalm Formations and the complete reconstructable hemipelagic Late Anisian to Early Jurassic succession of this facies belt (GAWLICK, 1996; GAWLICK et al., 2012). Late Anisian to Ladinian Reifling Limestone is also proven in the form of small components within late Middle Jurassic mass-flow deposits (GAWLICK, 1996, 2000b). The oldest continuously preserved sections start with well bedded, chert-rich limestone or hemipelagic dolomite of earliest Carnian age (GAWLICK, 1998). The Julian *Halobia* Beds did not form a uniform, laterally persistent sedimentary layer in this facies belt but are partly preserved in some sections (MANDL, 1984). In Late Carnian to Middle Norian times, mostly well-bedded cherty hemipelagic limestones of the Pötschen Formation with shallow-water allodapic limestone intercalations were deposited in more distal shelf areas (LEIN, 1985; GAWLICK, 1998; MISSONI & GAWLICK, 2011a), probably transitional to the red or variously coloured Hallstatt facies zone (LEIN, 1981; LEIN & GAWLICK, 1999). Hemipelagic dolomites (Pötschen Dolomite similar to the Baca Dolomite of the Slovenian Trough and equivalents in the Cukali area of Albania) and bedded cherty limestones occurred in more proximal position near to the transitional area of the carbonate platforms and ramps. Here the carbonate platform facies and evolution is reflected in the carbonate basinal facies (REIJMER & EVERAAS, 1991). Due to sea-level fluctuations occasionally shallow-water carbonates were deposited also (GAWLICK, 1998). Terrigenous input and synsedimentary tectonics (strike-slip related movements according to MISSONI et al., 2008), led to more complex sedimentary facies patterns in Late Norian to Early Rhaetian times. This is expressed e.g. in different lithologies of the Pedata Formation: e.g., Pedata Plattenkalk, Pedata Dolomite, Pedata Limestone (MANDL, 1984; GAWLICK, 1998, 2000a). Also the basinal areas of the Mürzalpen facies and Aflenz facies were deepened during this time interval (LOBITZER, 1974; LEIN, 1982). Since Rhaetian times (KRYSTYN, 1987, 2008) the marly Zlambach Formation was deposited, which passed gradually into the Early Jurassic Dürrnberg Formation (GAWLICK et al., 2001, 2009a). The youngest known sediments in the Hallstatt facies zone are thick cherty to marly successions of the Toarcian to Aalenian Birkenfeld Formation (GAWLICK et al., 2009a; Missoni & GAWLICK, 2011a, b).

Hallstatt Limestone facies zone

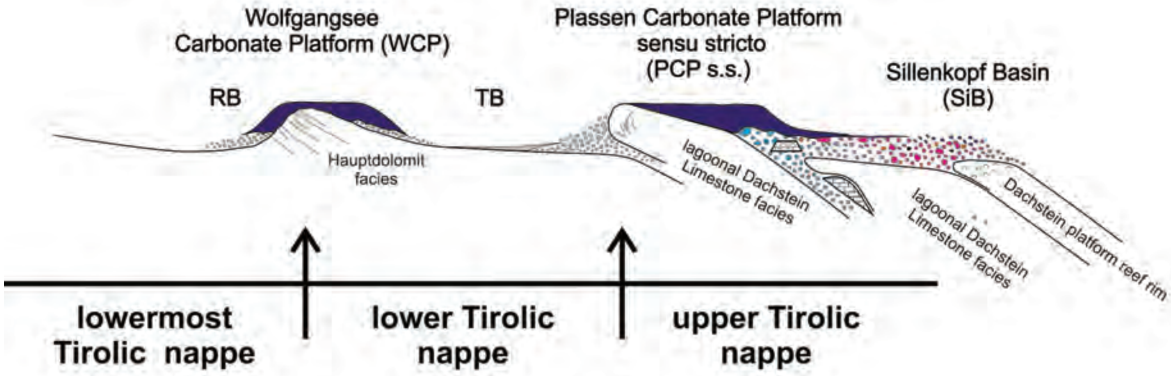
As distal continuation of the Zlambach facies zone (grey Hallstatt facies), the red or variously coloured Hallstatt facies (LEIN, 1987a; KRYSTYN, 2008) sedimentation started with the drowning of the Steinalm carbonate ramp in Anisian (Late Pelsonian) time. Early Triassic Werfen Formation is only proven as components in Late Triassic Hallstatt Limestone (LEIN, 1981). The Middle Anisian Steinalm Formation followed stratigraphically the lower Anisian Gutenstein Formation. Between these two shallow-water formations the more open marine Sulzkogel and Rabenkogel Members of the Annaberg Formation (LEIN et al., 2010) indicate the first flooding related to the continuing thinning of the underlying continental crust (LEIN, 1987a). Hemipelagic sedimention started in late Middle Anisian with the condensed red Schreyeralm Limestone (e.g., KRYSTYN et al., 1971; TOLLMANN, 1985), contemporaneous with the break-up of the Neotethys Ocean (GAWLICK et al., 2008), followed by the Grauvioletter-Graugelber Bankkalk (Ladinian), the Hellkalk (Late Ladinian to Early Carnian), *Halobia* Beds (Julian), the Roter Bankkalk (Tuvalian), the Massiger Hellkalk (Lacian), the Hangendrotkalk (Alaunian to Sevatian), the Hangendgraukalk (Sevatian to Early Rhaetian) (KRYSTYN, 1980, 2008) and the Zlambach Marls (Rhaetian: KRYSTYN, 1987, 2008). These passed gradually into the Early Jurassic Dürrnberg Formation which is overlain by the Birkenfeld Formation (see above).

Meliata facies zone to Neotethys Ocean

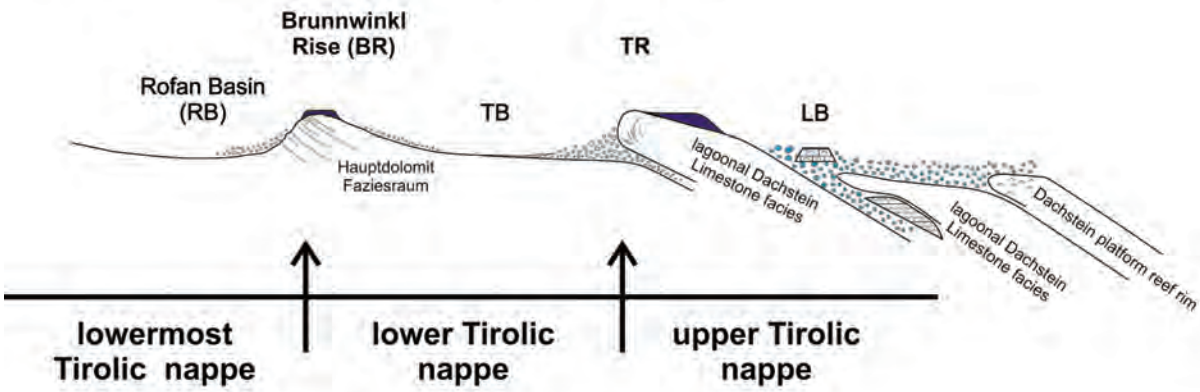
The Meliata facies zone represents the most distal part of the Triassic shelf area, the continental slope and the transition to the Neotethys Ocean. Rare remnants of this facies belt are described from the eastern (MANDL & ONDREJICKOVÁ, 1991, 1993; KOZUR & MOSTLER, 1992) and from the central Northern Calcareous Alps (GAWLICK, 1993; KRISCHE et al., in press). These remnants occur partly as metamorphosed isolated slides (Florianikogel area) or as breccia components in Middle/Late Jurassic or Cretaceous successions. A general stratigraphic reconstruction shows Middle Triassic radiolarites and partly cherty marls followed by Early Carnian *Halobia* Beds and Late Carnian to Early Rhaetian Hallstatt Limestone (red and grey). Younger sediments are so far not proven, but a similar sedimentary succession like in the Hallstatt Limestone facies zone can be expected. The Meliata facies zone is thought to have been the most oceanward facies belt underlain by continental crust, incorporated in the evolving imbricate wedge during the closure of the western part of the Neotethys Ocean (starting in the late Early Jurassic as mentioned by GAWLICK & FRISCH, 2003; GAWLICK et al. 2009a; MISSONI & GAWLICK 2011a, b). Recently also sequences of the Pötschen Limestone *sensu stricto* have been interpreted to derive from the transitional area of the Meliata facies zone to the Neotethys Ocean (MISSONI & GAWLICK, 2011a, b; compare GAWLICK et al.; 2008, 2009b). Remnants of the Neotethys Ocean are very

Figure 7 (next page)**:** Oxfordian to Kimmeridgian tectonic and sedimentary evolution of the southern Northern Calcareous Alps and nappe subdivision. **A**) After the Middle Jurassic imbrication of the Middle Triassic to Early Jurassic Hallstatt facies belt, a new nappe front was formed in the lagoonal Dachstein Limestone facies zone (= Trattberg Rise). North of this nappe front a new deep-water basin was formed (= Tauglboden Basin). In contrast to the more northern regions (Rofan Basin area), where thin radiolarite sequences were deposited, the sedimentation in the Tauglboden Basin was characterized by an up to 800 m thick succession, consisting of radiolarites, slump deposits and different types of mass flows and slides. The Trattberg Rise separated the upper Tirolic nappe from the lower Tirolic nappe. **B**) Due to further tectonic shortening in the younger Middle or Late Oxfordian, a new nappe front established further north (= Brunnwinkl Rise). This uplifted nappe front domain supplied the newly created Rofan Basin to its north with eroded material (mass flows and slides). The lower Tirolic nappe was subdivided in a lowermost and a lower Tirolic nappe. In the Late Oxfordian first shallow-water carbonates were deposited, initially only in the area of the Trattberg Rise and later, from the Oxfordian/Kimmeridgian boundary onwards, also in the area of the Brunnwinkl Rise (compare Fig. 20). The Plassen Carbonate Platform started sealing the older nappe structures. **C**) In the Early Kimmeridgian the Plassen Carbonate Platform rapidly prograded over the adjacent basins. The Plassen Carbonate Platform *s. str.* prograded unidirectionally towards south: The Trattberg Rise was uplifted and shielded the Tauglboden Basin to its north. In contrast the Wolfgangsee Platform prograded both in southern and northern directions.

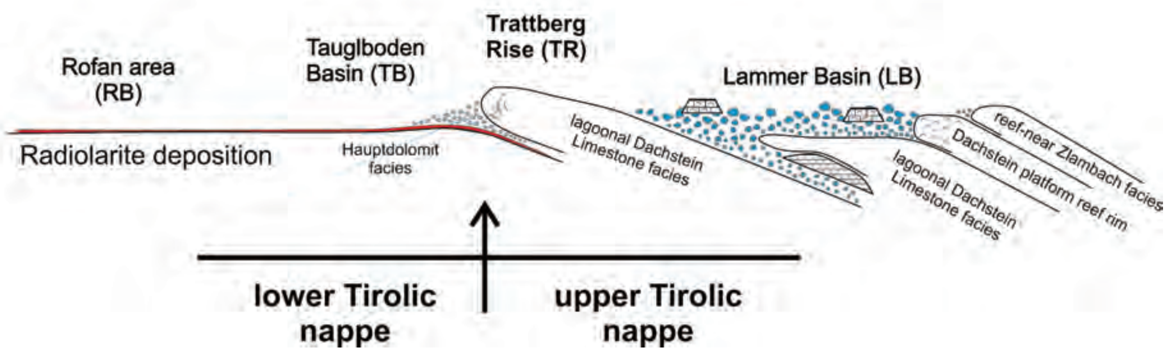
C) Early Kimmeridgian (~154 - 153 MA)
Evolution of the Plassen Carbonate Platform on top of the late Middle to early Late Jurassic nappe pile



B) Late Oxfordian (~156 MA)
Formation of the lowermost Tirolic nappe



A) Early/Middle Oxfordian (~161 - 158 MA)
Formation of the lower Tirolic nappe



scarce in the Northern Calcareous Alps. First ophiolite derived detritus occur in the Kimmeridgian Sillenkopf Formation (MISSONI et al., 2001; MISSONI, 2003; MISSONI & GAWLICK, 2011a, b) and more massive in the Early Cretaceous Rossfeld Formation (e.g., FAUPL & TOLLMANN, 1979; FAUPL & POBER, 1991; VON EYNATTEN & GAUPP, 1999; SCHWEIGL & NEUBAUER, 1997a, b), whereas sedimentary rocks of the Neotethys ocean floor (Triassic radiolarites) were only described from pebbles which occur in the basal parts of the Gosauic sequence in the southeastern Northern Calcareous Alps (SUZUKI et al., 2007). There they occur together with ophiolite rocks and Middle Jurassic amphibolites (SCHUSTER et al., 2007), most probably representing remains of the metamorphic soles as known from the Dinaride/Mirdita ophiolites (e.g. KARAMATA, 2006). Recently Triassic radiolarites from the Neotethys Ocean floor together with ophiolite material were detected also in the Early Cretaceous Rossfeld Formation in the central Northern Calcareous Alps (KRISCHE et al., in press).

Middle Jurassic to Early Cretaceous geodynamic evolution

In the Alpine-Carpathian domain the sedimentation pattern diachronously changed from carbonate to siliceous deposition in the Middle Jurassic (SCHLAGER & SCHÖLLNBERGER, 1974). Also the tectonic regime changed. A characteristic new feature was the formation of trench-like radiolaritic basins with up to 2.000 metres of sediment infill (GAWLICK, 1996) in their south-eastern, oceanward parts. This region was characterized by rapid subsidence due to tectonic load. In contrast, the northwestern, continentward edges of the Alpine-Carpathian domain were characterized by uplift and condensed sedimentation or erosion. The derivation of the resedimented components differs. In the southeastern basin group the material was shed either from the Triassic to Early Jurassic distal, hemipelagic to pelagic continental margin (Hallstatt and Meliata Zones) or from the Zlambach facies and the Dachstein reef rim zone. In contrast in the northwestern basin group, the material derived from the Triassic to Middle Jurassic lagoonal area (Dachstein and Hauptdolomit facies zones) (Fig. 6).

Each reconstruction of the Jurassic tectonic movements depends on detailed studies on the components and the stratigraphy of the siliceous matrix sediments. The following different carbonate-clastic, radiolaritic sequences with characteristic Middle to Late Jurassic sedimentation in the Northern Calcareous Alps can be distinguished (from south to north, except the Sillenkopf Basin which represents a remnant radiolaritic basin between the Lärchberg and the Plassen Carbonate Platform):

A. Florianikogel Basin with the Florianikogel Formation (Fig. 5): Its ?Bajocian to Callovian sediments contain material from the Hallstatt Limestone and Meliata facies zones (MANDL & ODREIJICOVÁ, 1991, 1993; KOZUR & MOSTLER, 1992; GAWLICK et al., 2009a) (Fig. 4, Fig. 6) and also include volcanogenic greywacke layers with erosional products derived from the Neotethys oceanic crust (NEUBAUER et al., 2007). This basin fill is similar to the Meliata Formation in the sense of KOZUR & MOCK (1985) in the Western Carpathians (KOZUR & MOCK, 1997; MOCK et al., 1998). For complications see AUBRECHT et al. (2010, 2012).
B. Sandlingalm Basin group with the Sandlingalm Formation (Fig. 5): These ?Bajocian/Bathonian to Late Oxfordian basins contain only material from the Hallstatt Limestone facies zone and limestones of the Meliata Zone (including the Pötschen Formation without shallow-water material; Fig. 4).
C. Lammer Basin with the Strubberg Formation (Fig. 5, Fig. 7): This Early Callovian to Middle Oxfordian basin contains mainly material from the Zlambach facies zone and the Dachstein Limestone reefs (GAWLICK, 1996; GAWLICK & FRISCH, 2003; MISSONI & GAWLICK, 2011a) (Fig. 5).
D. Tauglboden Basin with the Tauglboden Formation (Fig. 5, Fig. 7): In this Early Oxfordian to Tithonian basin (HUCKRIEDE, 1971; GAWLICK et al., 2009a), the first phase of resedimentation started in the Early Oxfordian (GAWLICK et al., 2007a) with material derived from the lagoonal Dachstein Limestone facies zone and ended around the Middle/Late

Oxfordian boundary. After a period of tectonic quiescence and low sediment supply in latest Oxfordian to Early Tithonian, the second phase of intense resedimentation had its climax in Late Jurassic reefal sediment clasts in the second phase is characteristic (STEIGER, 1981; GAWLICK et al., 2005).

E. Rofan Basin with the Rofan Breccia (Fig. 5, Fig. 7): Resedimentation started in the Late Oxfordian (GAWLICK et al., 2009a) with material derived from the Hauptdolomit facies zone (Fig. 5, Fig. 6; WÄCHTER, 1987) and prevailed until the Oxfordian/Kimmeridgian boundary or Early Kimmeridgian. By that time the sedimentation changed to mostly carbonate detritus, derived from a Late Jurassic carbonate platform to the south (Wolfgangsee Carbonate Platform - GAWLICK et al., 2007b, 2009a).

F. Sillenkopf Basin (Fig. 5, Fig. 7): The Kimmeridgian to ?Tithonian Sillenkopf Basin represents another type of basin. Its Sillenkopf Formation basin fill contains components of mixed palaeogeographic origin (MISSONI et al., 2001). The spectra of clasts in the Sillenkopf Formation prove the following provenance areas: A) The accreted Hallstatt units and an overlying Late Jurassic shallow-water carbonate platform, B) a deeply eroded hinterland further south (probably a part of the crystalline basement of the Northern Calcareous Alps), and C) an ophiolite nappe pile probably carrying an island arc (MISSONI & KUHLEMANN, 2001), similar to the obducted ophiolites which acted as source for radiolaritic-ophiolitic mélanges in the Dinaridic/Albanide realm.

The radiolarite basins A to E were formed in sequence, propagating from southeast to northwest (= from the Meliata to the Hauptdolomit facies zone) in the time span from the Bajocian to the Oxfordian/Kimmeridgian boundary. Basins A and C were accreted and overthrusted, basin B only partly. Basins D, E, F, and partly B existed in Kimmeridgian to early Early Tithonian times as remnant basins in between newly formed shallow-water carbonate platform areas of the Plassen Carbonate Platform *sensu lato*, the evolution of which commenced in the Late Oxfordian (AUER et al., 2009).

Another important tectonic pulse is related to mountain uplift, which started in Late Tithonian times. These relatively unexplored tectonic event and its influence on the tectonics which is partly reflected in the sedimentary record, was recently investigated in detail by KRISCHE (2012). This tectonic event resulted in the northward transport of the Haselgebirge Mélange, in parts including Hallstatt Mélange fragments, in the area of the Tauglboden basin. Mountain uplift and increasing erosion resulted in the diachronously drowning of the different parts of the Plassen Carbonate Platform (details in GAWLICK et al., 2009a, 2012). After the final drowning of the Plassen Carbonate Platform in Berriasian times (GAWLICK & SCHLAGINTWEIT, 2006) the erosional products of the uplifted mountain belt reached the northern part of the central Northern Calcareous Alps. Detailed component analysis of different mass-flows deposits in the Early Cretaceous Rossfeld Formation prove e.g. the existence of Triassic ophiolites south of the today´s Northern Calcareous Alps and it´s subophiolitic mélange (KRISCHE et al., in press). Components of the Triassic carbonate platforms or deep-shelf sediments were found nowhere in the Rossfeld formation, as stated by MISSONI & GAWLICK (2011a) for the type-locality or KRISCHE (2012) for all localities of the Rossfeld Formation in the central Northern Calcareous Alps. However, this result is another argument that the classical interpretations of an Early Cretaceous nappe thrusting model has to be changed.

4 The Field Trip

The main aim of this field trip is to understand the sedimentation of Austria's Northern Calcareous Alps and its tectonic circumstances from Triassic rifting/drifting to Jurassic collision/accretion, and the Early Cretaceous "post-tectonic" sedimentary history.
Another topic of this field trip through the central Northern Calcareous Alps (Fig. 8) is the study of the following deep-water basin fills with their underlying and overlying sedimentary successions:

- Sandlingalm Basin fill,
- Lammer Basin fill,
- Tauglboden Basin fill,
- Sillenkopf Basin fill (optional).

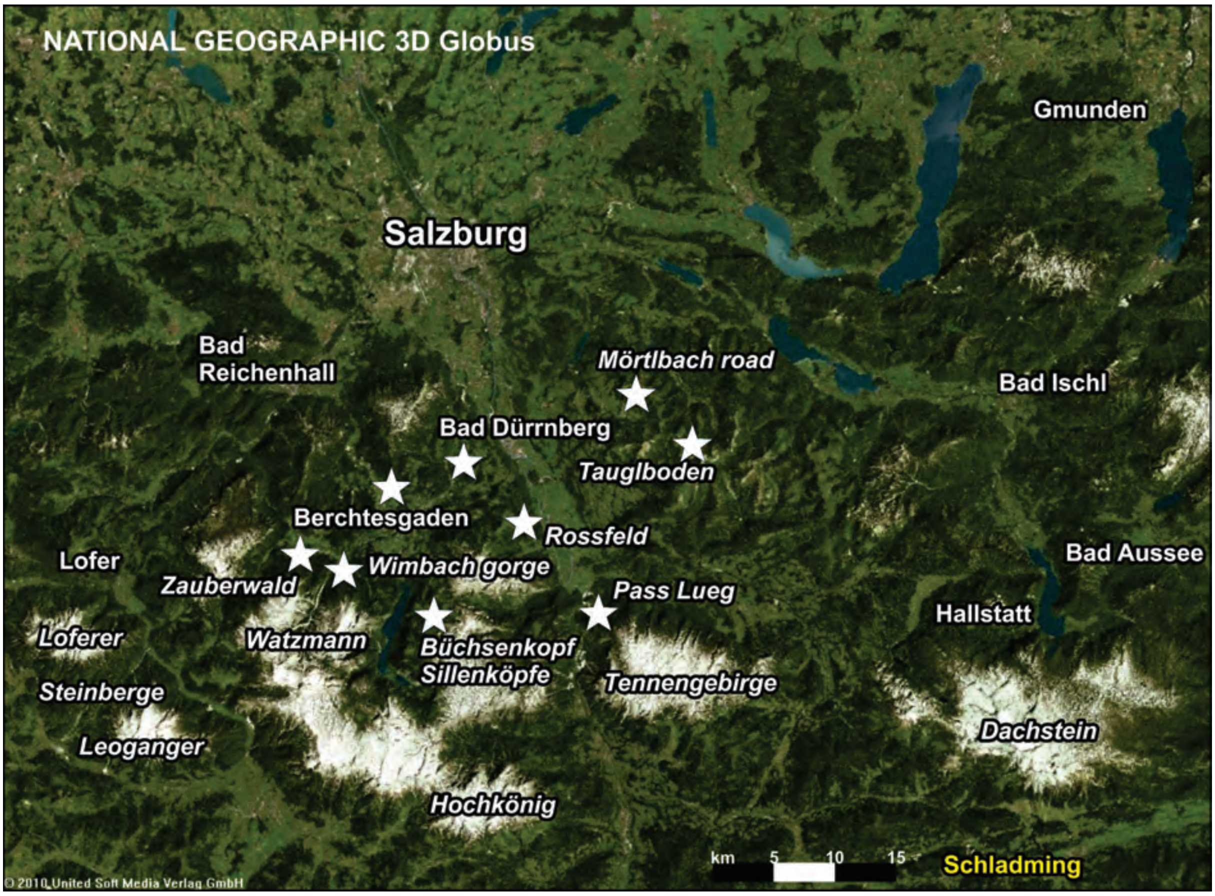


Figure 8: Satellite image of the central Northern Calcareous Alps, showing the localities which will be visited during this field trip (red stars). Around Pass Lueg and on the road along the Mörtlbach valley we will study the Norian/Rhaetian Hauptdolomit/Dachstein lagoon of the Hauptdolomit/Dachstein carbonate platform including the formation of the Rhaetian Kössen Basin (empty bucket). In the Wimbach gorge and on the road along the Mörtlbach valley we will study the Early-Middle Jurassic sequences. In the Bad Dürrnberg and Berchtesgaden area (Zauberwald) we will study the Sandlingalm Basin fill, in the Osterhorn block the Tauglboden Basin fill and the overlying resediments of the Plassen Carbonate Platform *s. str*. South of Berchtesgaden in the Nationalpark we will see the Lammer Basin fill (Büchsenkopf) and the Sillenkopf Basin fill (optional). For the Early Cretaceous we will visit the type-locality of the Rossfeld Formation (Rossfeld) which provides and also an excellent overview on the geological features in a regional scale of the Berchtesgaden and Salzburg Calcareous Alps.

The onset and drowning/demise of carbonate platforms (Plassen Carbonate Platform *sensu lato*) on top of the nappe stack and their progradation over the radiolarite basins and the remaining starved deep-water basins between the platforms is the second main topic of this field trip. We will have a look at the following parts and phenomena of the Plassen Carbonate Platform *sensu lato*:

- the fore-slope shedding of the Plassen Carbonate Platform sensu stricto (central platform),
- resediments from the Lärchberg Carbonate Platform (southern platform, optional).

On some days of the field trip, we will cross different basin fills and parts of the Plassen Carbonate Platform, respectively. To avoid confusion, the stop descriptions were sorted according to the different topics and not in strict chronological order according to the way of walking or driving.

4.1 The Late Triassic: Dachstein/Hauptdolomit Carbonate Platform

Hauptdolomit, Norian lagoonal Dachstein Limestone (Lofer cycles). Early Rhaetian Kössen Formation – formation of an empty bucket (Kössen Basin). Rhaetian reefal and lagoonal Dachstein Limestone.

4.1.1 Hauptdolomit (Mörtlbach road)

The Norian Hauptdolomit was deposited under partly restricted and hypersaline lagoonal conditions (e.g., CZURDA & NICKLAS, 1970; FRUTH & SCHERREICKS, 1984, 1985). Typical features are stromatolithic layers, shrinking structures, ripple marks, mud clasts and dolomitized grainstones with foraminifera, algae and gastropods. In the field trop area the thickness of the Hauptdolomit may reach 1500 metres, mainly light to middle grey dolostones. FRUTH & SCHERREICKS (1984) distinguished eight different facies units (Fig. 9) with limited water exchange and euxinic conditions (ZANKL, 1971).
We will visit an characteristic outcrop on the road along the Mörtlbach valley in direction to the village Krispl.

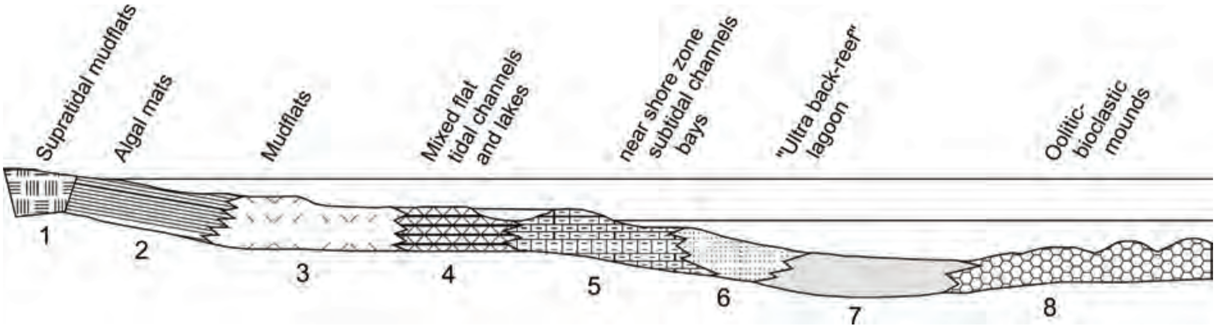


Figure 9: Eight facies units have been distinguished in the Hauptdolomit Fm. (after FRUTH & SCHERREIKS, 1984). They are interpreted to correspond to environmental belts, ranging from supratidal through subtidal.

4.1.2 Lagoonal Dachstein Limestone: The classical Lofer cycle (Pass Lueg)

Text from RICHOZ et al. (2012): In the central and eastern Northern Calcareous Alps, the cyclic, meter-sized bedding of the Dachstein Limestone is a characteristic morphological feature, well visible along the steep slopes as well as on the top of the large plateau mountain ranges. Meter-scale cycles were recognized as early as 1936 by SANDER. FISCHER (1964) gave a description of this phenomenon, which remains a classic even now. Based on sequences from the plateaus of the Dachstein and the Loferer Steinberge, FISCHER termed these units “Lofer cycles“. The cycles are interbedding of lagoonal limestones, thin layers of variegated argillaceous material, thin layers of intertidal to supratidal laminated or fenestral dolomites and dolomitic limestones The main sediment is a light-coloured limestone; (layer C, thickness up to some meters), containing oncoids, dasycladacean and codiacean algae, foraminifera, bryozoa, gastropods, large megalodontids and other bivalves. The weathered and solution-riddled surface of this limestone is overlain and/or penetrated by reddish or greenish argillaceous limestone (layer A), which may include limestone clasts and which are interpreted as former terrestrial soils. Layer A is commonly not developed as a distinct bed, because of its erosional origin; however, remnants of A are abundant infillings in veins, cavities, and biomoldic pores (gastropod and megalodontid shells). Layer B consists of intertidal carbonates of a variety of rock types like "loferites" or birds-eye limestone of laminated or massive type, non-loferitic mudstone and intraclasts. The flat or crinkled lamination is interpreted as filamentous algal mats, also characteristic of modern tidal flats. Fenestral pores and mud cracks seem to be the result of shrinkage of unconsolidated sediment due to desiccation. All types of layer B are more or less dolomitic, some of them formed as contemporaneous brittle surface crusts, as shown by intraclasts, demonstrating the intertidal/supratidal setting. FISCHER (1964) explains the formation of the cyclothems by periodic fluctuations of the sea-level which is superimposed on the general subsidence. An amplitude of up to 15 m and 20.000 to 100.000 years is assumed for one cycle. Because this model does not explain the gradual lateral transition into the Hauptdolomit Formation and the lateral wedging of intertidal and supratidal sediments within short distance, ZANKL (1971) proposed an alternative model: Current activity and sediment producing and binding algae created mud mounds and tidal mud flats. Subsidence and eustatic sea-level fluctuations of centimetre amplitudes and periods of several hundred years may have modified growth pattern and shape of the tidal flats by erosion and transgression. FISCHER (1964) interpreted the ideal Lofer cycle: disconformity, A, B, C as an upward-deepening facies trend. HAAS (1991, 1994) proposed a symmetrical ideal cycle, whereas GOLDHAMMER et al. (1990) and SATTERLEY (1994) proposed a shallowing upward interpretation. ENOS & SAMANKASSOU (1998) pointed to the lack of evidence for subaerially exposure and interpreted it as rhythmic cycle with allocyclicity as the predominant control. HAAS et al. (2007, 2009) and HAAS (2008) however provided several evidences for subaerially exposure and related karstification. HAAS et al. (2010) pointed a differential development of the Lofer Cycle on the Dachstein Range between internal area and sections situated near the margin of the platform. The cycles shown by HAAS et al. (2010) can be summarized:

The disconformity displays erosion features and karstification in both internal and marginal areas.

- Facies A is reddish or greenish, argillaceous, 1 mm to 10 cm thick. It is a mix of storm redeposited carbonate mud, air transported carbonate and argillite, blackened intraclast and consolidated sediment. It is thicker with pedogenese trace in marginal sea than in internal area.
- Facies B (stromatolites, loferites) is usually present in the internal part of the range, but absent in the marginal area.
- Facies C is a peloidal bioclastic wackestone in the platform area, whereas in the reef-near zone it is an oncoidal packstone or grainstone.

The differences can be explained by the setting. The marginal zone, near the offshore edge developed oncoid shoals, whereas stromatolites develop preferentially on the slightly deeper platform interior, protected by the shoals. The sea-level drop affected both areas, but the longer shoals allowed for the development of paleosoils in the marginal part. This model reinforces the shallowing-upward trend of FISCHER (1964).

At Pass Lueg itself a "Lofer Cyclothem" with partly reworked stromatolite, brecciated layers and bioclastic limestones rich in megalodontids, corals and echinoderm (FLÜGEL et al,. 1975) is exposed (Fig. 10). Several species of *Megalus, Parmegalus, Conchodus* have been described, but each levels are usually rich in individuals but poor in species number (FLÜGEL et al., 1975).

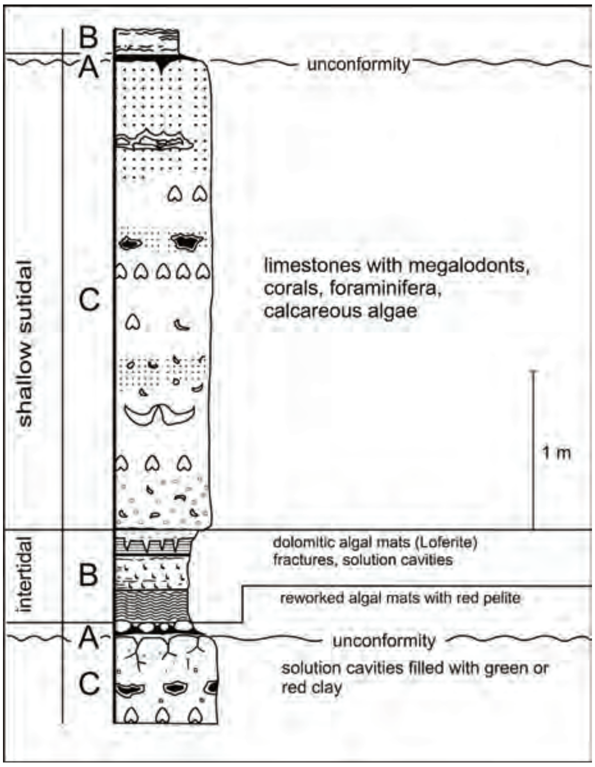


Figure 10: Schematic sketch of the Lofer cycle of the bedded Dachstein limestone (after FISCHER, 1964, 1975).

4.1.3 The Kössen Basin (Pass Lueg and Mörtlbach road)

In the Rhaetian increasing terrigenous influx reduced the areal extent of the Hauptdolomit/Dachstein platform. The Hauptdolomit facies zone and parts of the Dachstein lagoon became covered by the marly Kössen Formation. The newly formed Kössen Basin (empty bucket, intrashelf basin) was bordered in the south by a new reefal belt, which prograded in Rhaetian times rapidly to the north. In the Early Rhaetian subtidal mixed lime and clay bearing bioclastic rocks dominate. During this time the Kössen Basin had is southernmost extension. Whereas in the southernmost part of the Kössen Basin predominantly Middle to Late Rhaetian shallow-water limestones were deposited more northward basinal conditions prevailed (Eiberg Basin) (compare GOLEBIOWSKI, 1990a, 1991, RICHOZ et al., 2012).

North of Pass Lueg we will visit the sedimentary evolution of the southern Kössen Basin and a complete Rhaetian sequence (Fig. 11): The Early Rhaetian marly Hochalm Member is badly exposed. The overlying sediments became rich in corals. The "*Lithodendron* Limestone" is the most important lithofacies marker of the Kössen Formation. Whereas near the southern rim this level is overlain by shallow-water lagoonal Dachstein Limestone this level marks in the central basin (Fig. 12) a deepening below the wave base (GOLEBIOWSKI, 1990a, 1991; RICHOZ et al., 2012) and a transition phase between a deep, open marine lagoon (lower Hochalm Member) and the intraplatform basin deposition milieu of the Eiberg Member.

Reefal and shallow-water carbonate platform sedimentation was terminated at the end of the Rhaetian when the whole Austroalpine carbonate shelf was affected by subaerially exposure (BERNECKER et al., 1999). In contrast, in the Eiberg Basin deposition continued. In this basin the Triassic-Jurassic GSSP at Kuhjoch is situated (details in HILLEBRANDT & KRYSTYN, 2009; HILLEBRANDT & KMENT, 2011; RICHOZ et al., 2012).

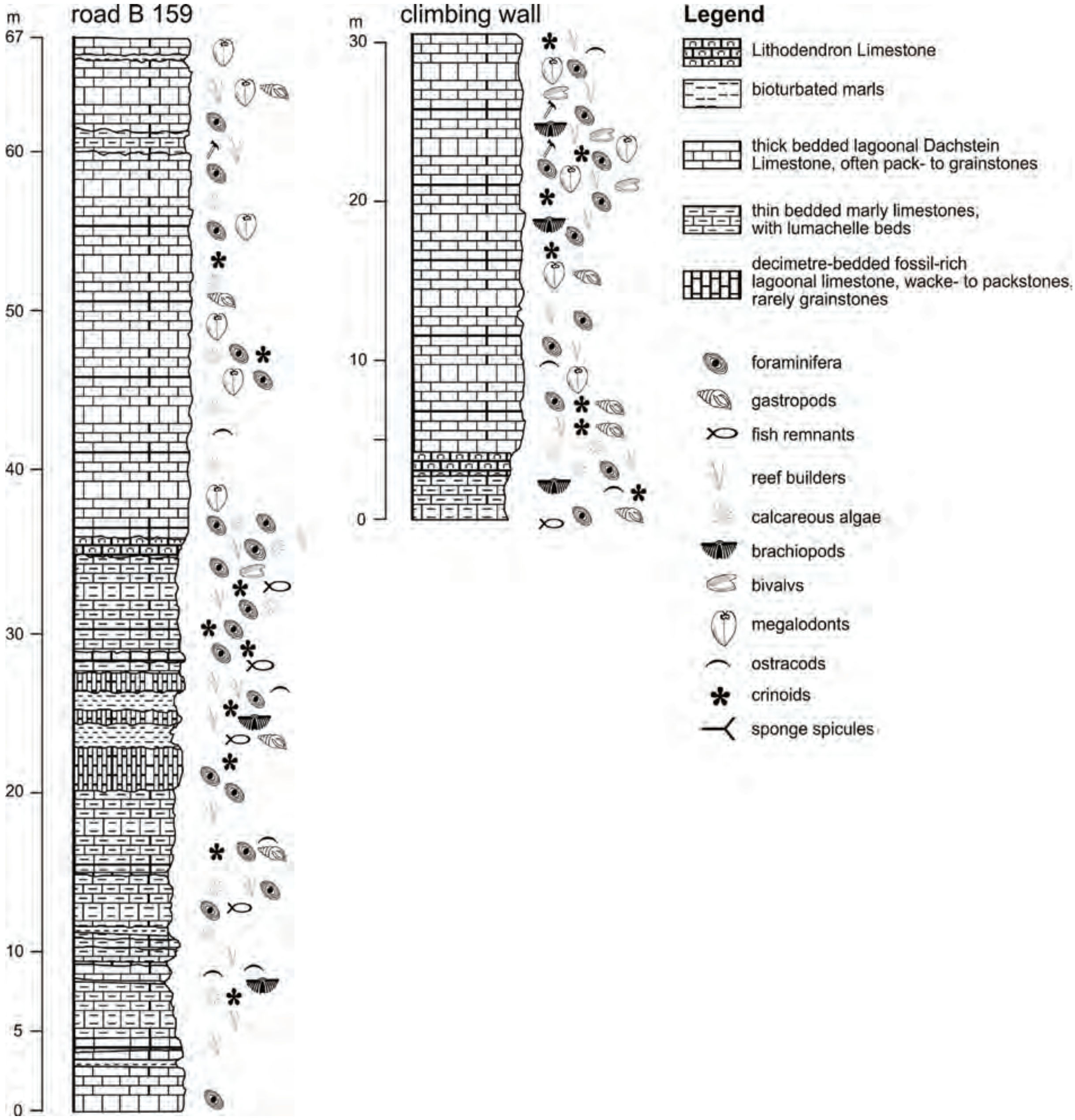


Figure 11: Section Rhaetian limestones succession (Kössen Formation and Dachstein Limestone) near the B 159 north of Pass Lueg (northern Tennengebirge Mts.). Partly modified after GAWLICK (1996, 2000a).
Section 1: Section near the road B159 from Pass Lueg to Luegwinkl.
Section 2: Section near the climbing wall north of Pass Lueg.

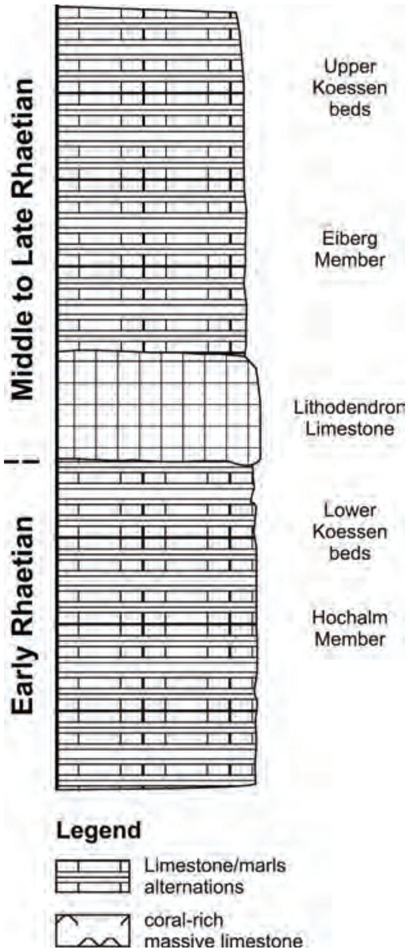


Figure 12: Sedimentary sequence of the Kössen beds in the Mörtlbachgraben (schematic). This succession is characteristic for a central Kössen Basin position (Eiberg Basin).

4.2 Jurassic

4.2.1 Hettangian to Aalenian

The Hettangian to Aalenian period was controlled by the following factors:

A) the end-Triassic morphology and biotic crisis,
B) crustal extension in the Penninic realm and in the adjacent Austroalpine domains resulted in the breakup of the South Penninic Ocean in the Toarcian (Figs. 13, 15), and
C) the onset of inneroceanic thrusting around the Pliensbachian/Toarcian boundary in the Neotethys Ocean.

In the earliest Jurassic four west-east (palaeogeographically southsouthwest to northnortheast) trending basins existed in the Austroalpine realm:

1) due to crustal extension the newly formed Bündner Schiefer Basin in the area of the evolving Penninic Ocean as part of the Alpine Atlantic,
2) the Allgäu (Restental) Basin (group) as northernmost basin in the Northern Calcareous Alps,
3) the Eiberg (Scheibelberg) Basin along the central axis of the Northern Calcareous Alps, and
4) the Hallstatt Zone (distal passive margin, "Hallstatt Basin" according to older references) facing the Neotethys Ocean (Figs. 5, 13–15).

Only in the basinal areas sediments were deposited in the earliest Jurassic, whereas the Late Triassic highs (with Rhaetian shallow-water sedimentation) may have emerged and did not receive any sediments. This is the reason, why a hiatus/gap exists between the Triassic and Jurassic sediments on top of most Rhaetian shallow-water carbonates of the Northern Calcareous Alps.

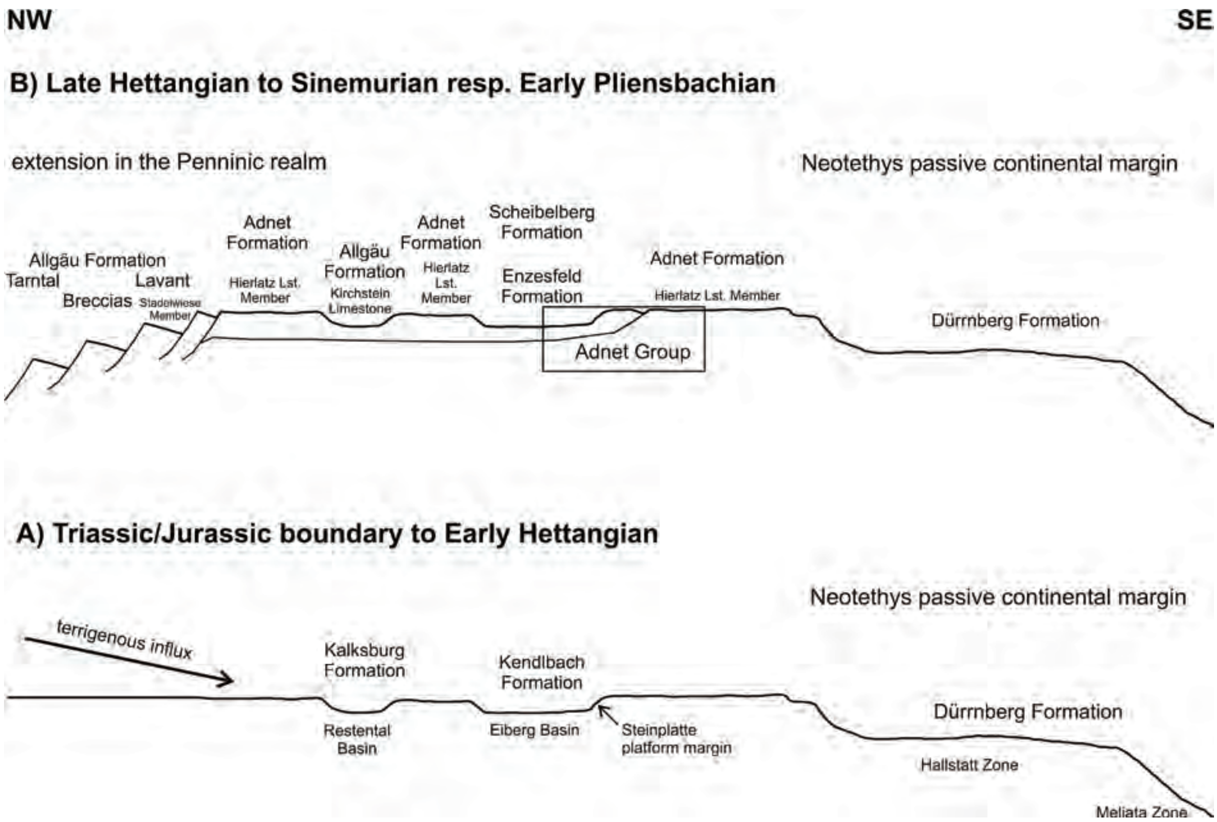


Figure 13: Two profiles showing the palaeotopographic situation in the Austroalpine domain. **A**) Sedimentation in the earliest Jurassic was controlled by the end-Triassic morphology of the exposed or drowned Hauptdolomit/Dachstein Carbonate Platform s. l. with the Eiberg Basin in a central position (e.g., GOLEBIOWSKI, 1991; KUERSCHNER et al., 2007; BONIS et al., 2009) and the Restental Basin (= later Allgäu Basin; GOLEBIOWSKI, 1990b) in a more continent-ward position. **B**) Later in the Early Jurassic (Late Hettangian) crustal extension in the Penninic realm controlled the basin formation, geometry and sedimentation. The Early Rhaetian Kössen beds below the Rhaetian Dachstein Limestone (south of the Eiberg Basin) and Oberrhät Limestone (north of the Eiberg Basin) could have formed the detachment horizon (line in upper profile), on which Penninic crustal extension affected also the Tirolic realm of the Northern Calcareous Alps in the Late Hettangian/Early Sinemurian. Breccia formation on the Penninic passive continental margin lasted from Late Hettangian to Early Pliensbachian times.

Figure 14 (next page)**:** Formations of the Adnet Group (according to BÖHM et al., 1999; BÖHM, 2003, modified) and transition to the Kendlbach, Enzesfeld and Scheibelberg Formations as well as to the Hierlatz Limestone Member. Arrows indicate gravitational transport induced by tectonic activity. For details see text.

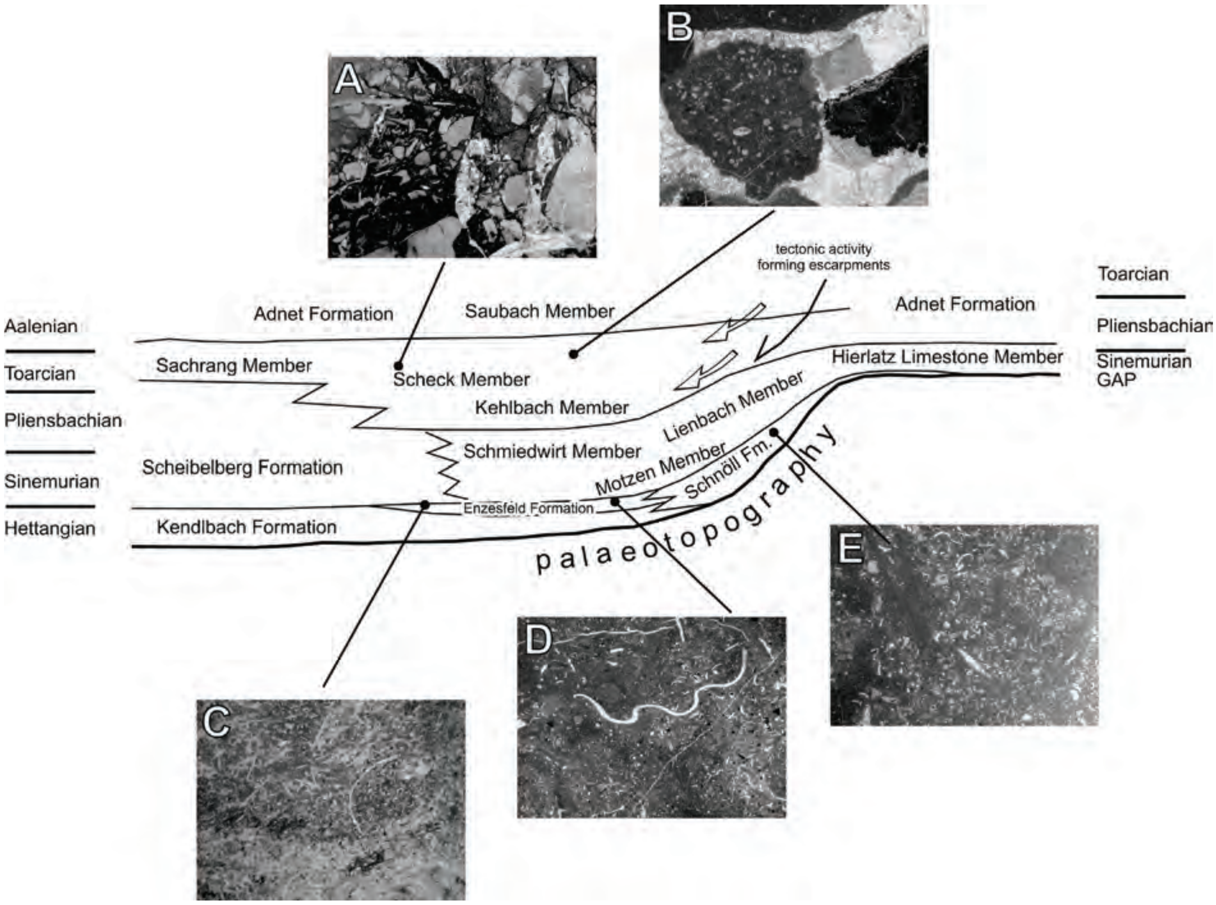
A) Distal Scheck Member, clasts occur in a red marly matrix. Sample Ber 24/21, Wimbach gorge (Tirolic units, Berchtesgaden Calcareous Alps). Width of photo: 1.4 cm.

B) Scheck Member of the type locality in Adnet (Tirolic units, Salzburg Calcareous Alps). Between different clasts occur a sparry calcite cement. Sample C 187. Width of photo: 0.5 cm.

C) Distal Enzesfeld Formation: Spicula- and echinoderm-rich packstone with some bivalves. Sample H 27, Hatschek quarry in Ebensee (Tirolic units, Salzkammergut area). Width of photo: 0.5 cm.

D) Intermediate Enzesfeld Formation from the type locality: wackestone to packstone with small scaled bivalves, ammonoidea and foraminifera (e.g., *Involutina liassica* (JONES)), slightly bioturbated. Width of photo: 1.4 cm.

E) Upper Schnöll Formation of the type locality in Adnet. Echinoderm- and foraminifera-rich wackestone to packstone with marls, slightly bioturbated. Width of photo: 1.4 cm.



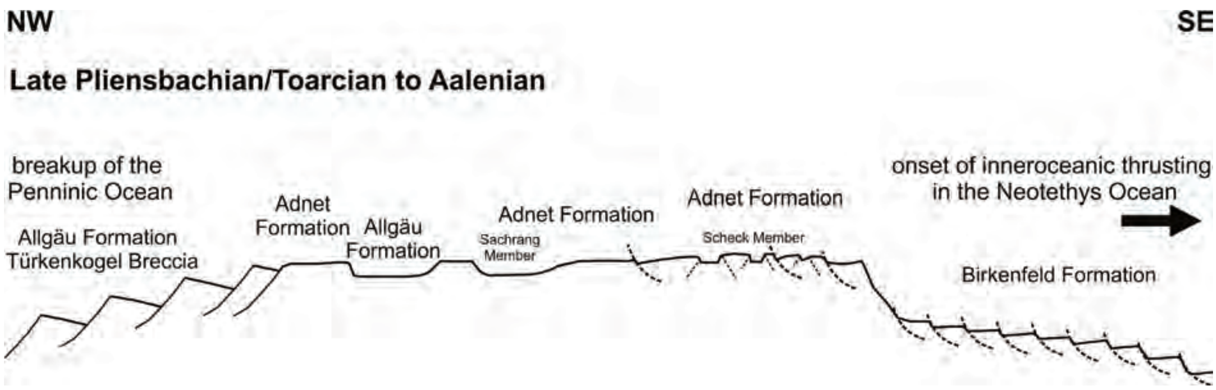


Figure 15: Palaeotopographic profile with formations in the time span Late Pliensbachian to Aalenian. The Lower Austroalpine domain was controlled by the final breakup of the South Penninic Ocean in Toarcian times (RATSCHBACHER et al., 2004), whereas the tectonic movements on the continental margin facing the Neotethys Ocean (Hallstatt Zone and later Tirolic units) was controlled by normal faulting due to the onset of eastward dipping inneroceanic thrusting in the Neotethys Ocean (e.g., GAWLICK et al., 2008). Therefore the newly formed horst-and-graben morphology is interpreted probably as a fore-bulge in the Austroalpine lower plate (compare Fig. 3).

4.2.2 Bajocian to Tithonian

The Bajocian to Tithonian period was mainly controlled by following factors:

A) the Toarcian/Aalenian morphology after the breakup of the South Penninic (Piemont) Ocean, especially in the Lower Austroalpine to the (westernmost) Bavaric units,
B) the onset of inneroceanic subduction processes in the Neotethys realm and the formation of a propagating thrust belt. Thrusting started in the outer shelf area (Meliata and Hallstatt Zones) in Bajocian and prograded towards the Tirolic realm in Oxfordian times.
C) the newly formed carbonate platform on top the nappe stack since the Late Oxfordian,
D) the gravitational collapse of this carbonate platform around the Early/Late Tithonian boundary due to uplift in the south and normal faulting in the north.

The Middle to Late Jurassic orogeny resulted in the destruction of the Neotethys-ward Middle Triassic to Early Jurassic passive continental margin (the Triassic south-eastern margin of Europe; Fig. 6) which had experienced crustal extension since Late Permian time. In late Early to Middle Jurassic times the geodynamic regime became convergent and inneroceanic subduction in the Neotethys Ocean commenced. As a consequence, the continental margin become tilted, progressively imbricated with the distal shelf area of the Meliata and Hallstatt Salzberg facies zones involved in stacking first, and obducted by ophiolites. Trench-like basins formed in front of advancing nappes.

As expression of this evolution in the Pliensbachian, sedimentation in the Hallstatt Zone changed from condensed cherty limestones to far more rapidly deposited massive dark-grey, clay-rich siliceous marls and cherty limestones (O´DOGHERTY & GAWLICK, 2008). The thickness of the sediments increased accordingly. In Late Toarcian to Aalenian times a thick siliceous marly-sedimentary succession was deposited. This change is interpreted as an effect of tilting and faulting of the distal passive margin due to the onset of thrusting in the Neotethys oceanic realm. Late Early to early Late Jurassic inneroceanic subduction is proven by metamorphic soles in the Dinarides (176-157 Ma: KARAMATA, 2006), the Albanides (174-162 Ma: DIMO-LAHITTE et al., 2001), and the Hellenides (181-172 Ma: RODDICK et al,. 1979; SPRAY & RODDICK, 1980). As an expression of this change, in the Dachstein Limestone facies zone a forebulge horst-and-graben morphology evolved in Late Pliensbachian to Toarcian times.

Thrusting in the Neotethys Ocean passive margin domain started in Bajocian time, creating the Meliata and distal Hallstatt nappes by imbrication of the outermost part of the former passive continental margin (Fig. 16). The Florianikogel Basin (Meliata Mélange) is the most oceanward preserved relic of a Middle Jurassic trench-like radiolarite basin in the Northern Calcareous Alps (Fig. 17). In the next stage of thrusting the Sandlingalm Basin group established. This comprised material mainly from the Hallstatt Salzberg facies zone. Parts of these older two basin fills became remobilised in the later stages of orogeny and can be found as resediments in the younger basin successions.

Further continuous shortening established the proximal Hallstatt nappes (Fig. 18, Fig. 19). Farer to the northwest in front of these nappes, new basins formed in the area of the former Dachstein Limestone lagoon in the Callovian and existed until the Oxfordian (Lammer Basin). Continentwards a flexural bulge with red nodular limestone deposition established and prevailed in the area of the later Tauglboden Basin until the Callovian/Oxfordian boundary. Initially the Lammer Basin received local material from the adjacent nappe front. Later, in the Middle/Late Callovian to Middle Oxfordian, the Zlambach facies zone became imbricated and uplifted. After that, predominantly eroded material from this facies domain was shed into the Lammer Basin.

Further tectonic shortening caused ongoing obduction of ophiolites, as proven in the Dinarides (SCHMID et al., 2008) or the Albanides (GAWLICK et al., 2008), and partial detachment and NW-directed transport of the older, south-eastern basin groups. Around the Callovian/Oxfordian boundary a northwestward shift of the Lammer Basin axis can be correlated with the formation of a new nappe front in the Dachstein Limestone reef zone, from which material was shed into this basin. Farther to the southeast, the evaporitic

Haselgebirge Mélange (SPÖTL, 1989; SPÖTL et al., 1998) was formed (Fig. 20). It contains Late Jurassic authigenic feldspars (154-145 Ma: SPÖTL et al., 1996, 1998), which are interpreted as being related to fluid circulation and mélange formation. The Haselgebirge Mélange carries metamorphosed Hallstatt Limestone, Pötschen Limestone, and Dachstein reefal limestone blocks as well as volcanic rocks, partly with sodic amphiboles (KIRCHNER, 1980a, b), and oceanic basalts, which were metamorphosed under HP/LT conditions (VOZÁROVÁ et al., 1999) (compare GAWLICK & HÖPFER, 1999; FRANK & SCHLAGER, 2006).

In the Early Oxfordian, thrust propagation established the upper Tirolic nappe front northwest of the Lammer Basin (Fig. 19) in the area of the Triassic Hauptdolomit lagoon, with the Trattberg Rise as its topographic expression. This rise was an area of intense erosion and the source region for breccias and mass flows in Early to Late Oxfordian times. Continued tectonic shortening led to thrusting over the southeastern margin of the Tauglboden Basin. In ?Middle/Late Oxfordian times, tectonic shortening again propagated northwestwards and the Brunnwinkl Rise was formed (Fig. 19, Fig. 20). This was the northwestern tectonic front of the Jurassic Northern Calcareous Alps nappe stack, with the Rofan Basin in its foreland.

In Late Oxfordian time, ongoing ophiolite obduction, salt flow and tectonic uplift of metamorphosed slices of the Hallstatt zone resulted in the creation of a chaotic mélange. The evaporitic Haselgebirge Mélange squeezed out in front of the arriving ophiolite nappes and took position on top of the Sandlingalm Formation around the Oxfordian/Kimmeridgian boundary (Fig. 21). In contrast, in the northwestern part of the preserved nappe stack north of the Hallstatt imbricates, a period of relative tectonic quiescence began. At that time the Plassen Carbonate Platform *sensu lato* started its progradation (Figs. 20, 21). Also the Kimmeridgian to Early Tithonian cherty limestones on top of the mélanges are part of the evolution of the Plassen Carbonate Platform *sensu lato* with the Wolfgangsee Carbonate Platform in the northwest, the Plassen Carbonate Platform *sensu stricto* in central position, and the Lärchberg Carbonate Platform in the southeast. Radiolaritic basins remained as starved basins in between the individual platforms (Fig. 21). At that time only the Sillenkopf Basin received Late Jurassic shallow-water debris, together with exotic clasts. Originating from a southern source area, the latter were transported into the Sillenkopf Basin through channels.

The Kimmeridgian to Early Tithonian time interval was characterized by platform progradation over the adjacent basins. Whereas into the Sillenkopf Basin material was supplied from the platforms on both sides, the Tauglboden Basin was shielded by the uplifted Trattberg Rise in its south (Fig. 22). In the imbricated wedge slight uplift started (Fig. 22).

In the late Early Tithonian, the uplift of the Juvavic nappe pile to the southeast led to northwestward gliding of several mélange blocks along low-angle planes, including the far-travelled “Sandlingalm“ Hallstatt Mélange onto the “Lammer“ Hallstatt Mélange (Fig. 23). Concomitantly, the Plassen Carbonate Platform *sensu stricto* on top of the former Trattberg Rise extensionally collapsed and the Wolfgangsee Carbonate Platform further northwest drowned. The already deeply eroded ramp anticline of the former Trattberg Rise became sealed by hemipelagic sediments with intercalated reef-slope sediments from a newly formed reef rim. In contrast, the southeastern nappe stack with the Lärchberg Carbonate Platform became uplifted around the Jurassic/Cretaceous boundary. The second metamorphic cycle around 145-135 Ma can most probably be correlated with the increasing heat-flow due to the uplift of the stacked Juvavic (Fig. 23) units in the southeasternmost part of the Northern Calcareous Alps.

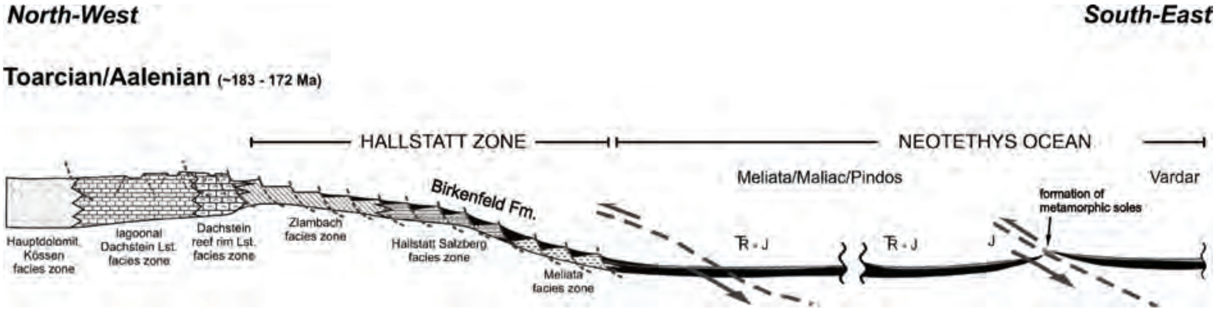


Figure 16: Reconstruction of the Toarcian/Aalenian to Callovian geodynamic evolution. Absolute ages after GRADSTEIN et al. (2004). See text for further explanation. NW-SE directions refer to Triassic-Jurassic palaeogeographic coordinates. Onset of inneroceanic southeastward subduction in Neotethys Ocean (GAWLICK et al. 2008; for discussion see: KARAMATA, 2006). Late Early to early Late Jurassic inneroceanic subduction is proven by metamorphic soles in the Dinarides (176-157 Ma: KARAMATA, 2006), Albanides (174-162 Ma: DIMO-LAHITTE et al., 2001), and Hellenides (181-172 Ma: RODDICK et al., 1979; SPRAY & RODDICK, 1980). Occurrences of supra-subduction volcanics in the ophiolite belt of Albania reflect an inneroceanic subduction stage (SHALLO & DILEK, 2003; KOLLER et al., 2006). Contemporaneously, the first ophiolithic mélanges were formed (BABIC et al., 2002). Slight south-eastward tilt of distal continental margin, formation of half-grabens in the Hallstatt Zone and horst-and-graben structure in Dachstein Limestone facies zone since the Late Pliensbachian (Adnet Scheck event: BERNOULLI & JENKYNS, 1974; BÖHM et al., 1995) belong to this event. In the Hallstatt Zone the normal faults cut into the Rhaetian Zlambach marls which probably acted as source area for the clay content in the Birkenfeld Formation beside eroded ophiolites. After MISSONI & GAWLICK, (2011a).

Figure 17: Reconstruction of the Early Callovian geodynamic evolution. Absolute ages after GRADSTEIN et al. (2004). NW-SE directions refer to Triassic-Jurassic palaeogeographic coordinates. The Florianikogel Basin (?Bajocian-Callovian; *FB*) constitutes the oldest radiolaritic trench-like basin in the most oceanward position. In the Early Callovian continentward propagation of thrusting led to the formation of the Sandlingalm Basin (*SaB*) in the Hallstatt Zone and to the formation of the Lammer Basin (*LB*) in the lagoonal Dachstein Limestone facies zone. In this early stage of the Lammer Basin only local material was shed from nearby source regions. Continentward a flexural bulge formed which was characterized by red nodular limestone deposition. This bulge with condensed sedimentation prevailed until the Callovian/Oxfordian boundary (e.g., HUCKRIEDE, 1971; MANDL, 1982) in the area of the later Tauglboden Basin. After MISSONI & GAWLICK (2011a).

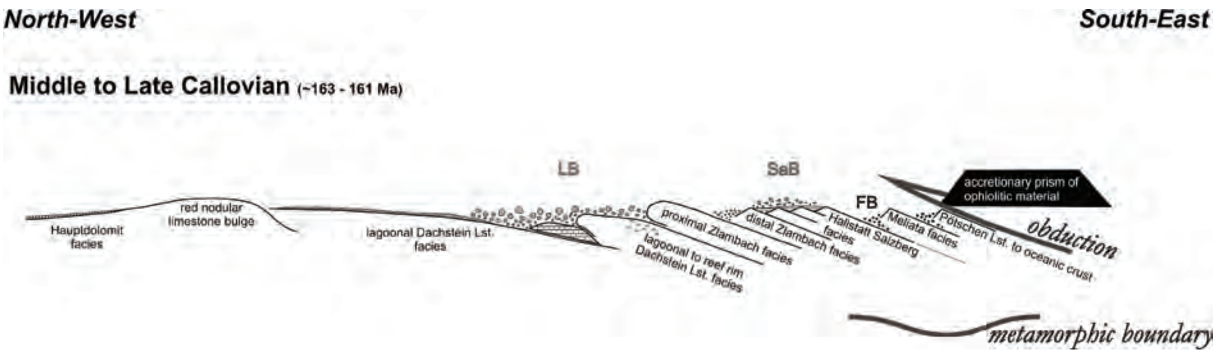


Figure 18 (previous page)**:** Reconstruction of the Middle to Late Callovian geodynamic evolution. Absolute ages after GRADSTEIN et al. (2004). NW-SE directions refer to Triassic-Jurassic palaeogeographic coordinates. Further tectonic shortening led to the formation of nappe fronts in the Zlambach facies zone. These nappe fronts shed material into the Lammer Basin in Middle Callovian to Middle Oxfordian times. FB: Florianikogel Basin. SaB: Sandlingalm Basin. LB: Lammer Basin. After MISSONI & GAWLICK (2011a).

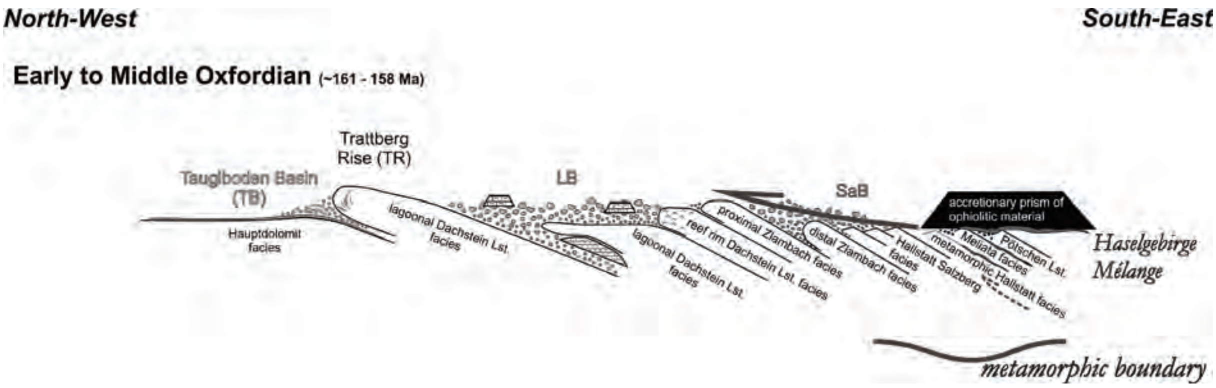


Figure 19: Reconstruction of the Early to Middle Oxfordian geodynamic evolution. Absolute ages after GRADSTEIN et al. (2004). NW-SE directions refer to Triassic-Jurassic palaeogeographic coordinates. Due to further tectonic shortening and ongoing obduction of ophiolites (Dinarides: SCHMID et al., 2008; Albanides: GAWLICK et al., 2008), the southern basin groups were sheared off and transported towards northwest. Contemporaneously, the basin axis in the Lammer Basin propagated northwestward, too, and the newly formed nappe front in the Dachstein reef rim zone shed its eroded material into this basin. The next nappe front formed in the transitional area of the lagoonal Dachstein Limestone facies zone to the Hauptdolomit facies zone. Eroded material from the uplifted hangingwall (Trattberg Rise) was shed into the newly formed Tauglboden Basin. SaB: Sandlingalm Basin. LB: Lammer Basin. After MISSONI & GAWLICK (2011a).

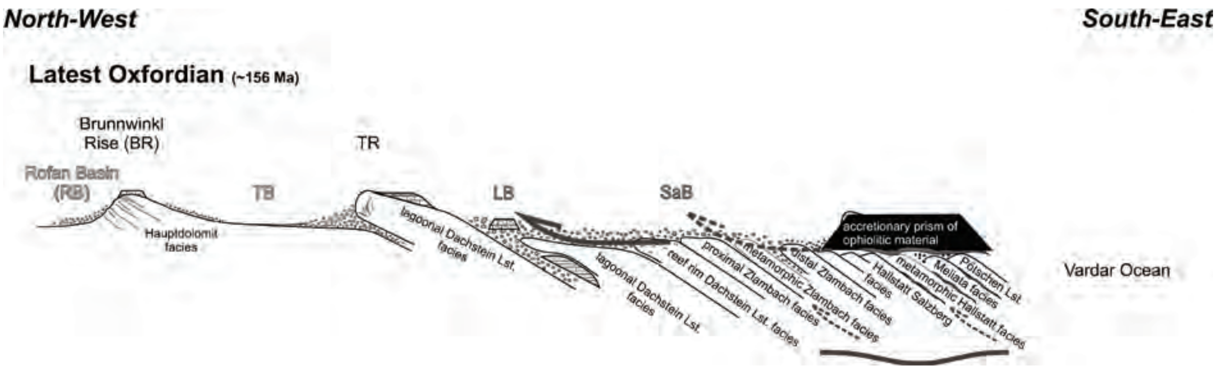


Figure 20: Reconstruction of the Latest Oxfordian geodynamic evolution. Absolute ages after GRADSTEIN et al. (2004). NW-SE directions refer to Triassic-Jurassic palaeogeographic coordinates. Ongoing obduction of the ophiolites, salt flow and tectonically uplifted metamorphosed slices of the Hallstatt Zone resulted in the formation of a chaotic mélange. Northwestward thrusting led to emplacement of a Sandlingalm Basin sheet on top of the Lammer Basin and upramping of the Trattberg Rise (*TR*) onto the south-eastern rim of the Tauglboden Basin. At the northwestern edge, the Brunnwinkl Rise (*BR*) formed as a new nappe front, with the Rofan Basin (*RF*) as trench-like basin in front. The evaporitic Alpine Haselgebirge squeezed out in front of the arriving ophiolite nappes and was emplaced on top of the Sandlingalm Formation until the Early Kimmeridgian. SaB: Sandlingalm Basin. LB: Lammer Basin. After MISSONI & GAWLICK (2011a).

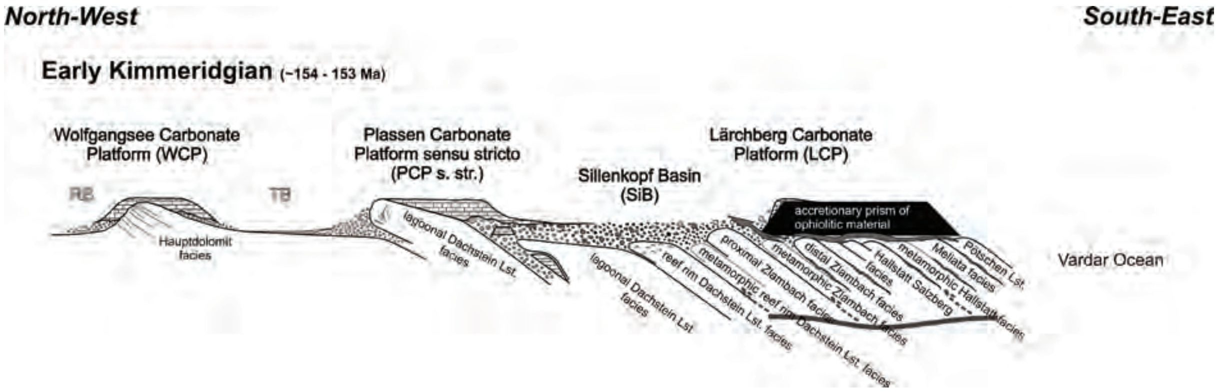


Figure 21: Reconstruction of the Early Kimmeridgian geodynamic evolution. Absolute ages after GRADSTEIN et al. (2004). NW-SE directions refer to Triassic-Jurassic palaeogeographic coordinates. Around the Oxfordian/Kimmeridgian boundary, the formation of shallow-water carbonates on top of the imbricated structures including the obducted ophiolites started. These platforms are summarized as Plassen Carbonate Platform *sensu lato* with the Wolfgangsee Carbonate Platform (*WCP*) in the northwest, the Plassen Carbonate Platform *sensu stricto* (*PCP s. str.*), and the Lärchberg Carbonate Platform (*LCP*) in the southeast. Radiolaritic basins remained as starved basins in between the individual platforms. Delivery of exotic material persisted only into the Sillenkopf Basin (*SiB*). After MISSONI & GAWLICK (2011a).

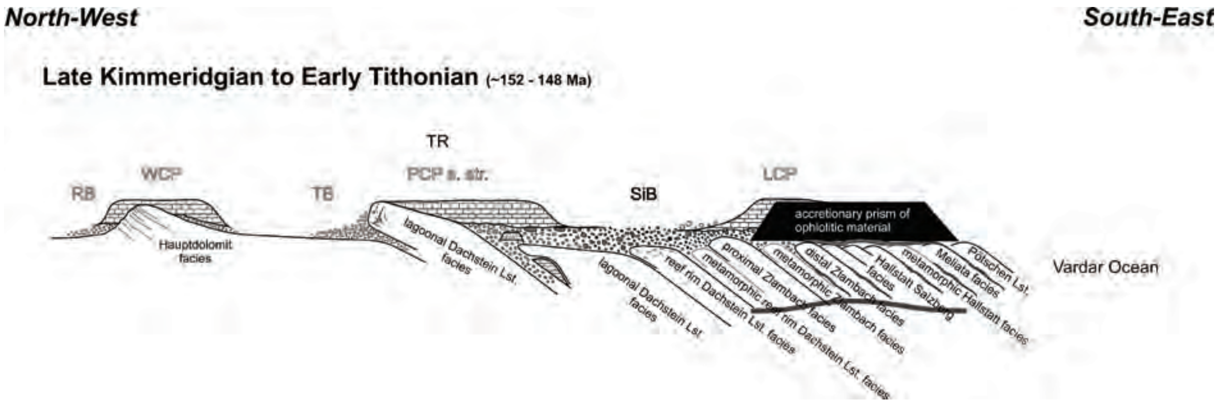


Figure 22: Reconstruction of the Late Kimmeridgian to Early Tithonian geodynamic evolution. Absolute ages after GRADSTEIN et al. (2004). NW-SE directions refer to Triassic-Jurassic palaeogeographic coordinates. This time interval was characterized by platform progradation towards the adjacent basins. Whereas platforms on both sides supplied material into the Sillenkopf Basin, the Tauglboden Basin was shielded to the south by the uplifted Trattberg Rise. In the stacked wedge slight uplift started. WCP: Wolfgangsee Carbonate Platform. TB: Tauglboden Basin. PCP *s. str.*: Plassen Carbonate Platform *sensu stricto*. SiB: Sillenkopf Basin. LCP: Lärchberg Carbonate Platform. After MISSONI & GAWLICK (2011a).

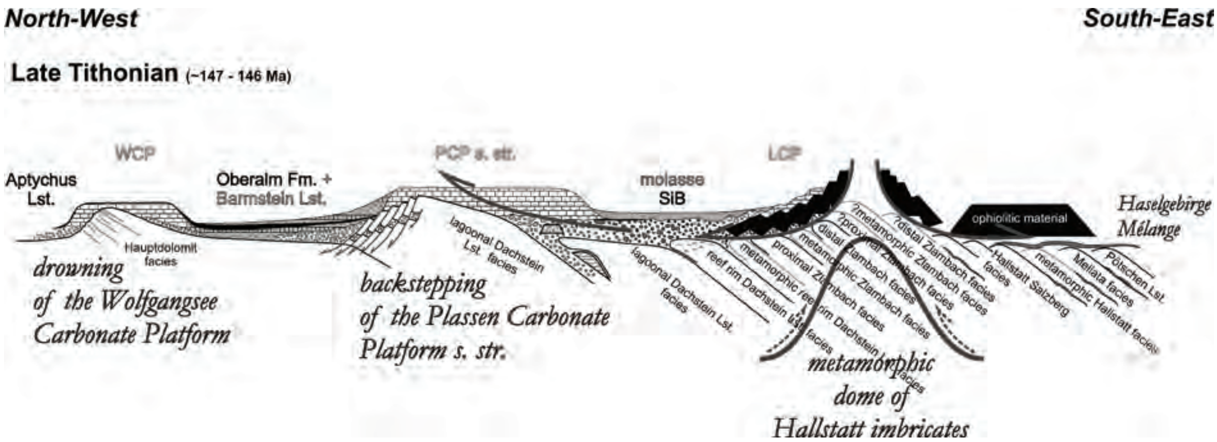


Figure 23 (previous page)**:** Reconstruction of the Late Tithonian geodynamic evolution. Absolute ages after GRADSTEIN et al. (2004). NW-SE directions refer to Triassic-Jurassic palaeogeographic coordinates. Uplift of the metamorphic dome in the eastern part led to the formation of high- and low-angle normal faults and likely also to strike-slip faults. This led to northwestward transport of several mélange slices and uplift and erosion of parts of the Lärchberg Carbonate Platform (*LCP*). At the northwestern edge, the Trattberg Rise broke down and the Plassen Carbonate Platform *sensu stricto* (*PCP s. str.)* built a new reef rim to the north and shed an enormous amount of carbonate material from there (Oberalm Limestone with intercalated Barmstein Limestone = mass flows consisting mainly of reefal material). Contemporaneously the Wolfgangsee Carbonate Platform (*WCP*) drowned (GAWLICK & SCHLAGINTWEIT 2010). After MISSONI & GAWLICK (2011a).

Section Wimbachklamm: Early Jurassic to basal Lammer Basin fill

In the Wimbach gorge section south of Berchtesgaden belong to the Watzmann Block. Here a complete Early to Middle Jurassic sedimentary sequence is preserved (according to MISSONI, 2003). The section starts with grey cherty limestones above Rhaetian lagoonal Dachstein Limestone. The contact is slightly faulted. Characteristic for the lower (Hettangian – Sinemurian) part of the succession are slumpings and oligomictic breccia layers (Fig. 24). Above these basal part a well bedded series of grey cherty limestones was deposited (?Late Sinemurian to Pliensbachian). This series is topped by mass flows and slumps consisting of

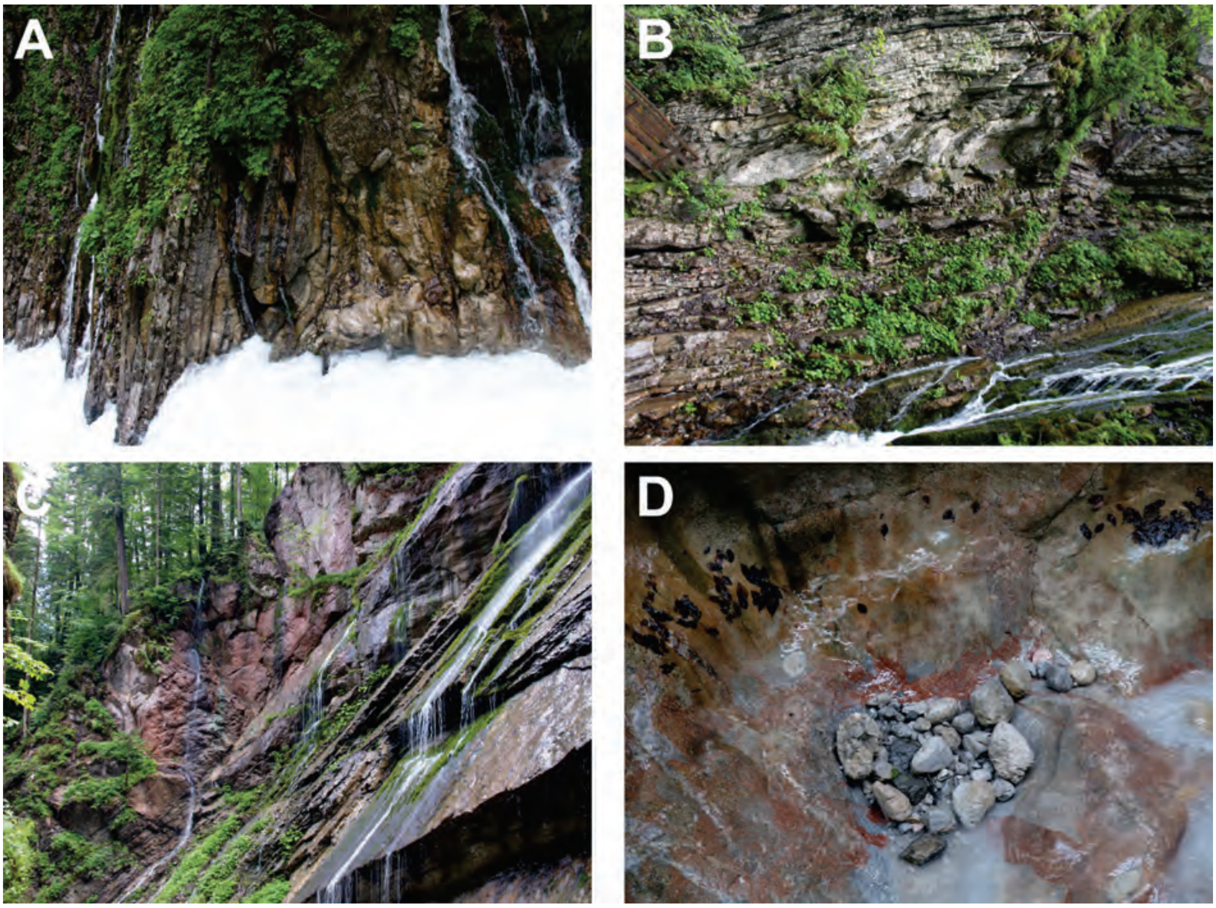


Figure 24: Early-Middle Jurassic sedimentary succession of the Wimbach gorge.
A) Oligomict mass flow and slumping in the ?Late Hettangian - Sinemurian part of the succession.
B) Slump fold in the lower part of the succession (?Late Hettangian – Sinemurian).
C) Mass flow of red nodular Adnet Limestone on top of the well bedded grey cherty limestones (Late Pliensbachian to Toarcian).
D) Carbonate breccia with red *Bositra*-Limestone matrix. This breccia-type occurs normally below the Lammer Basin fill, preserved not in this section but nearby in the Kühroint area (MISSONI et al., 2005).

red Adnet limestones (Late Pliensbachian to Toarcian). Above the red nodular limestones of the higher Adnet Formation were deposited. On top of these Adnet limestones a polymictic breccia follows: the red matrix consists of *Bositra*-Limestone (Middle Jurassic, most probably Bathonian), the clasts are Late Triassic lagoonal Dachstein Limestone and Early Jurassic limestones. Upsection, above these breccias, follow radiolarites of Callovian age. This succession documents clearly the two Early Jurassic tectonic events. The first (Hettangian-Sinemurian) event is related to the Alpine Atlantic extension and is followed by a period of quiet deposition. The second tectonic event (Late Pliensbachian-Toarcian) is related to the onset of contractional tectonics in the Neotethys Ocean. In Middle Jurassic times the formation of new basins started with deposition of carbonate breccias consisting of local material. Rapid deepening of the basin led to radiolarite deposition (Callovian).

Section Mörtlbachgraben: Early Jurassic to Tauglboden Basin fill

Another Jurassic section, but in a more northernward position as the Wimbach gorge section, is the section Mörtlbach valley in the Osterhorn Block (Fig. 25). The Jurassic developed above the Kössen Basin. The section starts with grey cherty limestones of Sinemurian to Early Pliensbachian age. The thickness of this sequence does not exceed 5 metres. These grey cherty limestones are overlain by reworked red nodular limestones forming a series of mass-flow deposits. This interval is rich in red marls making up the matrix of the different mass flows. The age of this interval is Late Pliensbachian to Toarcian. The lower Middle Jurassic (Aalenian) is preserved in the form of a very thin layer of *Bositra*-rich marly limestones. On top of these Aalenian sedimentary rocks, a ferro-manganese horizon reflects a long lasting depositional gap (Bajocian to Bathonian). Above, a black massive radiolarite of Callovian age was deposited. The thickness of the black radiolarite is about 1 metre. It changes colour upsection into a reddish radiolarite. The age of the more than 15 metres thick red radiolarite is Late Callovian to Oxfordian, most probably earliest Oxfordian according to radiolarian associations. Still in the Early to Middle Oxfordian the red radiolarite passed into dark-grey radiolarites and cherty limestones. The radiolarites of this part of the section are laminated and contain the first fine-grained turbidites. The clasts are too small to be determined regarding their stratigraphic affiliation. Upsection the turbidites become coarse-grained. The components mainly consist of Late Triassic lagoonal Dachstein Limestone, whilst Early to Middle Jurassic clasts occur only seldom. This component spectrum is identical to that of the Tauglboden valley resediments in the south. So is the age of the radiolarian rich background sediment: Early to Middle Oxfordian. In contrast to the thick succession in the Tauglboden valley, the thickness of the northern Tauglboden Basin succession does not exceed a few tens of metres (details in DIERSCHE, 1980) with a maximal thickness of the intercalated mass flows of only 10-20 centimetres.

The components in the different turbiditic layers exclusively derive from the lagoonal Dachstein Limestone facies zone. The component spectrum is identical with the one known from the Taugl valley to the south.

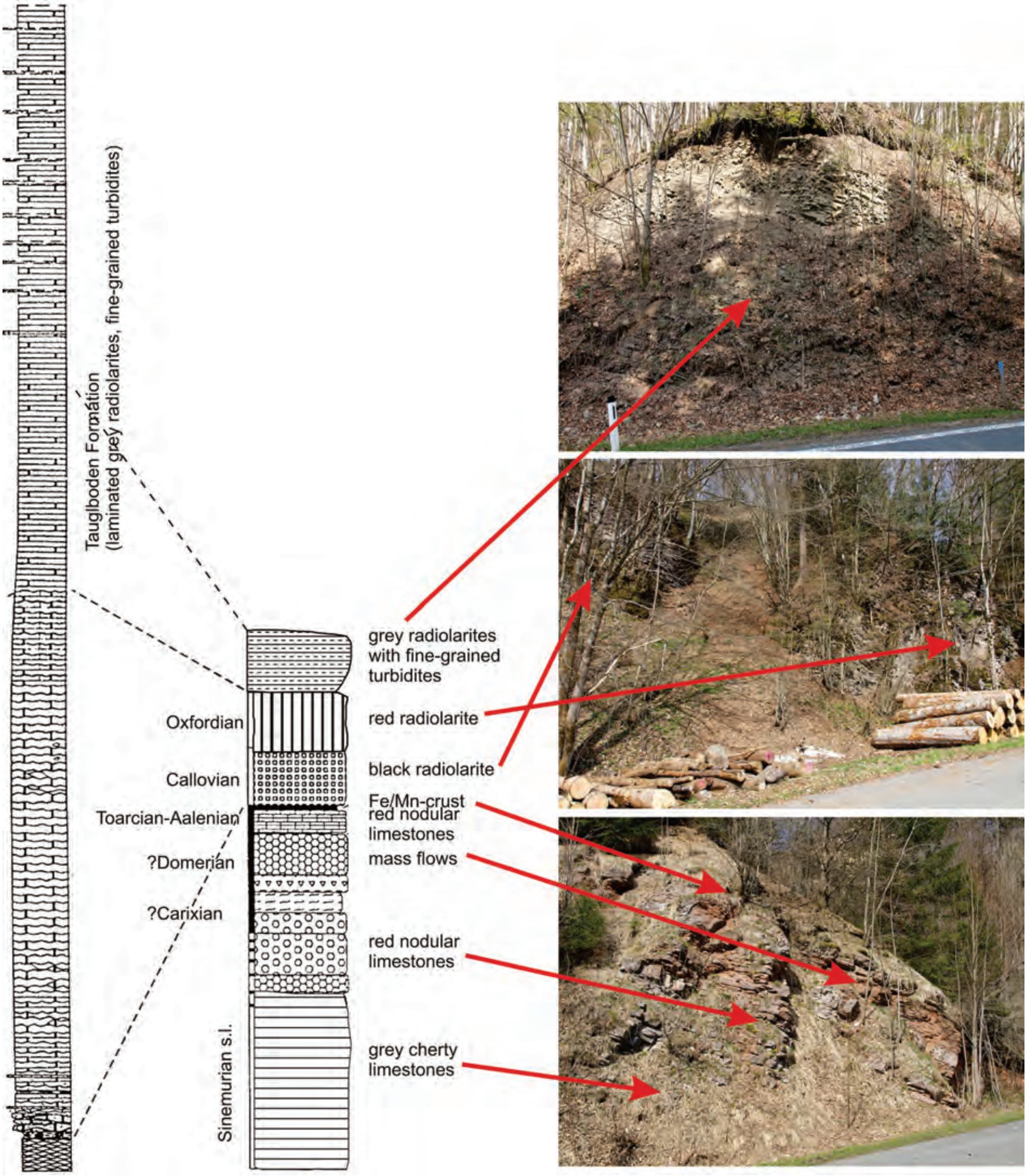


Figure 25: Stratigraphy and facies of the Early to early Late Jurassic section along the road to the village Krispl in the Mörtlbach valley (compare GAWLICK et al., 2012). Right section with photographs after BÖHM (1992), modified and completed for the Callovian-Oxfordian part. Left section from DIERSCHE (1980).

Locality Zauberwald and Berchtesgaden and Bad Dürrnberg area: Sandlingalm Basin

The Sandlingalm Basin fill contains blocks up to kilometre-size, which derived exclusively from the Hallstatt Limestone facies and the Meliata facies zones (including cherty Pötschen Limestone without reefal detritus) in a radiolaritic matrix. The sedimentary succession of the Sandlingalm Basin is composed of various slide masses in a Callovian-Oxfordian radiolaritic matrix (Fig. 26). Resedimentation of Hallstatt blocks in this basin started in the Early Callovian and ended around the Oxfordian/Kimmeridgian boundary with the emplacement of the Haselgebirge Mélange (MISSONI & GAWLICK, 2011a) and the subsequent sedimentation of grey siliceous deep-water limestones started. These limestones belong to the basinal sequence aside the early Plassen Carbonate Platform *sensu lato* and were deposited on top of slide masses sealing the chaotic basin fill (compare Figs. 17–22).

In the Zauberwald area the lower part of the basin fill is outcropping: different mass-flows consisting exclusively of Late Triassic red and grey Hallstatt Limestone clasts occur in a dark-grey to black Callovian radiolaritic matrix (details in MISSONI 2003).

In the whole area of Berchtesgaden to Bad Dürrnberg many slides of Hallstatt Limestone successions exist; for history of investigations and new data see e.g. GAWLICK et al. (1999a), MISSONI (2003), MISSONI & GAWLICK (2011a).

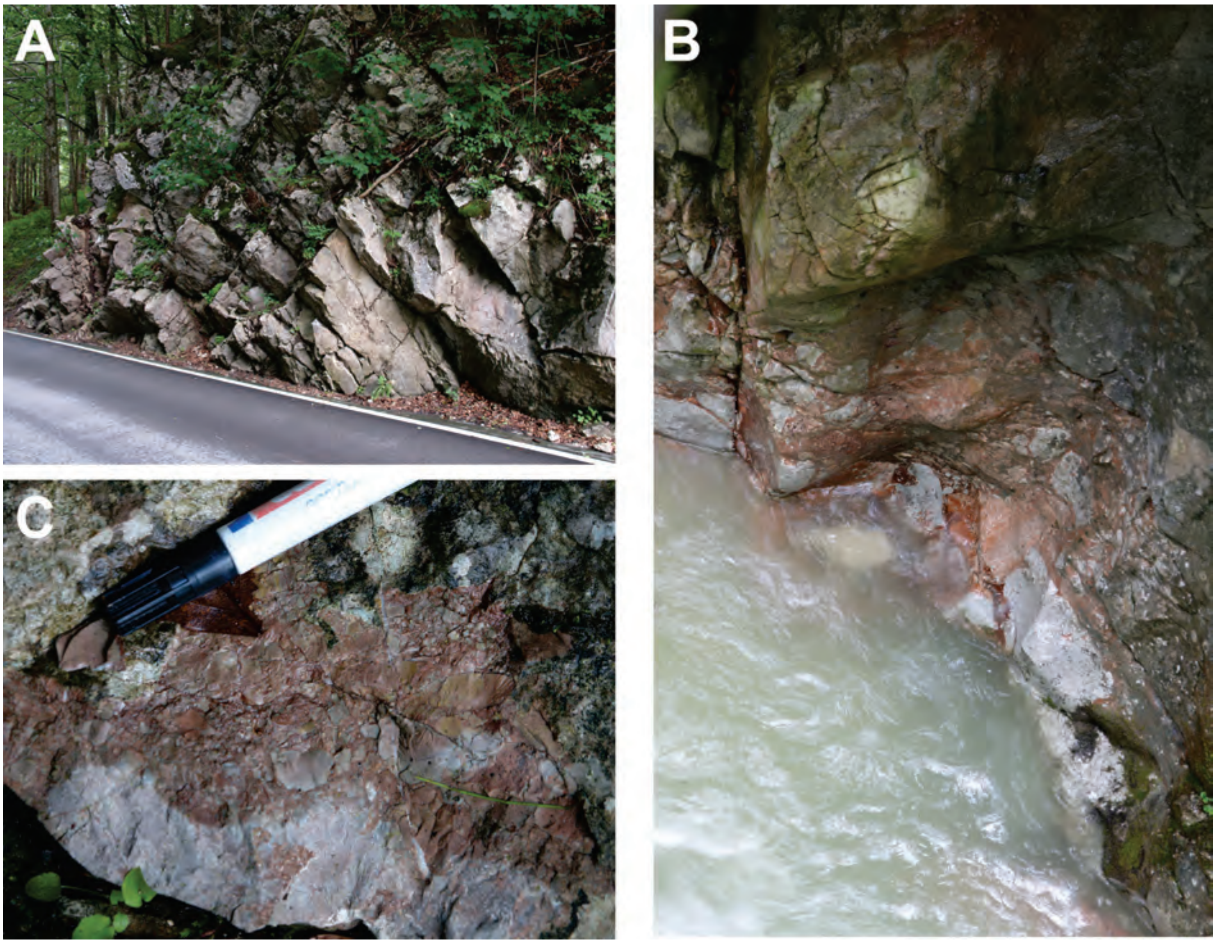


Figure 26: Sandlingalm Formation in the Zauberwald area.
A) Outcrop situation along the road. Different mass-flow deposits which consists of Hallstatt Limestone clasts. The mass flows area surrounded by a weathered landscape which consists of the radiolaritic matrix.
B) Polymictic mass-flow deposit in the gorge (Marxenklamm) on the forest road in direction Zauberwald. Red and grey Hallstatt Limestones clasts occur in a reddish-greyisch cherty matrix.
C) Polymictic breccia in the Zauberwald area. Most clasts are angular. The rare matrix consists of reddish radiolarian-rich cherty limestones.

Büchsenkopf area: Lammer Basin

In general, the sedimentary record of the Lammer Basin fill in the Salzburg and Berchtesgaden Alps documents a shift of depocentres within the basin (MISSONI & GAWLICK, 2011a, b): in an early stage of sedimentation the original depocentre of the basin was filled by slide blocks which derived from the accreted proximal Zlambach facies zone. The northern depocentre, after a shift of the basin axis, received material from the reefal part of the Late Triassic carbonate platform.

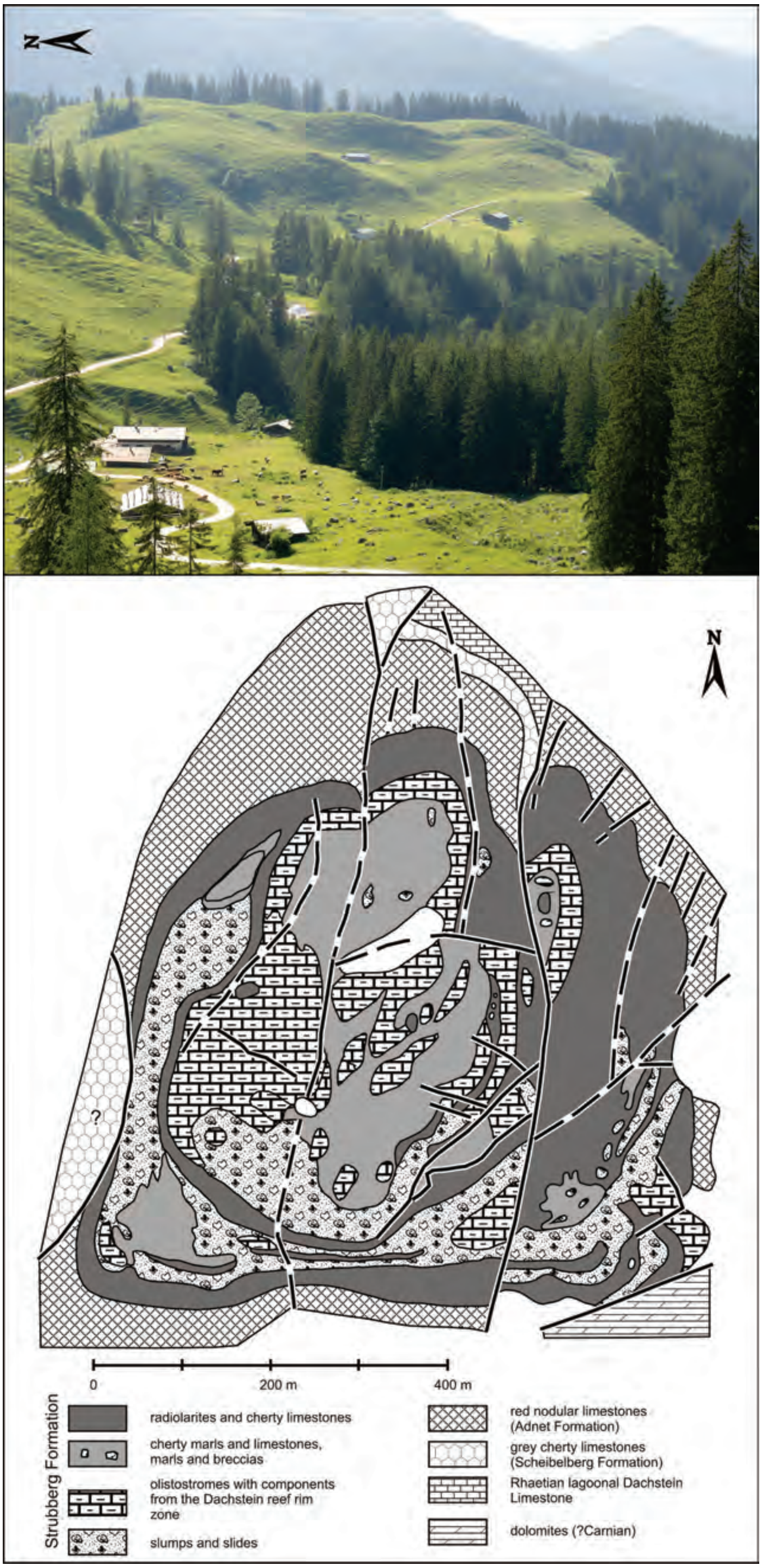


Figure 27: Photo and geological map of the Büchsenkopf area in the southern Berchtesgaden Calcareous Alps (based on DIERSCHE, 1978, after GAWLICK et al., 2003 and MISSONI, 2003).

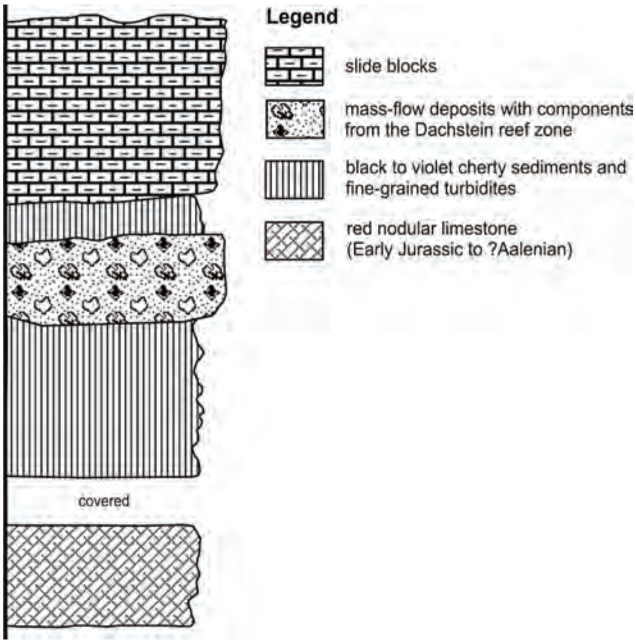


Figure 28: Generalized sedimentary succession of the Büchsenkopf area. The contact between the Early to Middle Jurassic red nodular limestones is not exposed. The black radiolarites below the first mass-flow deposits are dated as Callovian by means of radiolarians. The first resediments occurred in the Oxfordian according to GAWLICK et al. (2003) and MISSONI (2003). The thickness of the whole preserved succession does not exceed 150 metres. The section is not to scale.

The Büchsenkopf area (Fig. 27) comprises a complete Late Triassic to Late Jurassic sequence. The oldest sedimentary rock in the area is the Rhaetian lagoonal Dachstein Limestone which is overlain by Early Jurassic red nodular limestones (BRAUN, 1998). Middle Jurassic red nodular *Bositra* Limestones are missing. The black radiolarite (Callovian: GAWLICK et al., 2003; MISSONI, 2003) directly overlies the red nodular limestones (Adnet Formation) with a depositional gap in between. Resedimentation in the area started around the Callovian/Oxfordian boundary but more likely in the Early Oxfordian. Several polymictic olistostromes occur intercalated in black radiolarites to cherty limestones and, more seldom, argillaceous marls. Tens of metres sized slides make up the top of the preserved Büchsenkopf area sequence (Fig. 28).

The components of the different mass-flow deposits derive exclusively from the reef slope to reef area of the Late Triassic Dachstein Limestone carbonate platform. Upsection, on top of the Büchsenkopf sequence, larger slides of several hundred metres thickness (Fig. 29) occur. Fig. 29 shows the whole Late Triassic to early Late Jurassic sedimentary succession. The base of the succession is represented by Rhaetian lagoonal Dachstein Limestone. It is overlain by red nodular limestones of Early to Middle Jurassic age. Upsection follows a some hundred metres thick succession of radiolaritic sediments with intercalations of mass-flow deposits (= Büchsenkopf series). The sequence is topped by a several hundred metres thick slide from the Dachstein reef slope area (Mt. Jenner).

The radiolarians from the cherty limestones and radiolarites directly below the contact yielded a Callovian to Early/Middle Oxfordian age (MISSONI, 2003). The upper part of the sequence might have been eroded during the emplacement of the huge slide (compare MISSONI & GAWLICK, 2011a).

The matrix of these huge slides consists of dark grey to black cherty marls, cherty limestones and radiolarites, dated by means of radiolarians as Oxfordian (MISSONI, 2003). In the Berchtesgaden Calcareous Alps the deposition of the radiolarites of the Lammer Basin fill started in the Callovian and ended in the Oxfordian (MISSONI, 2003; MISSONI et al., 2005; MISSONI &, GAWLICK 2011a), similar as in the type region to the east.

Figure 29: Late Triassic to early Late Jurassic sedimentary sequence in the southern Berchtesgaden Calcareous Alps topped by a huge slide of Dachstein reef slope origin. After MISSONI & GAWLICK (2011a). View from the west (Büchsenkopf area).

Tauglboden valley: Tauglboden Basin

The Tauglboden Formation is composed of Oxfordian to Early Tithonian cherty matrix sediments with intercalated polymictic breccias and mass-flow deposits derived from the Trattberg Rise to the south (GARRISON & FISCHER, 1969; SCHLAGER & SCHLAGER, 1973; DIERSCHE, 1980), i.e., the lagoonal Dachstein Limestone facies zone. For a detailed description see GAWLICK et al. (2012).

Where the Urban valley approaches the Taugl valley (Fig. 30), the contact between the Early to Middle Jurassic red nodular limestones and the overlying radiolarite sequence is exposed. The age of the red nodular limestones is Late Bathonian to Early Callovian according to HUCKRIEDE (1971) and BÖHM (1992). On top of the red nodular limestone, a condensed layer contains rhyncholiths of Oxfordian age (HUCKRIEDE, 1971). The microfacies of the upper part of the red nodular limestone correspond to that of the overlying red radiolarite: Radiolarians from these red radiolarites yielded an Early to Middle Oxfordian age (GAWLICK, 2000b). The radiolarian associations are similar to the radiolarian associations of the grey laminated radiolarites higher in the section. Both the lithology and the colour of the radiolarites change gradually. The radiolarites turn from red over reddish grey and medium grey to finally dark-grey colours. The grey radiolarites are fine laminated. The clay content increases upsection and several few centimetres thick clay layers are intercalated between the radiolarite beds.

About five metres above the contact between the red nodular limestone and the radiolarite succession, the first coarse-grained mass-flow deposits are intercalated in the radiolarite sequence. The up to 20 cm thick breccia layers overlie the radiolarite beds practically without basal erosion; obviously the breccia layers show the characteristics of channels deposits. Below the breccia layers a layer of green volcanic ash is locally preserved.

The components in the mass-flow deposit derive exclusively from the lagoonal Dachstein facies zone. Components of the Early Rhaetian Kössen Formation are rare whilst components of Rhaetian lagoonal Dachstein Limestone strongly predominate. Early to Middle Jurassic clasts occur in rock-forming quantities, too. Early Jurassic grey cherty limestones (Scheibelberg Formation), chert nodules and red nodular limestones (Adnet Formation) dominate. In contrast, Middle Jurassic *Bositra* Limestone components are seldom.

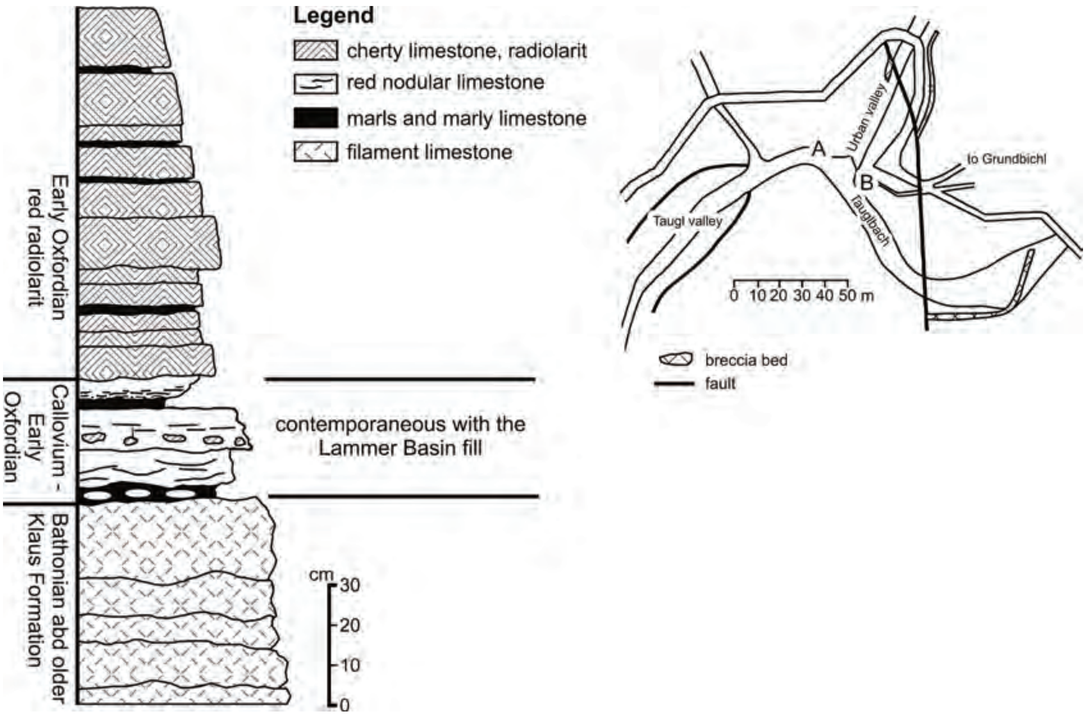


Figure 30: Area of the Urban creek/Taugl creek in the central Salzburg Calcareous Alps, exposing excellent sections of the succession around the boundary Klaus Formation/radiolarite (Tauglboden Formation) in the. The drawn detailed section is from west of the Urban valley (A). An equivalent section is seen east of the Urban creek (B). Redrawn after HUCKRIEDE (1971).

A strongly variable outcrop situation is met on the walk along the forest road Kesselstrasse. In a small valley beside the forest road and along the forest road there are some good outcrops giving an insight into the early phase of the Tauglboden Basin evolution. The age of the succession along the road is still Early to Middle Oxfordian as proven by radiolarians. Dark grey to black laminated radiolarites with changing clay content, slump deposits and mass flows are the typical sedimentary features of the succession. The slump deposits consist partly of cherty sediments without older components, large blocks of older components incorporated in the argillaceous matrix, and debris flows. Generally, the older clasts are the same as in the basal breccia layers along the Taugl road, but Jurassic clasts are both smaller in number and older in age. The erosion cut into the Norian lagoonal Dachstein Limestone.

In the curve before the waterfall, a only few metres thick succession of dark grey to black radiolarites to cherty limestones free of mass flows intercalations occurs on top of the amalgamated sequence. The radiolarites from this amalgamated series below yielded still an Early to Middle Oxfordian age. Thus the whole around 200 metre thick sequence is Early to Middle Oxfordian in age.

Above this radiolarite succession again a thick radiolarite sequence with slumps and mass flows occur along the way. Here, several metres above this mass flow free radiolarites, some layers of volcanic ashes (metabentonites – GAWLICK et al., 1999b) of ten centimetres thickness are intercalated in the sequence. Radiolarians from these volcanic ash layers yielded an Early Tithonian age (GAWLICK et al., 1999b). This means, that the time span Latest Oxfordian to Early Tithonian is characterized by a starved sequence. The volume of material shed into the basin decreased rapidly in the Late Oxfordian. In comparison, the Kimmeridgian was characterized by radiolarite deposition.

Later, in the Early Tithonian, a new depositional cycle with mobilisation and redeposition of large volumes of rocks started. The series again is characterized by slump deposits, mud and debris flows. Whereas the older components in the different chaotic deposits were still the same as in the Early to Middle Oxfordian sequence, the content of Jurassic clasts was very low. Reworked Norian to Rhaetian clasts are dominating the component spectrum.

Radiolarites in this part of the succession are scarce, with cherty marls and cherty limestones being the typical matrix sediment. The preservation quality of the radiolarians in these matrix rocks is generally very bad.

By reaching the waterfall we will see a several tens of metres thick sequence of dark-grey well bedded cherty marls and cherty limestones, intercalated by several slump deposits, mud flows and debris flows (Fig. 31). The series is also characterized by the intercalation of semi-consolidated volcanic ash layers.

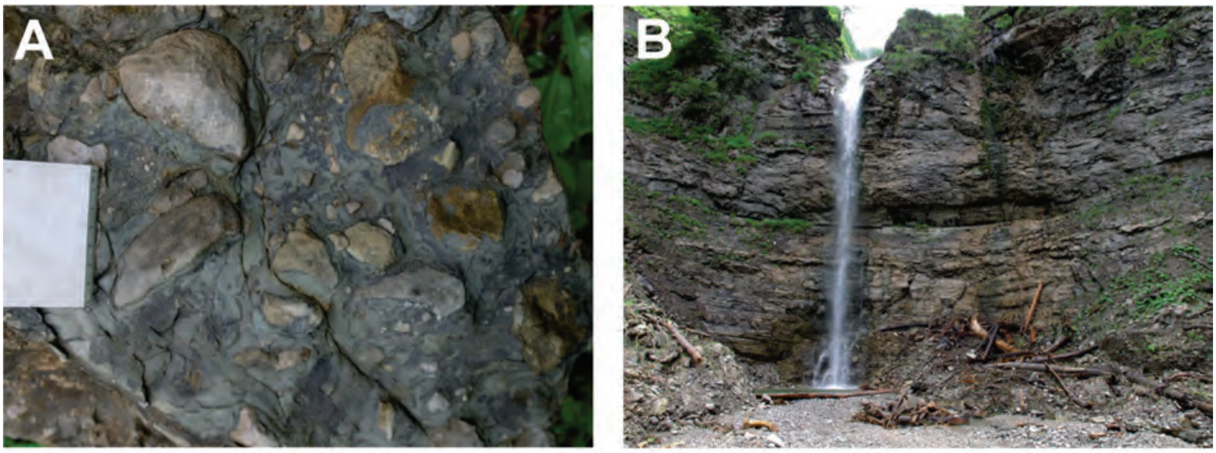


Figure 31: A) Early to Middle Oxfordian mud flow with large boulders of Late Triassic lagoonal Dachstein Limestone on top of well-bedded grey laminated radiolarites. Kesselstrasse forest road, Taugl valley. **B**) Early Tithonian sedimentary succession with slump deposits, mud flows and debris flows in a matrix of cherty marls and cherty limestones. Waterfall Kesselstrasse, Taugl valley.

4.3 Early Cretaceous

The increase of clastic material supply caused the drowning of the Plassen Carbonate Platform *sensu stricto* in Middle to Late Berriasian time and the establishment of a sedimentary succession with increasing siliciclastic input. The Valanginian to Barremian evolution is documented by an increasing supply of siliciclastic and ophiolitic-related detritus into the former Tauglboden/Oberalm Basin area (Rossfeld Molasse - GAWLICK et al., 2008). Ongoing uplift of the Juvavic nappe stack in the Early Cretaceous was accompanied by continued erosion and further northwestward gliding of several mélange blocks along low-angle faults in the Valanginian. In the Valanginian and in the Late Barremian, mass-flow deposits with mixed exotic and local material occurred, best explained by regressive cycles at this time (GRADSTEIN et al., 2004). The Rossfeld foreland basin fill and equivalents to the south represents the final stage of the mountain building process along the Neotethys suture (Fig. 3). Around the Barremian/Aptian boundary or in the Early Aptian these basins became filled (FUCHS, 1968; PLÖCHINGER, 1968; FAUPL & TOLLMANN, 1979). This is marked by a facies change to fresh-water conditions with local remnants of coal and amber (PLÖCHINGER, 1968).

Roßfeld road

The Roßfeld area along the Roßfeld road is the type area of the Early Cretaceous Roßfeld Formation (Fig. 32).

In the Rossfeld Basin type area, which represents the westward continuation of the Tauglboden Basin north of the Trattberg Rise of Mt. Kehlstein, the sedimentation lasted until the ?Barremian (TOLLMANN, 1985). Around the Early/Late Tithonian boundary the sedimentation changed from the radiolaritic Tauglboden Formation to the Late Tithonian to Middle Berriasian hemipelagic limestones of the Oberalm Formation intercalated with slope breccias of the Barmstein Limestone (GAWLICK et al., 2005).

In the Late Berriasian (not Valanginian) (MISSONI & GAWLICK, 2011a; KRISCHE, 2012; BUJTOR et al., 2013) a slight increase of the fine-grained siliciclastic material led to the sedimentation of the Schrambach Formation (TOLLMANN, 1985; RASSER et al., 2003). The change from hemipelagic carbonates to siliciclastically influenced siliceous carbonates and marls occurred contemporaneously with the drowning of the Plassen Carbonate Platform sensu stricto to the south (GAWLICK & SCHLAGINTWEIT, 2006). The Rossfeld Formation overlies the Schrambach Formation and is characterized by a coarsening upward trend.

In former interpretations the Rossfeld Basin was a newly formed Early Cretaceous flysch basin in a migrating foredeep in front of advancing Juvavic nappes (FAUPL & TOLLMANN, 1979; TOLLMANN, 1985; FAUPL & WAGREICH, 2000; NEUBAUER et al., 2000; FRANK & SCHLAGER, 2006). The sedimentation should have been terminated by the overthrust of these nappes, documented by the Hallstatt outliers on top of the Rossfeld Formation. By this interpretation mass-flow deposits, intercalated in calcareous sandstones and cherty limestones of the upper Rossfeld Formation should contain the complete component spectrum of the arriving nappes (e.g., PESTAL et al., 2009) as documented in the Jurassic basins.

However, new results on the uninvestigated carbonate components in these mass flows of the type locality (MISSONI & GAWLICK, 2011a) and all surrounding areas (e.g., Leube quarry, Weitenau area, Bad Ischl: KRISCHE, 2012) show clearly that not a single component of the so-called "Juvavic nappes" exist in the Rossfeld Formation. Triassic-Jurassic components from the Hallstatt Zone (Hallstatt and Pötschen Limestones) or Triassic shallow-water carbonate components of the Upper Tirolic Berchtesgaden unit as well as components of the Alpine Haselgebirge are completely absent.

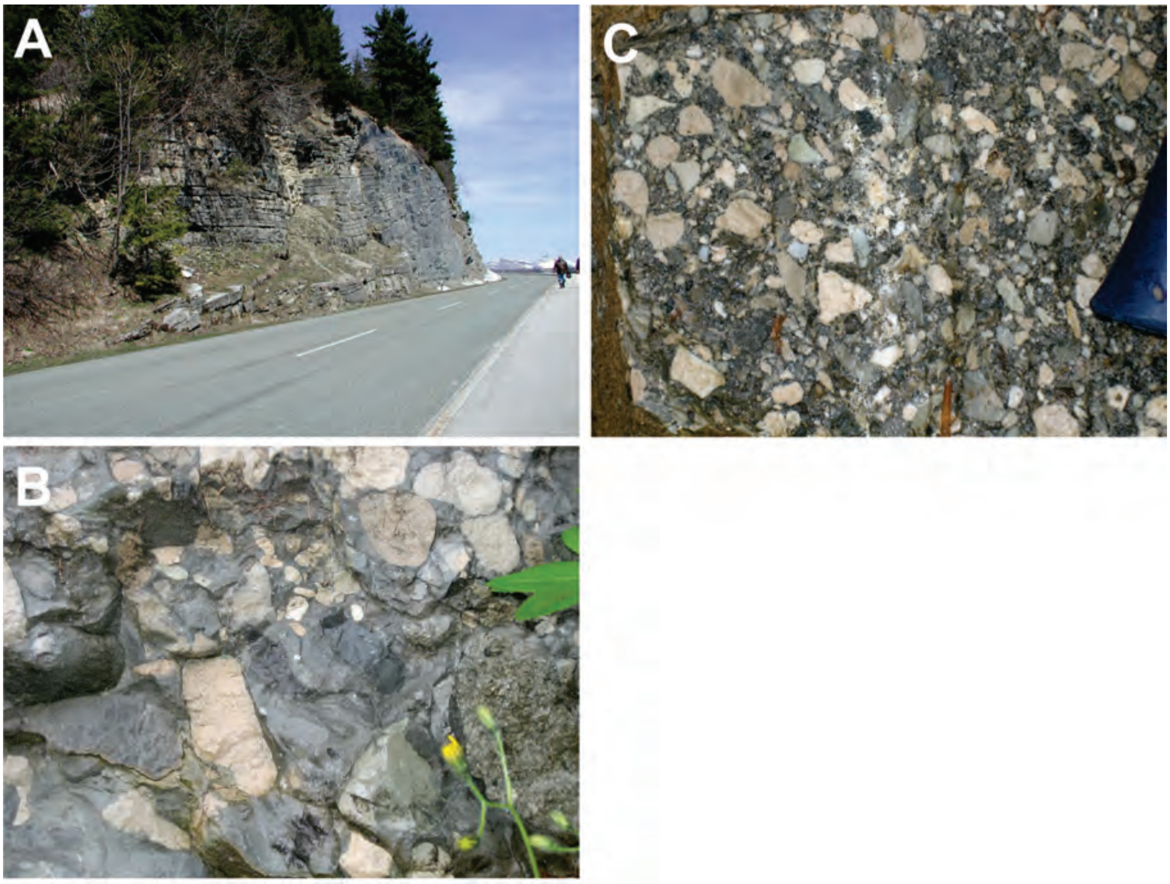


Figure 32: A) Ross Formation at the Hahnenkamm locality on the Rossfeld Panorama road. Calcareous sandstones with intercalated mass-flow deposits. **B**) Coarse-grained polymictic breccia of the Rossfeld Formation along the Rossfeld Panorama road. Beside the dominating carbonate clasts (Late Jurassic – Early Cretaceous) few radiolarite components (Triassic and Jurassic radiolarites) occur. **C**) Finer-grained polymictic breccia. Beside the dominating carbonate clasts radiolarites and ophiolitic grains occur.

Beside the already known siliciclastic, volcanic, and ophiolitic components (POBER & FAUPL, 1988; FAUPL & POBER, 1991; SCHWEIGL & NEUBAUER, 1997b; EYNATTEN et al., 1996; EYNATTEN & GAUPP, 1999; FAUPL & WAGREICH, 2000) occur only Late Jurassic to Early Cretaceous shallow-water carbonates and Triassic and Jurassic radiolarites. For details on component analysis see KRISCHE (2012), KRISCHE et al. (in press).

In addition from the Rossfeld Panorama road the Trattberg Rise (Fig. 33) to the south and the Lammer and Tauglboden Basin fills to the east resp. northeast are visible (Fig. 34).

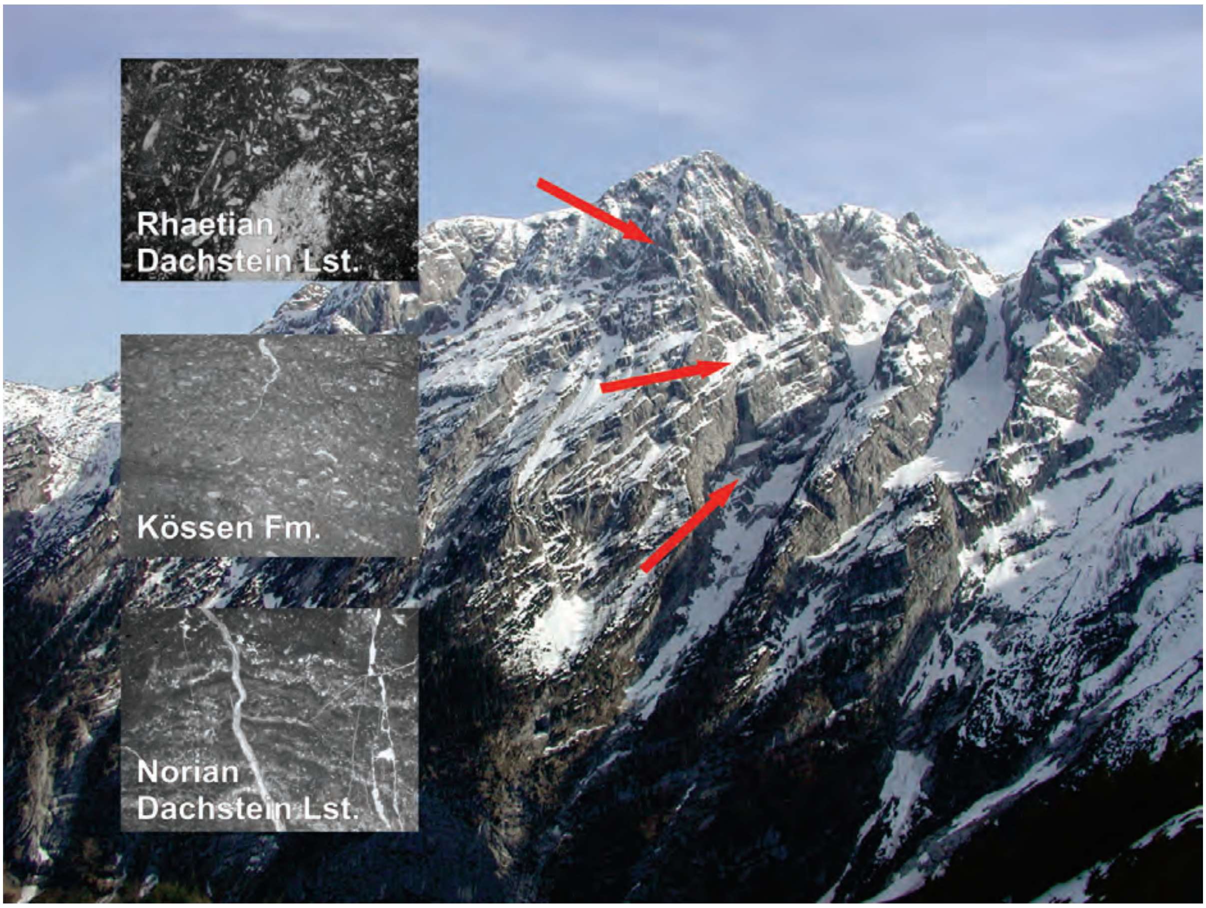


Figure 33: Late Triassic sedimentary succession of the Trattberg Rise, Mt. Hohes Freieck east of Mt. Hoher Göll. Insets show typical microfacies of the Late Norian to Rhaetian succession. The Rhaetian reef faces the Kössen Basin to the north. This clearly documents the palaeogeographic position of the area near the southern rim of the Kössen Basin and far away from the Dachstein Limestone reef zone facing the Hallstatt Zone.

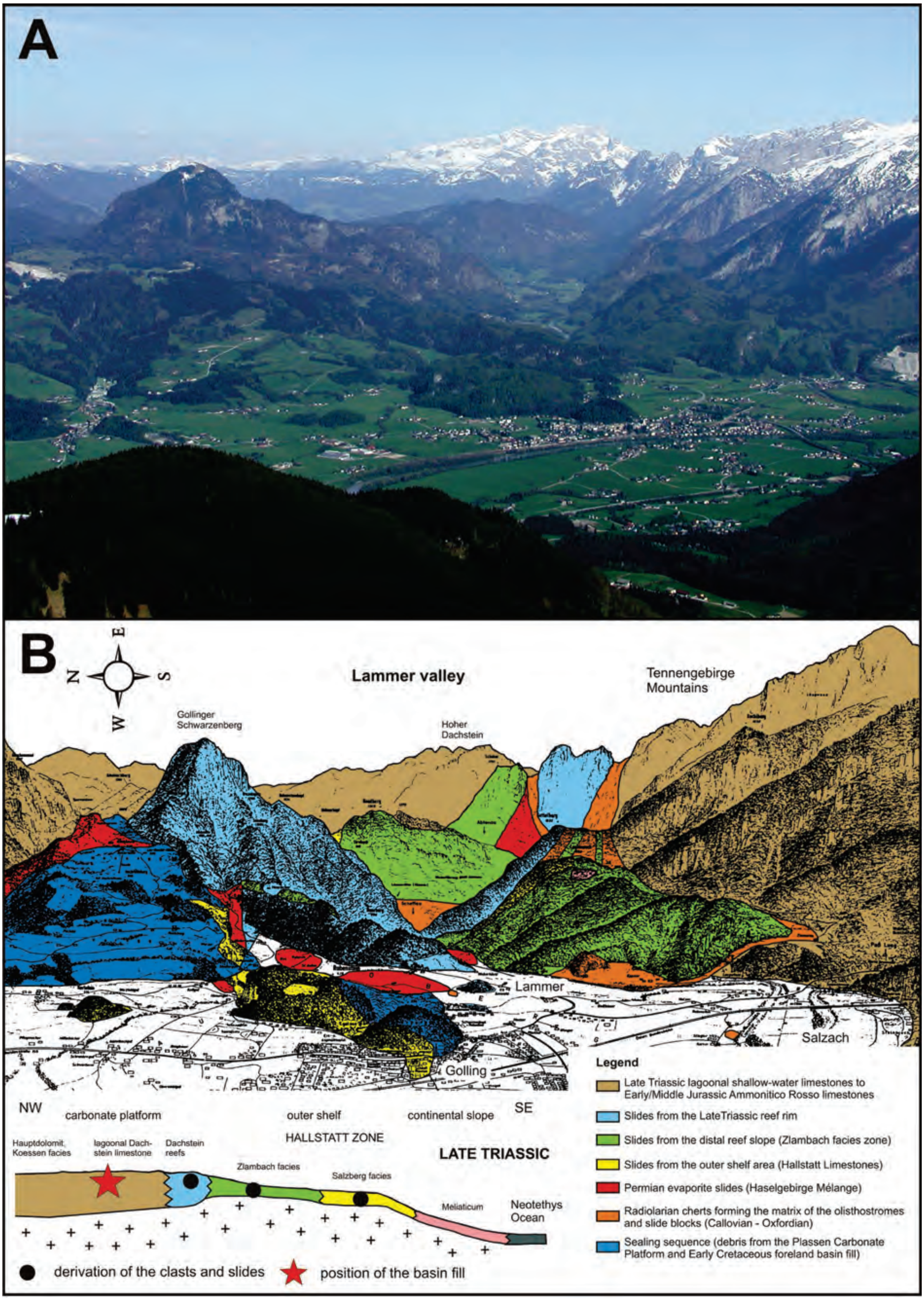


Figure 34: A) View from the west showing the type area of the Lammer Basin fill. **B**) Geological interpretation of the landscape picture. The basin fill consists of allochthonous material of different age and facies provenance, which generally derives from the outer shelf area transitional to the Neotethys Ocean.

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Field Trip B3: Lower to Middle Devonian algal limestones of the Graz Palaeozoic (Austria)

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Abstract

The Devonian (Emsian to Eifelian) calcareous green algal flora of the Graz Palaeozoic (Austria) contains representatives of *Pseudolitanaia*, *Pseudopalaeoporella*, *Zeapora*, *Maslovina* and a new lanciculoid genus. Findings are restricted to a couple of localities in the "Rannach Facies" of the Graz thrust complex and may be characterised as monogeneric mass occurrences. Consequently, they are interpreted as algal bafflestones originating from halimedalean meadows.

The Graz Palaeozoic

Palaeozoic remnants of the Eastern Alps belong to the Upper Austroalpine Nappe System (SCHMID et al., 2004) whose nappe stacking was created during Cretaceous times. Today weakly and unmetamorphosed Palaeozoic successions are irregularly distributed in Austria (Fig. 1). Separated by the Periadriatic Fault, Southern Alpine sequences (i.e., Carnic Alps and Karavanke Mountains) oppose Eastern Alpine Variscan sequences (i.e., Greywacke Zone, Gurktal Nappe System, Graz Palaeozoic and some isolated outcrops in south Styria and Burgenland).

Figure 1: Austria and its disconnected Palaeozoic units (shaded areas).

The "Graz Palaeozoic" located in eastern Austria (Styria) is isolated from other low metamorphic Palaeozoic occurrences in the alpine region by tectonic borders to the north, east and west as well as by its younger overlays in the south (Fig. 2).

Depending on the tectonic concept the Graz thrust complex may be subdivided internally into three (lower, intermediate, and upper; FRITZ & NEUBAUER, 1990) or only two (lower and upper; GASSER et al., 2010) nappe groups. However, both tectonic concepts have in common that the upper nappe group is characterized by basal Silurian volcanic rocks, exposed around the small town Kehr. They are overlain by Devonian to Carboniferous successions of dolomites, sandy and tufaceous dolostones, limestones and marly shales of the "Rannach Facies" (exposed west of the Mur valley and in the Hohe Rannach area), and of the "Hochlantsch Facies" (exposed in the Hochlantsch massif). The "two nappe concept" also includes parts of the "Kalkschiefer Facies" characterized by successions of carbonaceous schists, sandstones and limestones. The lower nappe group (i.e., "Schöckel Facies"; including the "Laufnitzdorf Facies", and parts of the "Kalkschiefer Facies" in the concept of GASSER et al., 2010) was intensely deformed with penetrative foliation and pronounced stretching lineation under upper greenschist facies conditions. In contrast, the Upper Nappe System experienced only very low to low grade metamorphism hence preservation of fossils is mostly acceptable (HUBMANN & MESSNER, 2007, cum lit.).

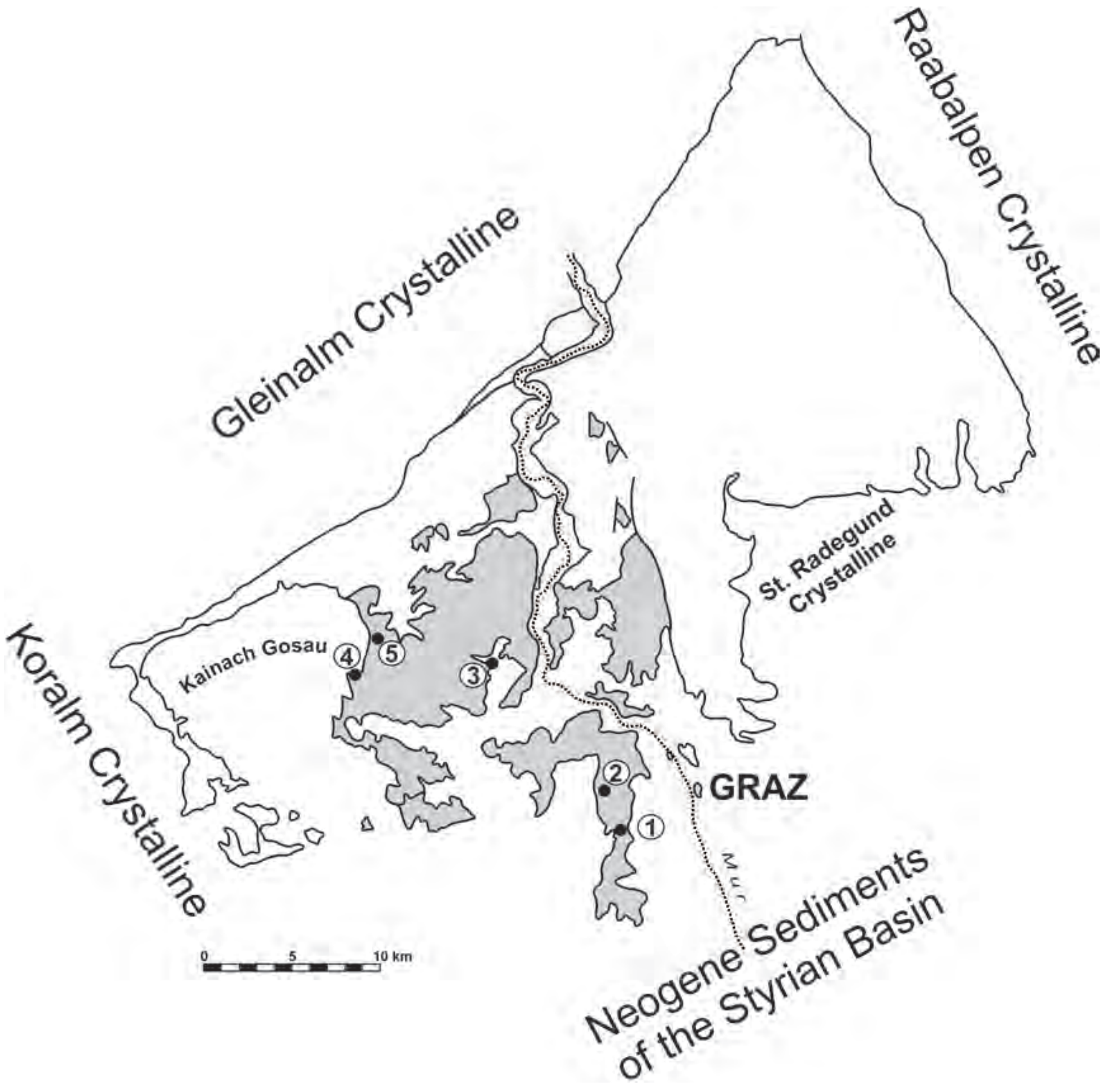


Figure 2: Simplified sketch of the Graz Palaeozoic. The northwestern and western parts are bordered by polycrystalline units (i.e., Gleinalm Crystalline, St. Radegund and Raabalm Crystalline). In the south, Neogene sediments of the "Styrian Basin" are transgressively overlain; the southwestern sector of the Graz Palaeozoic is unconformly covered by Upper Cretaceous sediments of the Kainach Gosau. Shaded patches correspond with outcropping area of the Rannach Facies. Dots with numbers indicate localities with algal findings (further information see text).

Since the "Rannach Facies" which is part of the Upper Nappe System is famous for its shallow marine fossil content, it has been a favoured destination during the last two decades for geologic excursions and, as a result, several excursion guides were published (HUBMANN & HASENHÜTTL, 1995; EBNER et al., 2000, 2001; HUBMANN et al., 2003; HUBMANN & FRITZ, 2004; HUBMANN & MESSNER, 2005; SUTTNER & HUBMANN, 2009; HUBMANN & WEBER, 2010; EBNER & HUBMANN, 2012). The present guide therefore intentionally wants to provide necessary information succinctly; for more detailed information on the stratigraphic development of the Graz Palaeozoic the reader is referred either to the before mentioned field trip guides or to HUBMANN et al. (2013) and complementary literature listed there.

The Rannach Facies: Stratigraphical overview and environmental architecture

The sedimentary sequence of the Rannach Facies (Fig. 3) indicates a change of the depositional area from a passive continental margin with a continental breakup (alkaline volcanism) to shelf and platform geometries during the Upper Silurian to Middle Devonian (FRITZ et al., 1992). During Middle/Late Devonian time the deposition environment changed from near-shore to open platform facies. During Frasnian time the facies changed to a pelagic environment (Forstkogel Group) which continued until the Serpukhovian and is followed by limestones and slates of the Dult Group (Bashkirian).

The sequence starts with more than 100 m thick alkaline basic volcanites and volcaniclastics (Kehr Fm.) which change over to dolostones (Kötschberg Fm.) locally rich in fossils (orthocon cephalopods, bivalves, corals) indicating at least a Ludfordian age (HISTON et al., 2010).

A succession predominantly composed of platy crinoidal limestones intercalated with sandy marls and sand/siltstones (Parmasegg Fm.; Pragian) passing into mostly monotonous light grey late diagenetic dolostones which may be intercalated in different stratigraphic levels by reddish-purple to green volcaniclastics, pure quartz sandstones, marly dolomites, and biolaminated and bioclastic dolomites (Flösserkogel Fm., ?lower Pragian-Emsian) follows. The latter are interpreted as depositions of a supra- to shallow subtidal, barrier-surrounded lagoon, and tidal flats (FENNINGER & HOLZER, 1978).

Overlying and/or interfingering the Flösserkogel Fm. the Plabutsch Fm. (Eifelian) is dominated by dark marly bioclastic limestones. In the lower parts of the formation, especially at the boundary to the Flösserkogel Fm. yellow to brownish shales occasionally blotched with moulds of chonetid brachiopods are characteristic. In the upper parts of the formation intercalations of red marls and marly limestones are common. The limestones predominantly contain typical “reefbuilding organisms” (HUBMANN, 1993, 2003) deriving from coral-stromatoporoid-carpets.

This phase is terminated by biolaminated dolomites, mudstones to bioclastic dolostones and clayey siltstones obviously caused by a eustatic sea level fall (HUBMANN & BRANDNER, 2009). An anew transgression resulted in a sequence with sharp (bio)facial contrasts between patch-reefs and monotonous mudstones (Kollerkogel Fm., Givetian). According to the *Polygnathus-Icriodus* ratio a higher energetic open platform environment is assumed (EBNER, 1998).

During the uppermost Givetian to lower Frasnian the sedimentation changed to variegated micritic cephalopod limestones (Steinberg Fm.) which continue up to the Bashkirian (Sanzenkogel Fm.). The thickness of this pelagic sequence reaches approximately 100 m, except in the eastern part of the Rannach Facies it is reduced due to karstification around the Devonian-Carboniferous boundary (EBNER, 1978, 1980). After an erosional gap at the top of the Sanzenkogel Fm. dark coloured limestones containing birdseye-structures which are interfingering/superposed with/by an alternation of shales with black limestones occur (Höchkogel Fm.).

The sequence of the Rannach Facies is terminated by approximately 50 m thick black shales, sometimes with intercalations of silt- and sandstones with fine phytoclastic material (Hahngaben Fm.). Due to the lack of diagnostic fossils the age of the formation is unknown, however an upper Bashkirian or even younger age is possible (EBNER, 1998).

Algal horizons

Localities with remains of algal thalli are known from the Lower Devonian (Pragian?-Emsian) Flösserkogel Fm. and lower Middle Devonian (Eifelian) Plabutsch Fm.. All these algal findings have in common that they represent monogeneric mass occurrences which are interpreted as (par)autochthonous bafflestones originating from halimedalean meadows (HUBMANN et al., 2008).

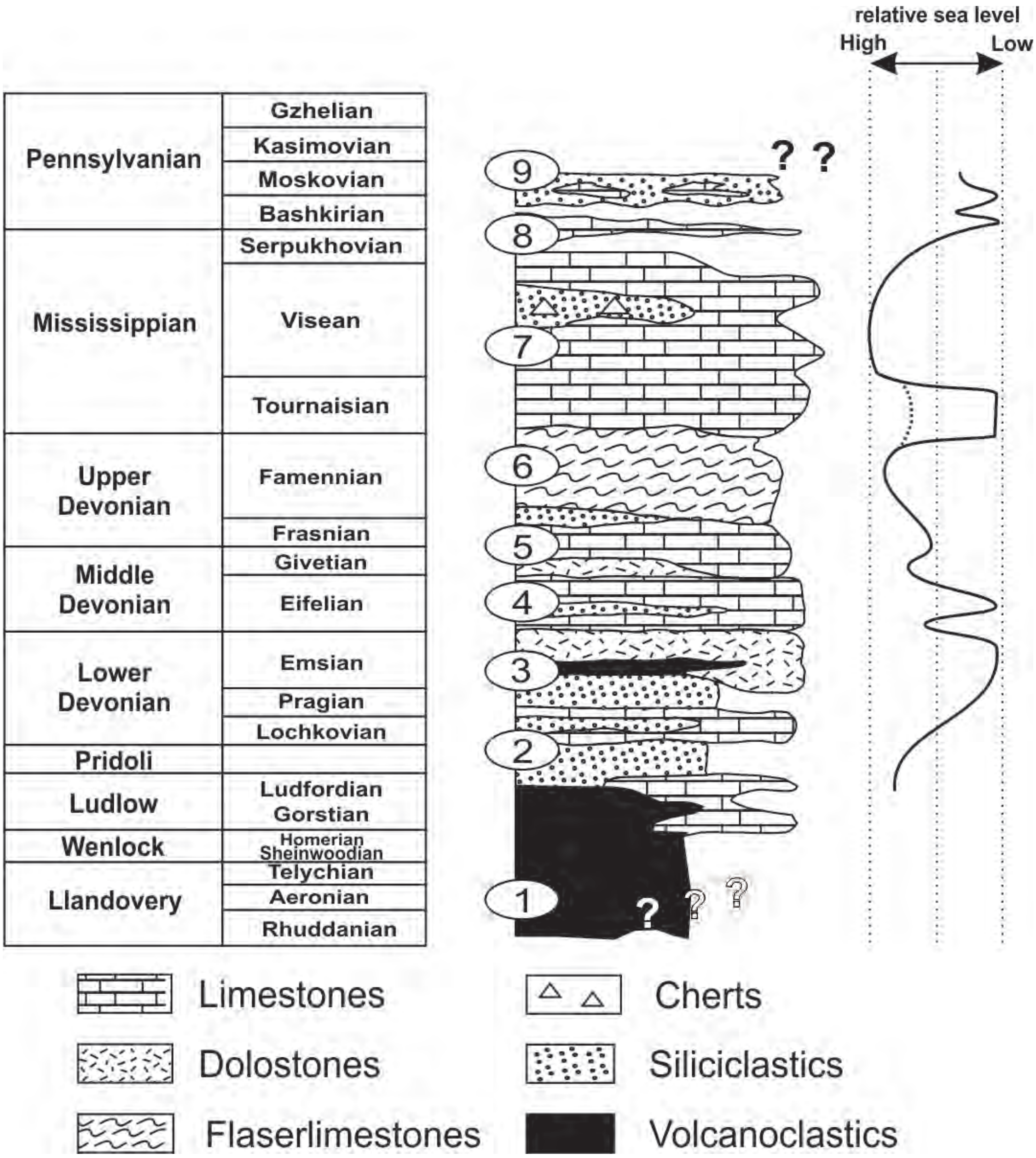


Figure 3: Stratigraphic column of the Rannach Facies and relative sea-level curve estimated from sedimentological and palaeontological data. 1 ... Kehr Fm., Kötschberg Fm., 2 ... Parmasegg Fm., 3 ... Flösserkogel Fm., 4 ... Plabutsch Fm., 5 ... Kollerkogel Fm., 6 ... Steinberg Fm., 7 ... Sanzenkogel Fm., 8 ... Höchkogel Fm., 9 .. Hahngraben Fm.

Localities

The geographic position of localities which will be visited during the excursion are shown in Fig. 2. All below mentioned algal findings have in common only a slight disarticulation of the thalli. Additionally, they occur in clayey lime- to dolostones pointing to hydrodynamically low depositional environments.

(1) Lower part of the Plabutsch Fm. (Eifelian) at Kollerkogel: Dark grey marly limestones of the southern slope of Kollerkogel (near the border to the urban area of Graz), a few meters above the abandoned illite mine contain in scattered occurring patches *Zeapora gracilis* (PENECKE, 1894). Primarily *Zeapora* was mistakenly assigned to the Bryozoans, later to Amphiporoids (see HUBMANN, 2000) (Fig. 4).

(2) Upper part of the Plabutsch Fm. (Eifelian) at Fuchsloch: Along a forest road on the southern slope of the Frauenkogel a sequence of alternating layers of clayey limestones, red mudstones and marls is developed. In the clayey limestones of this alternating sequence *Pseudopalaeoporella lummatonensis* (ELLIOTT, 1961) and subordinate *Pseudolitanaia graecensis* (HUBMANN, 1999) occur (Fig. 5, 6).

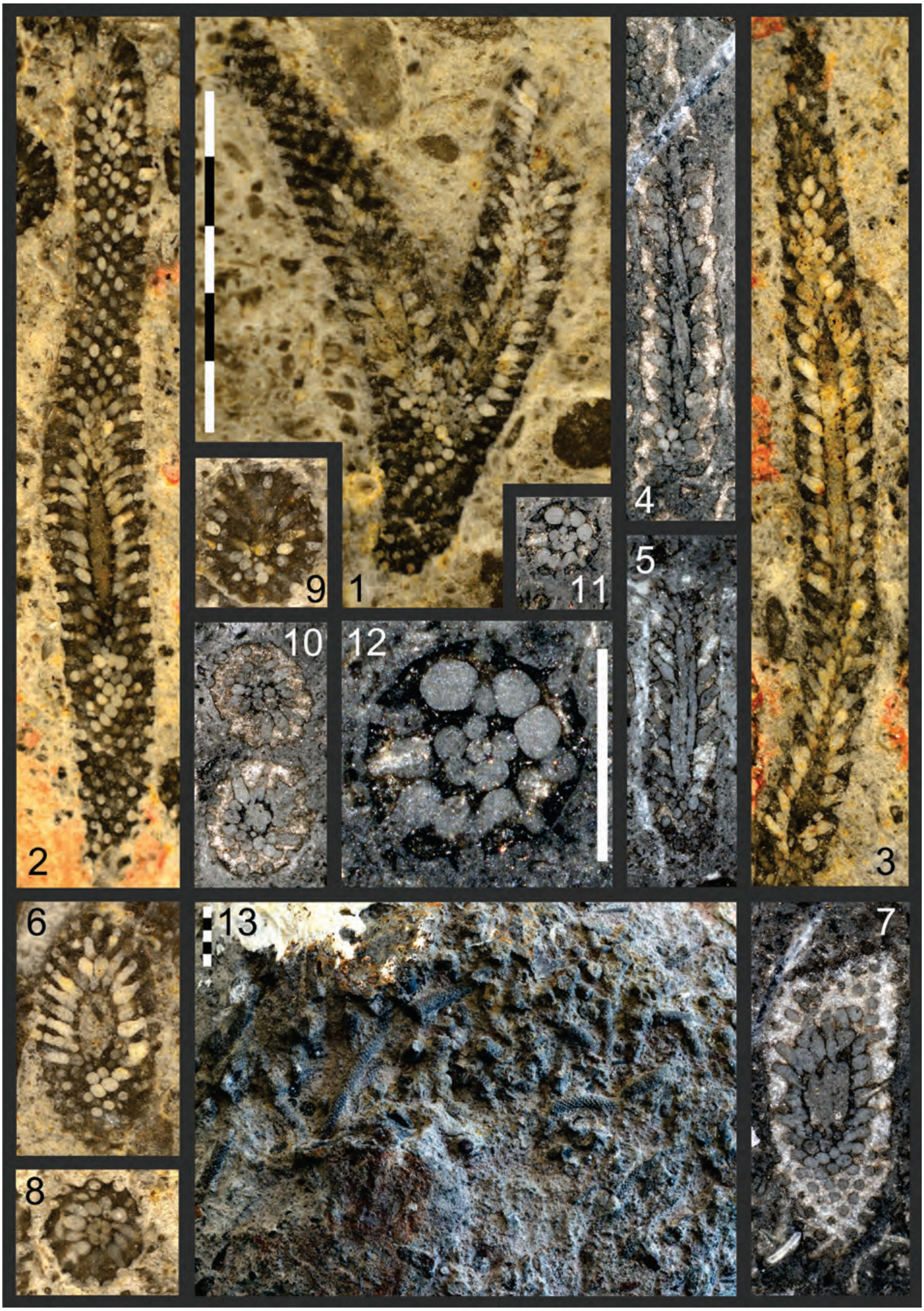
(3) Lower to middle part of the Flösserkogel Fm. (Emsian) at southeastern slope of Mount Hochstein near Rein monastery: Along a recently built forest road on the southern slope of Hochstein dark-grey micritic to pelmicritic dolomites contain a new genus of lanciculoid algae. Algal thalli show only little disarticulation thus individuals show up to 30 or more patelliform segments (articuli) (Fig. 7).

(4) Lower part of the Plabutsch Fm. (Eifelian) at St. Pankrazen: Along the road from Stiwoll to the North some 2 km before St. Pankrazen dark-grey micritic limestones at the base of the Plabutsch Fm. contain a new species of *Maslovina* (*Maslovina* sp. A). The respective horizon lies only a few dm above the basis of a shale horizon which corresponds in its position to the illite horizon of the Kollerkogel (Fig. 8).

(5) Middle(?) part of the Plabutsch Fm. (Eifelian) at the eastern slope of Mount Platzlkogel (approx. 3 km west of “Abrahamwirt”: Along a forest road light-grey micritic limestones contain a new species of *Maslovina* (*Maslovina* sp. B) which has apparently greater dimensions of thallus diameters (Fig. 9).

Figure 4 (next page): *Zeapora gracilis* (PENECKE, 1894) of locality 1.
The thalli consist of numerous peripheral tubules arranged around a central axis filled with a bundle of medullar filaments. The medullar zone consists of 4 to 6 (up to 10 and more) slightly interwoven filaments. The cortical zone is filled with massive carbonate deposits and perforated by roundly-elongated, densely packed filaments. Cortical filaments show bowling-like shapes.
Scale for 1 to 11: length of measuring bar 5 mm; 12: length of bar 1 mm; 13: length of bar 5 mm.

1 … Ramification of thallus; slightly oblique longitudinal section. 2 … Peripheral longitudinal section exhibiting cortical filaments in numerous longitudinal and cross sections. 3 … Longitudinal section; sector in the middle exposes the central part of the thallus. 4 … Longitudinal section showing interwoven medullar filaments. 5 … Longitudinal section with straight medullar filaments. 6, 7, 9 … Oblique transversal sections; note clubbed shapes of cortical filaments (6) and the offsets of cortical filaments branching off coarse medullary filaments (7). 8, 9-12: Transversal sections exhibiting five or six central filaments. 13 … Weathered surface of algal limestone of locality 1 built up exclusively by densely packed thalli of *Zeapora gracilis*. The hand rock sample illustrated was a present for the Institute collection by PENECKE in 1894.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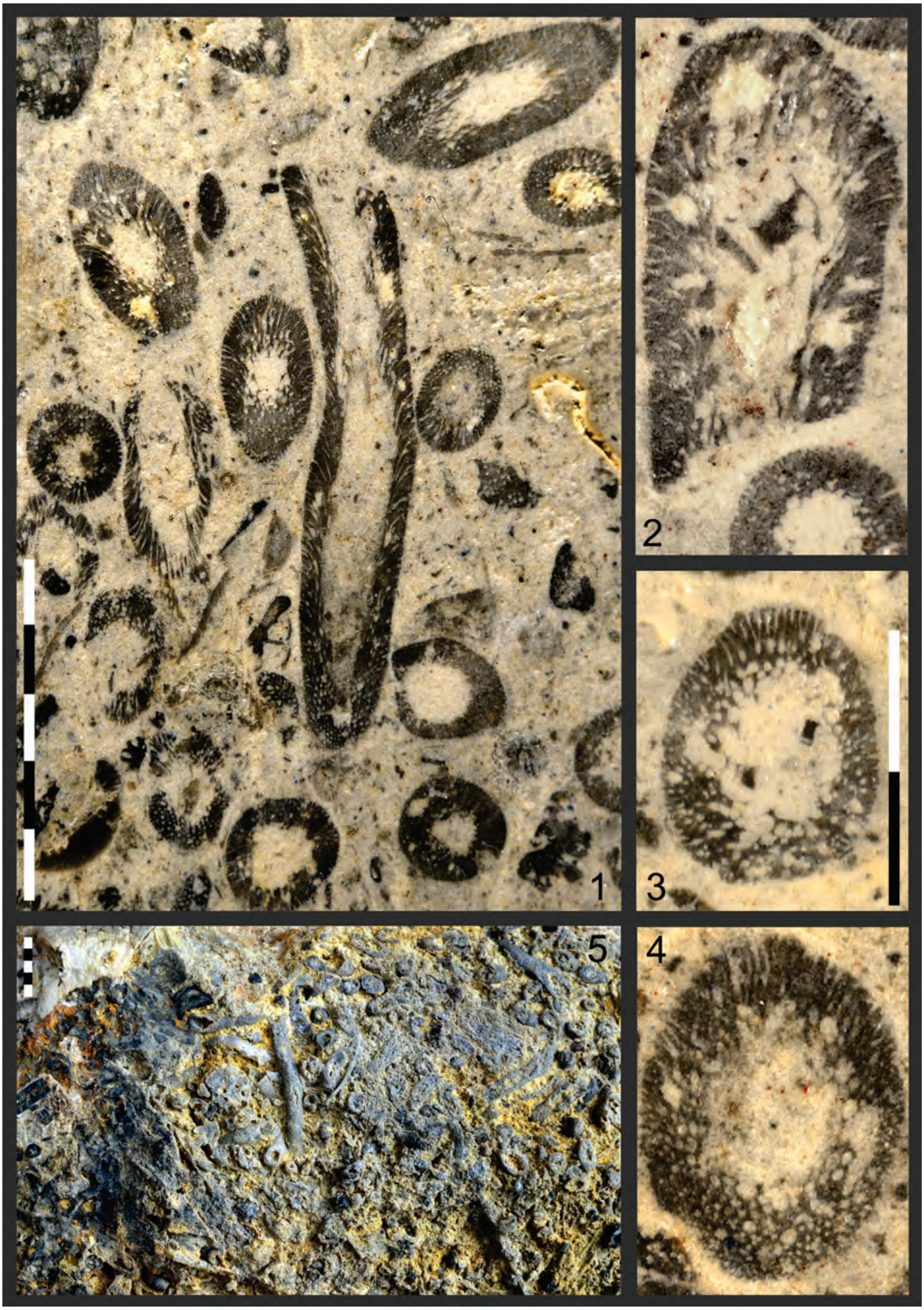
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Figure 5 (previous page): *Pseudopalaeoporella lummatonensis* (ELLIOTT, 1961) of locality 2.
Thalli are cylindrical in shape, sometimes they may slightly be undulant, with a weakly calcified medullar zone and an extensive radial envelope. The medullar zone is composed of several central tubes (up to 20?) and makes up approximately half the entire thallus diameter in cross section. Central filaments are arranged parallel to the thallus axis and are closely spaced. From central tubes cortical filaments develop in acute angles into numerous lateral tubes with a second and third order dichotomy. The filaments are commonly swollen just below the points of branching and widen trumpet-like towards the thallus surface.
Scale for 1 length of measuring bar 5 mm; 2-4: length of bar 2 mm; 5: length of bar 5 mm.

1 … Section parallel to bedding plane with various sectional planes of *Pseudopalaeoporella lummatonensis*. Note in the left upper corner a cross section of *Pseudolitanaia*. 2 … Slightly oblique longitudinal section exhibiting globular spaces in the inner cortex. 3, 4 … Slightly oblique transversal sections. 5 … Surface of algal limestone from locality 2 with densely packed thalli of *Pseudopalaeoporella lummatonensis*.

Figure 6 (next page): *Pseudolitanaia graecensis* (HUBMANN, 1990) of locality 2.
Thalli erect, cylindrical and continuous. The medullar space is built up by 4 to 12, generally 8 irregular filaments Cortical filaments are more or less oblique with a significantly increasing diameter and a spatula-shape. They end up as fine filaments of second order dichotomy.
Scale for 1-4: length of measuring bar 5 mm; 5: length of bar 2 mm.

1 … Section parallel to bedding plane with various sectional planes of *Pseudolitanaia graecensis* together with more delicate *Pseudopalaeoporella* sections. Note right to the measuring bar a section through a thamnoporid tabulate coral. 2 … Central longitudinal section. 3 … Oblique longitudinal section. 4, 5 … Sections through cortical fragments.

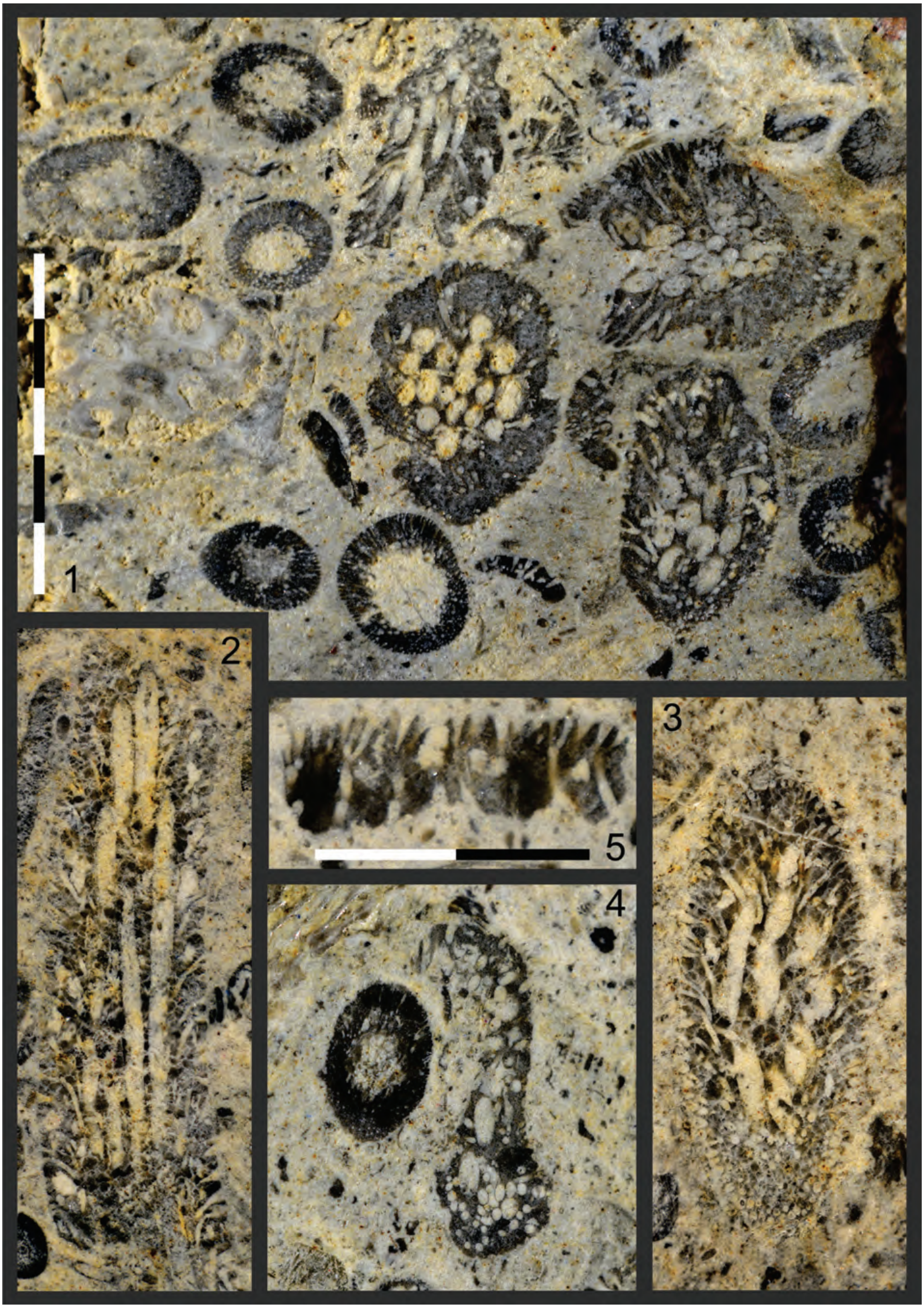
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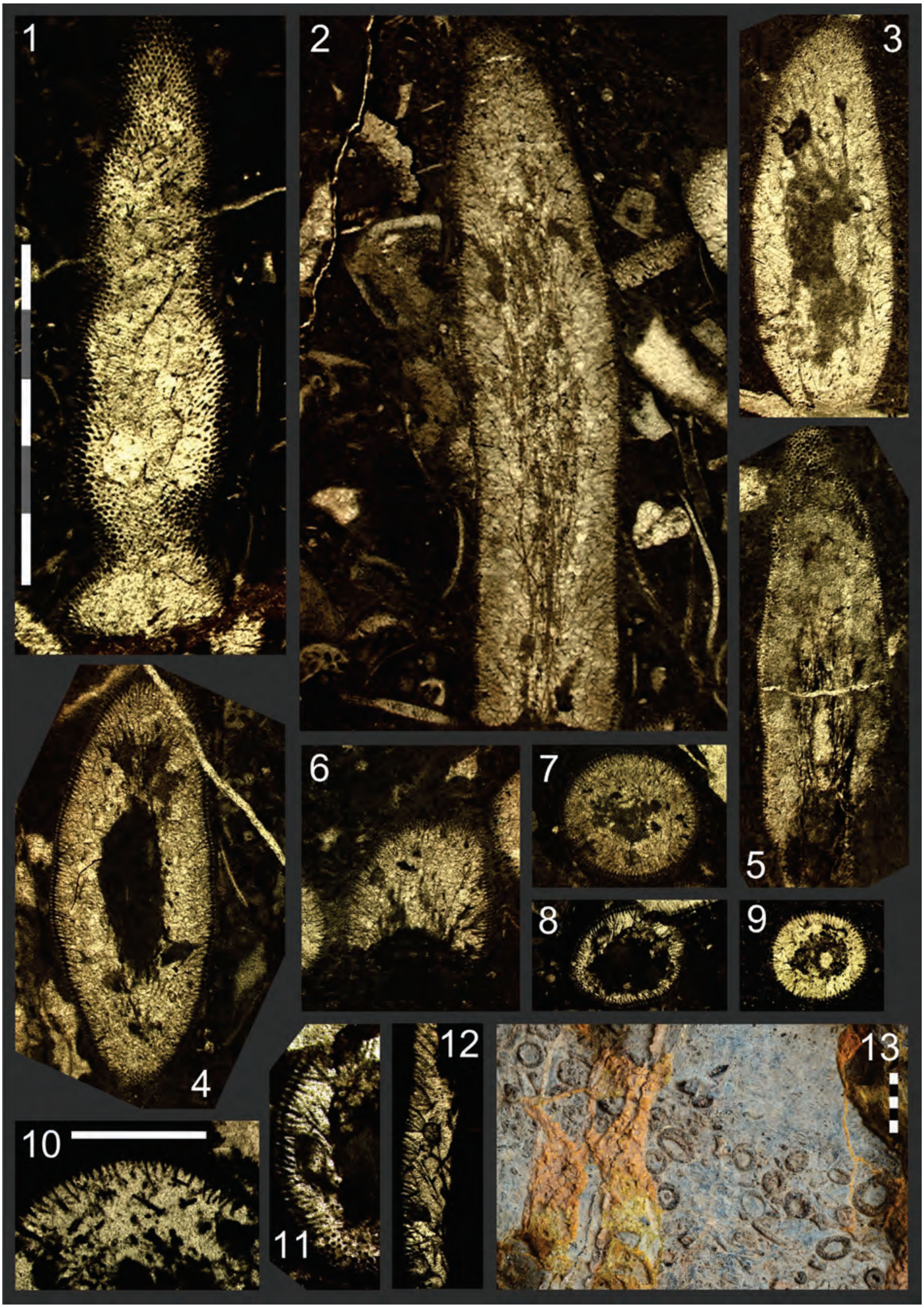
Figure 7 (previous page): New genus of lanciculoid algae of locality 3.
Thalli regularly segmented; individuals consist of up to 25 bowl-shaped elements (articuli, chalices) surrounding a straight or slightly bent stem (rhachis). Occasionally thallus ramifications are observed (see 1).
The internal assembly of four central filaments pervades the whole thallus. They apparently do not vary considerably in diameter, but may be slightly curved or undulating. From medullary filaments a great number of cortical filaments branch off radially and perpendicularly to the central axis decreasing their angles with growth. Each tapered segment contains two rows of cortical filaments and increases its diameter towards growth direction. These segments resemble the bell of a trumpet and are densely stacked one above the other.

Scale for 1 to 6: length of measuring bar 5 mm; 7: length of bar 2 mm; 8: length of bar 5 mm.
1 … Ramification of thallus; longitudinal section with approx. 30 articuli. 2 … Longitudinal section of a benting individual. 3-7 … Cross sections of articuli showing frazzled terminations. 5 … Microphotograph of thin-section illuminated by darkfield condensator exhibiting four, respectively 5 coarse medullary filaments. 8 ... Weathered surface containing densely packed thalli of the new of lanciculoid algae. Location for 5, 8: Ulrichsberg near Rein.

Figure 8 (next page): *Maslovina* sp. A of locality 4.
Thalli of a straight, cylindrical shape, occasionally undulated. Internally organised into a generally poorly calcified medullar area and a cortical zone. The medullar part consists of a high number (>40) of interwoven filaments which give rise to finer, cortical filaments. They divide up dichotomously at an acute angle and reach a third order dichotomy at the outermost cortical part. At this stage cortical filaments develop towards densely packed amphora-shaped utricles which constitute the thallus surface. The outermost cortical filaments develop into a layer of tightly packed amphora-shaped utricles.
Scale for 1 to 9: length of measuring bar 5 mm; 10-12: length of bar 1 mm; 13: length of bar 5 mm.

1 … Peripheral longitudinal section showing undulant shape of thallus . 2 … Central longitudinal section exhibiting numerous medullar filaments. 3, 4 … Oblique transversal sections exhibiting delicate cortical filaments. 5 … Slightly oblique longitudinal section showing peripheral layer of tightly packed utricles. 6 … Apical ending of thallus in longitudinal section. 7-9 ... Various cross sections of *Maslovina* sp. A. 10-12 ... Sections through cortical parts. Note globular and irregular spaces within the outer cortex. 13 … Weathered surface of a sample showing prostrate orientation of *Maslovina* thalli.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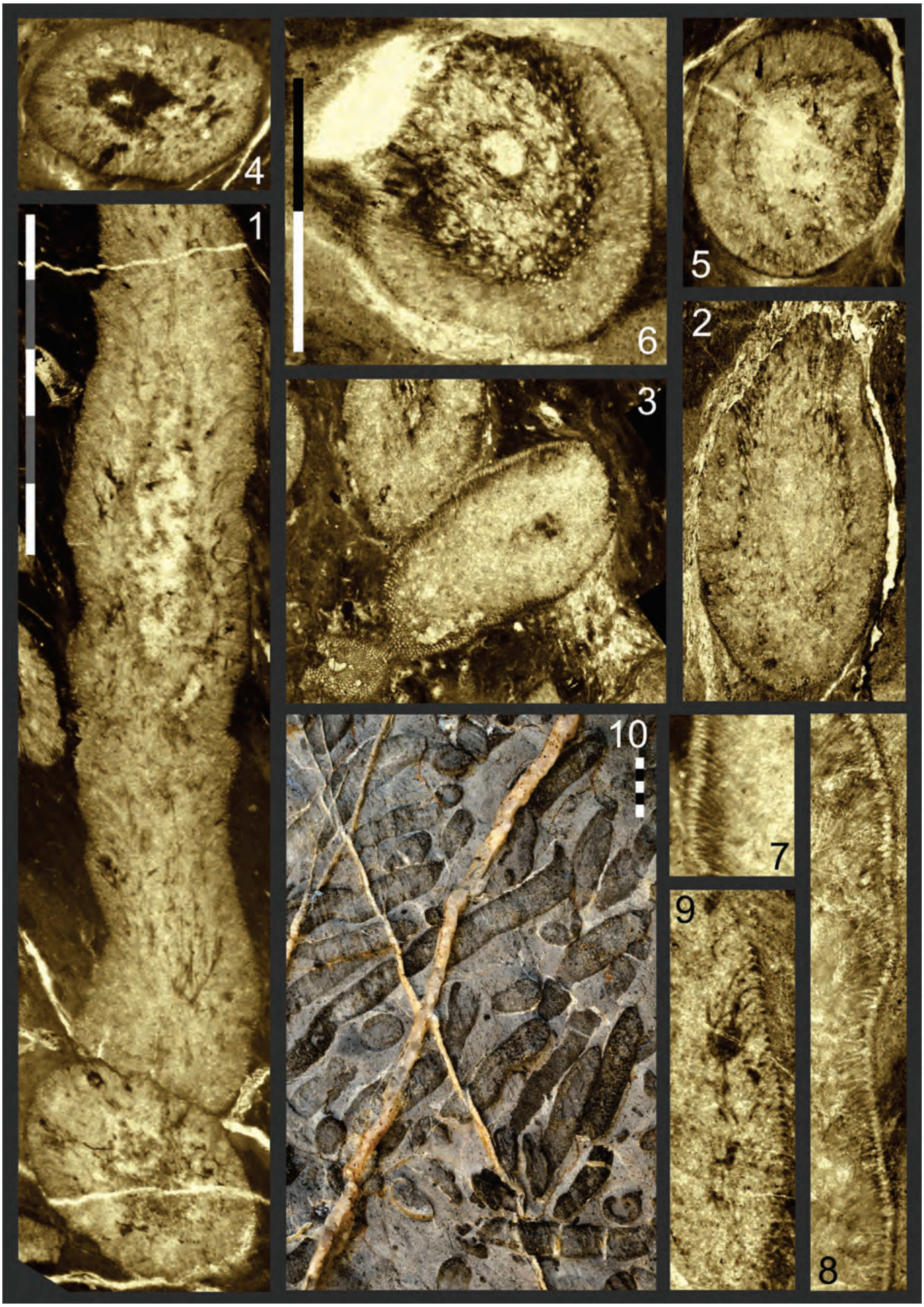
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Figure 9 (previous page): *Maslovina* sp. B of locality 5.
Straight cylindrical thalli, occasionally undulated. In very few individuals a high number of central filaments are observable in the poorly calcified medullar zone. Medullar filaments give rise to finer, cortical filaments which dichotomously ramify at the outermost cortical part forming an irregular 'epiderm'. *Maslovina* sp. B differs from *Maslovina* sp. A in having fine cortical filaments from which tightly packed utricles branch off forming a tight layer at thallus terminations. Utricles are inverted pear-shaped. Additionally, *Maslovina* sp. B has greater thallus dimensions.
Scale for 1 to 5: length of measuring bar 5 mm; 6-9: length of bar 2 mm; 10: length of bar 5 mm.

1 … Longitudinal and transverse section. 2 … Oblique longitudinal section exhibiting cortical filaments at the periphery of the medullar zone. 3-6 … Cross sections showing arrangement of cortical filaments. 6 … Cross section; albeit calcification of the central zone is rather poor an internal arrangement of numerous very fine filaments may be 'foreshadowed'. 7-9 Longitudinal sections through peripheral cortical parts. Note last ramifications of filaments forming an 'epiderm'. 10 ... Weathered rock surface with *Maslovina* sp. B of locality 5.

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