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13th Workshop on Alpine Geological Studies

September 7th-18th 2017
Zlatibor Mts. (Serbia)

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CONTENT

Episodic igneous activity and crustal recycling in the Balkan: Evidence from zircons and rutiles in basement rocks and river sediments of Northern Greece

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The Balkan is a collage of Peri-Gondwana Cadomian and Avalonian terranes that were foundered on the late Neoproterozoic active margins of the Supercontinent, rifted from it during the consecutive opening of oceanic basins, and variably involved in Ordovician, Variscan, and Alpine orogenies. The Serbo-Macedonian (SMM) and the Rhodope massifs are major Balkan terranes that were subsequently involved in Paleozoic, Mesozoic and Cenozoic phases of magmatism and metamorphism. These terranes therefore portray the prolonged evolution of the SE European continental crust over a ~0.6 Ga time scale. Here we present zircon U-Pb-Hf and rutile U-Pb data from basement rocks of the SMM and Rhodope as well as of beach placers from large river mouths draining the region towards the Aegean Sea (Axios, Strymon, Nestos and Evros Rivers). Basement igneous rocks of the SMM and circum-Rhodope are late Neoproterozoic (598 Ma), Ordovician (460 Ma), Carboniferous (300 Ma), Triassic (250 Ma), Paleocene (61 Ma), and Miocene (ca. 23 Ma), thus demonstrating the episodic Paleo-Meso-Cenozoic crustal evolution of this terrane assemblage. Hf-in zircon shows these episodic intrusions evolve from negative $\varepsilon Hf_{(t)}$ values in the Ordovician towards positive values in the Eocene, grossly fitting the evolution trend of external orogenic belts. Zircons in the beach placer samples also show distinct age peaks that grossly fit the episodes of igneous activity in the source terranes, with the addition of Jurassic (ca. 150 Ma) zircons. However, beach placer zircons portray a wider range of εHf values that is less distinct than that of the basement igneous rocks. Therefore, the trend of εHf enrichment in the igneous rocks is only a part of the whole Balkan crustal evolution picture, as the beach placer samples indicate that together with episodic igneous crustal addition, a large portion of zircons follows a progressive recycling trend bound by evolution lines pointing to model ages of Hf-T_{DM}=0.7-1.7 Ga. This trend reflects, in our view, the ongoing recycling of the Cadomian/Avalonian basement of the SMM and Rhodope that provided the crustal ingredients for recycling, and only a few outcrops of it have survived. Some extent of juvenile crustal addition on this evolving Cadomian/Avalonian substrate brings about the shallow rise in $\varepsilon Hf_{(t)}$ values we observe in the igneous basement rocks. Rutiles in the beach placer samples record only the final orogenic phase during Alpine orogeny, with only a few grains preserving Triassic and Jurassic ages. Our data indicate that the Balkan terranes evolved via prolonged but episodic crustal evolution, beginning on the northern margin of Gondwana in the late Neoproterozoic, and through the continuous evolution and recycling of this Peri-Gondwana crust over the Phanerozoic.

The carbonate factory in the lacustrine system: An example from Jarando Basin, Southern Serbia

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After recent major hydrocarbon discoveries of the Pre-Salt of the South Atlantic, the lacustrine carbonates are recognized as a very important reservoir. Still, surface analogous that could provide better insights into reservoir characteristics are lacking. Therefore, this study is aimed at assessing controlling factors on the nature of lacustrine carbonate sedimentation. The asymmetric extensional Jarando Basin (Southern Serbia) is an optimal place to study the nature of the carbonate factory in lacustrine systems. The basin was formed in the course of the Miocene extension affecting the whole Alpine-Carpathian-Dinaride system. The initiation of this supra-detachment basin was partly contemporaneous with calk-alkaline to ultrapotassic volcanism. Basin fill is characterized by the shallow water carbonates and travertines deposited along the `passive` basin margin and lake profundal, respectively, during late syn-rift and post-rift phase of the basin development.

The detailed petrographic, C- and O-isotopes, TOC, major, trace and REE elements, and palynofacies analysis were carried out on 30 core samples of carbonates located in the late syn-rift and early post-rift successions (Piskanja boron deposit). The preliminary data on Jarando Basin cores display excellent examples of travertines saturated with oil and microbial mats, mudstones, packstones and grainstones. The kerogen assemblage of the travertines comprises of amorphous organic matter (AOM), sporinite and freshwater lacustrine algae (*Botryococcus*). The fluorescent AOM includes two components, bacterial (microbial mats) and terrestrial derived organic matter. The TOC and sulphur contents are very low in general less than 1 %. The travertines are characterized by the high boron (< 2000 ppm) content. The results of this study reveal a wide distribution of dominantly positive carbonate and oxygen isotope values in carbonates, 1.8 ‰ to 7.4 ‰ and 17.10 ‰ to 31.9 ‰, respectively. The oxygen and carbon isotope correlation, geochemistry and petrography of studied carbonates reflect deposition in a semi-closed to closed saline playa lake environment. High boron contents and isotope ratios in travertines suggest that cold and hot fluids played important role in carbonate deposition in the profundal parts of the lake. The carbonate factory in the lacustrine systems, such as Jarando Basin, is generally controlled by the interplay between tectonics and climate. In such basins closely associated with volcanism associated hot and cold springs affect the lake water chemistry and significantly contribute to the overall variability of carbonate deposition and basin architecture.

Orogenic magmatism during continental collision: A numerical modelling approach

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The orogenic magmatism contributes significantly to the overall growth of the continental crust through the addition of juvenile and recycled material. Further on, the variability of magmatism in terms of volume, composition, spatial extent and temporal distribution plays a key role in the compositional evolution of continental crust. Still, the tectonic mechanisms driving the large magmatic diversity observed in many continental collisional systems are not fully understood and are difficult to quantify by conventional observations or geochemical techniques. Therefore, we have conducted a series of 2-D petrological-thermomechanical numerical experiments on oceanic subduction and subsequent collision to study the link between lithospheric scale processes and orogenic magmatism.

Our results confirm that magmatism and rheological stratification of the continental crust influence the broad geometry and dynamics of collisional zones. In addition, magma emplacement may control changes in deformational style, locally. The modelling also demonstrates that foreland-directed migration of deformation and magmatic fronts may be driven by the indentation of the lower continental crust. Furthermore, the foreland-directed migration of magmatic front is associated with a gradual change in magma source composition from predominantly mafic to more felsic ones. Finally, our simulations provide further contributions to better understanding the dynamics of collision and magmatism observed in a chosen natural example of the Dinarides Mountains of Central Europe.

Structural and petrofabric analyses in the hanging-wall of a passive crustal-scale detachment (Syros, Aegean region)

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New detailed (micro-)structural investigations, quartz petrofabric analyses and geological/structural mapping in southeast Syros (Cycladic massif, Aegean region) allow us to place new constraints on the tectonic evolution of the Vari Unit. The Vari Unit belongs to the Uppermost unit of the Cycladic massif and is subdivided into two subunits (a) the structurally highest Gneiss subunit, which consists of felsic orthogneisses, and (b) the structurally lowest meta-volcano-sedimentary subunit (MVS), which is represented by schists/phyllites and serpentinite lenses. The Vari Unit has been affected by a Cretaceous lower amphibolite-facies metamorphism followed by a greenschist-facies overprint at late Eocene-Oligocene. The latter metamorphic event is mainly recorded in the MVS subunit.

The deformation history of the Vari Unit includes four phases. The early deformation (D_1) is associated with the tectonic juxtaposition of the Gneiss subunit against the MVS subunit and was probably synchronous with the Cretaceous lower amphibolite-facies metamorphism. The Eocene – Oligocene deformation history in the hanging-wall of the Vari Detachment is associated with SW-directed ductile shearing. This history includes an early distributed constrictional deformation (D_2) expressed by transport-parallel upright folds, L-tectonites and cleft girdles quartz c-axis fabrics that were formed at temperatures ca. 500 °C. Ductile deformation progressively localized at the bottom of the unit leading to the formation of a greenschist-facies mylonitic zone (D_3). Mylonitic deformation occurred under plane strain conditions as it is supported by cross-girdles quartz c-axis fabrics. The ongoing mylonitization is associated with progressive downward strain localization and a temporally increasing pure shear component of deformation coupled with cooling from ca. 500 °C to ca. 400 °C. Ductile structures were overprinted by the SSW-directed Late Vari Detachment (D_4). This brittle detachment fault exhibits similar kinematics with the West Cycladic Detachment System and, therefore, can be considered as a branch of this system.

We suggest that the Vari Detachment represents a passive normal-sense roof fault resulted from the NE-directed ductile extrusion of the Blueschist unit (footwall) at middle Eocene – Oligocene times. In the middle Miocene was formed the SSW-directed Late Vari Detachment (D_4), which contributed to the brittle exhumation of both the Blueschist unit and the early Vari Detachment.

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Structural-tectonic interpretation of Stružec gas and oil field

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The Stružec field is located at the northwestern, deep part of the Sava depression, along the southwestern margin of the Pannonian Basin. Interpretation of three-dimensional seismic data on the Stružec field has been done using the Petrel software package. The interpretation has included mapping of characteristic horizons. Types of faults were determined according to the relative movement of the hanging wall with regard to the footwall. By this way, the faults were interpreted as reverse and normal. Reverse faults interpreted in the area of Stružec anticline are generally oriented in the east-west direction, whereas normal faults are nearly perpendicular to them, extending in the north-south direction (Šumanovac, 2012). The basic structure observed at the Stružec oil and gas field is an elongated anticline, i.e. brachyanticline extended in the east-west direction. The anticline is bounded by two main reverse faults and is faulted by a series of transverse normal faults. Other faults are extending approximately parallel to the main reverse faults.

Geodynamic evolution of the Pannonian Basin has been described in many papers and has been commonly considered in relation to the Alpine and Carpathian orogeny (Tari & Pamić, 1998). The main extensional phase in the southwestern part of the Pannonian Basin ends between Sarmatian and Pontian. The extension ended during the Pontian, and during the Pliocene orientation of stress changed with the development of compressional forces. Transect through the Sava Suture Zone (Ustaszewski et al., 2010) depicts inversion of numerous normal faults after the Pontian, showing tilted and deformed Pontian sediments. That is in agreement with earlier work in adjacent parts of the Pannonian Basin suggesting compressional and/or transpressional reactivation of extensional faults (Tari & Pamić, 1998). Compressional stress is still going on, which causes the formation of flower structures and anticlines (Horvath, 2006).

Structure formation in the Stružec field can be considered in two basic approaches. The first one defines two tectonic phases. The first phase begins in the Pliocene where compressional forces cause reverse faulting and anticline forms by deformation of the hanging wall. The seismic amplitude and attribute sections show positions of the main reverse faults, which caused the formation of Stružec anticline. In the second phase, normal faulting of the anticline is caused by an extension. The second approach considers only one phase. That is the parallel formation of reverse and normal faults. The compression causes the formation of reverse faults and strong deformations of the hanging wall with the development of a steep anticline. At the same time at the crest of the anticline normal faults are formed under stress relief.

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Pre-Alpine (Variscan) inheritance: A key for the location of the future Valaisan Basin and Penninic Thrust (Western Alps)

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The boundary between the Helvetic (=Dauphinois) and the Penninic (= Briançonnais) Zones has long been recognized as a major fault ("Penninic Front" or "Penninic Thrust") in the Western Alps. A narrow oceanic domain has been postulated at least along part of this boundary (the Valaisan Ocean). However, the information provided by the pre-Triassic basement has not been fully exploited and will be discussed here in detail.

The igneous and metamorphic history of the pre-Triassic basement shows significant differences between the Helvetic Zone (Argentera, Pelvoux, Belledonne, Aiguilles Rouges – Mont Blanc, Aar), with abundant late Carboniferous granites, and the basement of the Penninic Zone (Vanoise, Grand Saint Bernard, Dora-Maira, Gran Paradiso, Monte Rosa), devoid of Carboniferous granites. A major coal-bearing basin, the "Zone Houillère", one of the largest Carboniferous basins inside the Variscan belt, opened along this boundary. It is a limnic intramontane basin and its tectonic origin has never been properly investigated. The Zone Houillère is not comparable with the external, paralic, flexural, basins on both sides of the Variscan belt, but shows similarities with the Saar-Saale basin. Like the latter, we interpret the Zone Houillère as a transtensional basin opened along a major, crustal-scale, fault zone (possibly the East Variscan Shear Zone). The Permian magmatism and sedimentation displays contrasting distributions, being absent or very localized in the Helvetic Zone, and widespread in the Penninic Zone.

The above data indicate that the structural inheritance from the Variscan belt plays a major role in defining the future boundary between the European palaeomargin and the Briançonnais microcontinent.

Contrasting deformation styles across the Split-Karlovac Fault (External Dinarides) induced by reactivation of pre-existing structures

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It is widely known that pre-existing fault zones, which occur either at facies transitions or at inherited and reactivated structures play important role in strain partitioning and distribution of deformational styles in orogens. This is also the case in the External Dinarides, where long-lasting convergence between Eurasia and Adria deformed and inverted the Mesozoic Adriatic Carbonate Platform in Cenozoic times. The growth of the Adriatic carbonate platform was controlled by the interplay of eustatic sea level changes and tectonic subsidence, but also by underlying pre-existing faults, leading to a structurally complex and laterally heterogeneous carbonate platform evolution and deformation. Here, we address the role of such pre-existing faults on pronounced along-strike variations in shortening across the Split-Karlovac Fault during Cenozoic contraction in the External Dinarides.

From geological maps covering the External Dinarides fold-thrust belt, it is known that Late Permian gypsum deposits are exclusively found on the eastern side of the Split-Karlovac Fault (SKF), thus suggesting that they formed the main detachment horizon for the eastern part of the fold-thrust belt. The geologically most viable kinematic forward model across the western part and an unpublished cross section across the eastern part reveal that the SKF separates two structural domains with contrasting deformation styles. Nappe stacking (doubling) of the Carbonate Platform characterises the eastern domain, whereas the SW-vergent antiformal stack that led to the formation of the Bruvno anticline to the west of the SKF characterises the western domain that is structurally controlled by a stratigraphically much deeper (pre-Carboniferous) detachment horizon. Here, a missing Permian to Lower Triassic succession suggests that the Bruvno anticlinal dome paleogeographicaly formed a possibly fault-bounded structural high during that time. We suspect that during Mid-Eocene contraction, the SW-bounding normal fault of such a high was reactivated as a large-scale top-to-the-NE backthrust, which inhibited further propagation of the deformation front towards the SW.

Our kinematic forward model also suggests that the SKF was initiated as a thrust fault along a Late Jurassic facies boundary, which in turn was inherited from Late Permian times. Shortly after its initiation, the SKF developed into a dextrally transpressive tear fault. This led to the top-SW nappe stacking in the eastern and synchronous deformation of the Bruvno anticline in the western domain, respectively. Passive W-ward tilting of the backthrust in the hangingwall of the Bruvno anticline resulted in the uplift of the Velebit monocline, which hence became subject to accelerated erosion. Based on field observations we conclude that the dextral reactivation of the Split-Karlovac Fault, the uplift of the Bruvno and Velebit anticlines as well as the subsidence of the Promina flexural foreland basin happened simultaneously and started in Mid-Eocene times.

Non-typical Alpine orogen of the Western Carpathians in geophysical imagery

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The Western Carpathians belong to the young orogenetic mountain ranges of Europe and Asia, which final formation occurred in the Neogene. Their tectonic structure is the result of a long-term tectonic development. The tectonic elements of the Western Carpathians originated in two main orogenic stages – the Hercynian and the Alpine. The Alpine orogenesis consists of several Mesozoic and Tertiary phases. These are conventionally divided into Paleo-, Meso- and Neoalpine phases, using the principle of the closing of the oceanic domains in the space between European and African plates. We assume the existence of three oceanic basins with different development in the Mesozoic and Tertiary. Depending on their closure, the principal Alpine tectonic units of the Western Carpathians originated in different time and space. Recent division of the Western Carpathians is based on the Neoalpine tectonic processes, which resulted in the accretion of flysch nappes of the Outer Carpathians as a consequence of the oblique collision of the Inner Carpathian block with the European platform. The Inner Carpathians consist of incorporated tectonic units of Palaeoalpine and Hercynian stages of tectonic development and in the present structure of the Western Carpathians they crop out in isolated mountain ranges (horsts) separated by Neogene grabens. During the oblique collision, the North Penninic flysch basin was closed by transpressional movement of different tectonic blocks. Neoalpine faults are mostly of strike-slip character, that document „strike-slip type“ of the final stage of Western Carpathian Neoalpine orogeny, which ended by „basin and ranges type of structure“ connected with volcanic activity.

The lithological and tectonic complexity of the Western Carpathians is also reflected in the geophysical image. Several geophysical methods were used in the research. The individual geophysical methods have different possibilities and detection limits of the lithological and tectonic interfaces. The oldest tectonic elements of the Western Carpathians are fragments of Cadomian blocks in the substratum (European platform in the north, fragments in the substratum in southern Slovakia) – exhibit higher density and magnetisation. Hercynian lithotectonic units can be distinguished by different conductivity. The Paleoalpine tectonic units of the Inner Carpathians (near-surface nappes and crustal units) we can observe in seismic profiles effects as overthrusting tectonic units borders. The youngest Neoalpine structural elements of the Inner Western Carpathians are sedimentary basins and neovolcanic complexes. These shallow structures are characterised by higher conductivity in contrast to the bedrock. The Flysch nappes of the Outer Carpathians can be also identified by geophysical methods. Typical features for young tectonic development is the occurrence of steep shear-zones (mainly of strike-slip and normal fault character) revealed in geoelectrical profiles as high conductive zones. Magnetic map of Slovakia shows the distribution of rock complexes with higher magnetic properties. Large deep-seated magnetic anomalies are caused mainly by a heavy and magnetic crust of Cadomian basement and by asthenolite ascent accompanied by basic intrusions into crust.

Inferences on landscape development in Southern Montenegro and Northern Albania from geomorphic and drill core data

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The region around Shkodër Lake between Bar, Podgorica (both Montenegro), Shkodër and Lezha (both Albania), represents one of the seismically most active regions in Europe, suffering numerous intermediate as well as occasional heavy earthquakes of the order of the Mw 7.2 Montenegro event in 1979 (Benetatos and Kiratzi, 2006). Forming part of the External Dinarides-Hellenides fold-and-thrust-belt that takes up large portions of the deformation related to the collision between Adria and Eurasia, earthquake focal mechanisms as well as recent GPS data indicate a prevalence of NE-SW-directed contractional tectonics for this region (e.g. D'Agostino et al., 2008, Jouanne et al., 2012). In accordance with this, we present a selection of geomorphic features and field evidence indicative of ongoing shortening and surface uplift: Coast-parallel anticlinal structures are traversed by windgaps of various ages containing relict river gravels. Lithological and structural mapping shows an involvement of uplifting sediments as young as Holocene and provides data for first attempts to calculate the amount of bulk shortening. In the region around Podgorica, deeply incised stream channels in young sediments, as well as aggradational river terraces, equally validate the anticipated uplift further inland. Shallow drillings, predominantly performed between Shkodër, Katërkolle and the Adriatic Sea, prove that major parts of the plain between Lezha, Ulcinj and Shkodër have been flooded, presumably until Holocene times. According to simulations on DEMs illustrate that only minor amounts of uplift rates or sea level changes, respectively, would suffice to couple or decouple Shkoder Lake and the Adriatic Sea. Given that sea level is constantly rising since the Last Glacial Maximum (e.g. Vacchi et al., 2016), this provides more evidence of an enhanced recent surface uplift and opens up possibilities of quantifying uplift rates by dating drill core material.

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Ophiolite complex of Demir Kapija-Gevgelija

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Ophiolite complex of Demir Kapija-Gevgelija is the largest block of the Vardar oceanic lithosphere preserved and situated in the central subzone of the Vardar zone. The complex has a NW-SE strike dipping towards northwest. In the territory of the Republic of Macedonia, it is 50 km long and 25 km wide. The complex extends further south in the territory of neighbouring Greece where it is known as Gevgelli series. The northwest position of the complex situated in Macedonia is covered by Upper Eocene – Pliocene layers of the Tikvesh valley. Towards southeast it is covered, in part, by Pliocene – Quaternary layers extending further south to the territory of Northern Greece. Investigations carried out so far on the geology, tectonics and lithostratigraphy of the ophiolite complex determined the following geologic structure: a formation of gabbros and accompanying plutons; a vein complex; a formation of massive basalts; a formation of spilitized pillow basalts; a spilite – keratophyre level; a basalt chert formation; a flysch formation and carbonate formation of Upper Tithonian age.

The gabbroic formation is composed predominantly of fine-grained and medium-grained clinopyroxene gabbros, rarely of olivine gabbros, pyroxene gabbros with olivine, troctolites and amphibole gabbros and quite rare are serpentinized dunites and hornblende peridotites as well as dykes of basalts, gabbropegmatites, aplites, granite – porphyry and quartzdiorites. The presence of various types of intrusive and vein type rocks are a result of magmatic differentiation and the processes of amphibolitization.

Ultrabasics are present as tectonically forced masses along fault structures or occur along with troctolites. They are present as serpentinized dunites, amphibolized peridotites as well as websterites. They are made up of hornblende, serpentine, actinolite, olivine and accessory magnetite.

A vein complex occurs in the contact parts of the gabbroic formation and the formation of massive basalts as a well developed 200 to 300 (maximum 500) meters zone made up of basalt – dolerite dykes and segmented gabbro masses. The mineralogical composition is similar to the massive basalt and gabbroic mass.

Massive basalts are found in the central and eastern portions of the ophiolite complex. They are present as fine-grained ophiolite and intersertal composition with occasional occurrences of entire recrystallization of the glass groundmass. They are altered rocks in which feldspars are heavily albitized. Basic plagioclases occur as relic (labradorite – bytownite). Femic minerals are augite, hornblende, secondary chlorite, epidote, magnetite, and apatite.

Spilite – keratophyre level occurs in the top most portions of the formation of basaltic pillow lavas. It is present as a concentration of dykes and outpourings of keratophyre masses, quartzkeratophyres, rhyolites and seldom andesites which form keratophyre level together with spilitized basalts. These acid differentiates occur as pink to red, grey – green to grey – white rocks with micro porphyritic to porphyritic structure composed of altered feldspathic masses with relics of plagioclase (oligoclase – albite), K – feldspar, also chlorite, quartz, epidote, seldom crystals of hornblende, chloritized biotite and calcite.

The upper parts of the ophiolitic complex are composed of chert formations, flysch formations covered by the massive Upper Tithonian reef limestones.

Paleozoic magmatism in the Sakar unit of the Sakar-Strandzha Zone, Bulgaria

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The Sakar-Strandzha Zone (SSZ) straddles the Bulgarian-Turkish border within the Alpine orogen in SE Europe. Previously, Late Paleozoic zircon ages (309 Ma and 271 Ma) were reported for intrusive magmatism in the SSZ part of Turkey and were related to the Paleotethys evolution (Okay et al., 2001). Here, we present new U-Pb LA-ICP-MS zircon geochronology results for the Sakar batholith and one magmatic body within the batholith metamorphic country rocks. Both belong to the Sakar unit of SSZ. The Sakar batholith consists predominantly of equigranular biotite granite and K-feldspar porphyroid granite of calc-alkaline affinity (Kamenov et al., 2010). The batholith is internally undeformed and weakly foliated in places at the contacts with the country rocks. The batholith contains country rock xenoliths. The amphibolite-facies country rocks consist of interlayered schist, gneiss and amphibolite, and they host a small stock-like body of weakly foliated leucocratic granite, which is located east of the Sakar batholith. The country rocks are overlain by the metaclastic Paleocastro Formation of assumed Early Triassic age that in turn is overlain by metaclastic-metacarbonate Ustrem Formation of Middle Triassic biostratigraphic age in its uppermost fossil-bearing levels (Chatalov, 1988). The metamorphic degree of both formations reaches up to amphibolite facies in the Ustrem Formation to visibly lower greenschist-facies of Middle Triassic marbles to recrystallized limestone of the overlying fossiliferous Srem Formation. Four zircons out of the analyzed thirty grains yielded a concordia age of 295.3±1.9 Ma for the magmatic crystallization stage of the Sakar batholith equigranular granite. Discordant zircon ages range from 329 Ma to 288 Ma and inherited concordant zircon ages of 602 Ma, 448 Ma and 413 Ma. Three zircons out of twenty-nine analyzed grains yielded a concordant U-Pb age of 461.6±2.7 Ma for the magmatic crystallization stage of the leucocratic granite intruding the country rocks of the Sakar batholith. The discordant zircon ages range between 485 Ma and 396 Ma, with few inherited zircon ages ranging between 497 Ma and 481 Ma. The chemical compositions of the Sakar equigranular granite and the leucocratic granite both differ with respect to ocean-ridge granite and demonstrate continental input with chondrite-normalized negative Nb, Pb, P, Ti anomalies and high LILE-LREE/HFSE-HREE. The trace element (Rb,Y,Nb) discrimination diagrams suggest a volcanic arc setting. The new results reveal that the Permian acid intrusive magmatism extended much more northwards in Bulgaria within the SSZ, and in addition, they indicate the presence of Ordovician magmatism in the SSZ. The Late Carboniferous-Permian magmatism was related to the closure of the Paleotethys linked to its subduction beneath the Eurasian continental margin (Okay et al., 2001), whereas the Ordovician magmatism might be evidence for a magmatic pulse along the northern periphery of Gondwana, and records a previous Prototethys magmatic event in the SSZ basement.

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Are the Alps an alpine-type orogeny? A multi-disciplinary mapping project

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The European Alps are a wonderful mountain belt not only due to the beauty of the landscape but also due to its geology. They have been studied for nearly 200 years and still new discoveries surprise us! Many data and knowledge are available and always remain lively debates about some basics: how many oceans were involved during the Alpine orogeny? What kind of subduction (oceanic or intra-continental) was active? How old are the subductions?…).

However, due to the vast amount of knowledge accumulated over several decades, the Alps offer the opportunity to better understand mechanisms of formation of Alpine-type orogens with even more details.

Based on a vast collection of data on the Alps gathered all along more than a hundred years, this compilation also takes into account most recent works (e.g. Schmid et al., 2004; Ziegler and Dèzes, 2006; Handy et al., 2010, Bousquet et al., 2012a, b), this mapping project at the scale of one million covers a domain spanning from Corsica until the Vienna basin. We are acquiring and compiling geological, structural, metamorphic, geophysical and geochemical data.

Based on several maps and cross-section, we are able to evidence substantial differences in the geodynamical evolution along strike of the Alpine orogen.

The Western Alps did not reach the mature stage of a head-on colliding belt as is indicated by a continuous metamorphic evolution, representing all the subduction related processes ranging from lower greenschist to UHP conditions. All the metamorphic rocks behind the frontal thrust (Pennine front) were already exhumed to upper crustal level during ongoing oceanic and continental subduction and before a collision with the Dauphinois domain from around 32 Ma onwards. Hence, the Western Alps can be seen as a frozen subduction zone. Since then the only exhumation by erosional processes affected the inner parts of the orogen.

The rest of the Alpine orogen later underwent a more important collision process due to the ongoing head-on geometry of subduction and collision. It therefore often but not always shows a bimodal metamorphic evolution with two distinct P and T peaks. The intensity of the thermal overprint relates to the amount of crustal material incorporated to the orogenic wedge and migrated with time from the backstop in the south towards the north.

With this in mind, this work is representative of a state of the art at a given moment, giving cause to a number of questions, and constituting therefore only a fundamental element for future discussions. From this perspective, this mapping project proposes a global approach to this Alpine belt chain.

New radiolarian data from the Late Jurassic mélange of Avala Mountain (Serbia)

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Numerous radiolarian assemblages were found from blocks of radiolarian cherts in the mélange of Avala Mountain located south from Belgrade, Serbia. These assemblages range from the Middle Triassic (early Ladinian) to the Upper Jurassic (middle Oxfordian - lower Tithonian) (Bragin et al., 2011). This was the first evidence of Triassic blocks in the mélange that has been considered to be fully Jurassic. The studied area is situated on the SE flanks of Avala Mt. and it belongs to the Eastern Vardar Zone. The obtained data are of the utmost importance for interpretations related to the geodynamic evolution of the Eastern Vardar Zone.

Avala mélange in the vicinity of Ripanj Village was resampled in order to enable a better understanding of age and nature of this mélange. It should be noted that there we had only one sample with undoubted Late Jurassic age during our previous study. The mélange in Ripanj Village is characterized by a highly tectonized matrix composed of greenish claystone. Olistolites are small (ranging from 1-2 to 15-20 cm) and represented by cherts and cherty tuffs. Four samples contained well preserved radiolaria, one of them with late Oxfordian to early Tithonian age. The upper age limit of this assemblage is determined by the ranges of *Eoxitus dhimenaensis*, *Spinosicapsa chandrika* and *Triactoma foremanae*, that have their last appearances in the Zone 11 (late Kimmeridgian - early Tithonian; Baumgartner et al., 1995). The lower limit is estimated due to the range of *Acaeniotyle umbilicata* that has its first appearance in Zone 10 (late Oxfordian - early Kimmeridgian). Therefore we can date this sample as late Oxfordian to early Tithonian. This finding supports our previous conclusions about the latest Jurassic age of the Avala mélange.

The Eastern Vardar ophiolites are generally considered as remnants of a short-lived intra-oceanic back-arc basin which opened above a subduction zone, between an island arc and Eurasian continental margin (e.g. Zachariadis, 2007).

A widely used is an interpretation of Serbian Eastern Vardar ophiolites as being tectonically emplaced onto the Serbo-Macedonian massif in the Late Jurassic (Schmid et al., 2008). The obtained radiolarian ages suggest that the obduction could be only post early Tithonian. Eastern Vardar ophiolites in Serbia lack sub-ophiolitic mélange, as well as a metamorphic sole, which complicates an explanation of their emplacement by obduction. Results of our recent investigations allow the presence of a true sub-ophiolitic mélange (as below the Western Vardar ophiolites) on Avala Mt. However, this has not been confirmed in other parts of the Eastern Vardar Zone. An alternative model interprets Serbian part of the Eastern Vardar Zone as dipping eastwards beneath the Serbian Macedonian Massif (e.g. Petrović et al., 2015) and ophiolites being emplaced via accretion mechanisms. If we accept this interpretation, mélange and ophiolites on Avala Mt. are parts of a fossil accretionary wedge formed during subduction below the European plate.

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Upper Triassic radiolarians from the hemipelagic chert-carbonate sections of Southwestern Serbia

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Middle to Upper Triassic sedimentary units of Southwestern Serbia comprise two distinct facial types: thick shallow-water deposits of carbonate platforms with common reefal limestone, and hemipelagic deposits of moderate thickness, which are represented by platy limestone intercalated with marl and clay, in parts with coarser-grained allodapic layers and common chert nodules. The hemipelagic sediments are known as the Grivska Formation. According to Dimitrijević (1997), these rocks represent huge olistoplacae that are in tectonic contacts with the underlying and the overlying rocks.

The term Grivska Formation has been used broadly for all Ladinian to Late Jurassic stratified cherty limestones in all units that derived from the Adriatic passive margin. Due to the fact that in this case the Grivska Formation includes genetically different sedimentary successions, Missoni et al. (2012) restrict the name Grivska to Triassic hemipelagic sequences and advocate the term Grivska Group, which comprises different Middle and Late Triassic hemipelagic bedded cherty limestones with shallow-water debris.

In order to obtain new data that will enable future complete revision of the Grivska Formation, we started investigations in carbonate-chert units in the area of Zlatar Mt. Two sections of Triassic carbonate-chert units were sampled recently: 1) along the road Kokin Brod – Nova Varoš, and 2) in the valley of Lim River near the mouth of the Bistrica River. Section Nova Varoš is represented by cherty limestone with chert interlayers, clayey thin-bedded limestone and subordinate claystone. Radiolaria are present in cherts. The radiolarian assemblage consists of *Muelleritortis cochleata* (Nakaseko & Nishimura), *Paronaella* sp. cf. *P. glaber* (Kozur & Mostler), *Pseudostylosphaera* sp., *Tritortis ariana* (Cordey), *Tritortis kretaensis* (Kozur & Krahl) that confirm Early Carnian *Tritortis kretaensis* Zone (Kozur, 2003).

Section in the valley of the Lim River is represented by a thick succession of micritic limestone, mostly plated, with numerous chert nodules with radiolarian assemblage: *Capnodoce anapetes* De Wever, *Capnodoce* sp. cf. *C. sarisa* De Wever, *Capnuchosphaera* sp. cf. *C. deweveri* Kozur & Mostler, *Capnuchosphaera* sp. cf. *C. tricornis* De Wever, *Monocapnuchosphaera* sp., *Praehexasaturnalis tenuispinosus* (Donofrio & Mostler), *Triassocrucella* sp. cf. *T. triassica* (Kozur & Mostler), *Xiphothecaella longa* (Kozur & Mock). This assemblage indicates a latest Carnian to Early Norian age (Bragin, 2007).

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The Lower Cretaceous deposits from the Reşiţa-Moldova Nouă zone (Southern Carpathians, Romania) and the Kučaj zone (Carpatho-Balkanides, Eastern Serbia): a comparison

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The south-eastern part of the Southern Carpathians continue south of Danube in Eastern Serbia with the Carpatho-Balkanides. The Reşiţa-Moldova Nouă zone of the South Carpathians is an area with Upper Paleozoic and Mesozoic sedimentary deposits. The Mesozoic succession is represented by terrigenous Lower and Middle Jurassic deposits, deep-water to slope Middle-Upper Jurassic and Lower Creatceous (Berriasian-Hauterivian) carbonate deposits, and shallow-water, platform carbonates in Urgonian facies (Barremian-Aptian). The Kučaj zone of the Carpatho-Balkanides (Eastern Serbia) represents the continuation south of Danube of the Resiţa-Moldova Nouă zone. The aim of this study is a comparison between the Lower Cretaceous deposits in Urgonian facies from the Resiţa-Moldova Nouă and the Kučaj zones. To perform this comparison several sections have been investigated in the Kučaj zone between Pirot (to the south) and Zaječar (to the north). Within the Lower Cretaceous shallow-water carbonate deposits of the Reşiţa-Moldova Nouă zone, two formations have been separated: (1) The Plopa Formation (with Valea Lindinei and Valea Nerei members), and (2) The Valea Minişului Formation. The Valea Nerei limestone Member and the Valea Minişului Formation represent the carbonate deposits developed in Urgonian facies. The depositional facies of these limestones comprise the whole range of carbonate platform sediments, from super- and intertidal, to platform interior, and to platform exterior, and upper slope deposits dominated by bioclastic and oolitic facies and less frequent by bioconstructed facies. The age of these limestones was established based on foraminifers (mostly orbitolinids): *Paracoskinolina*? *jourdanensis* (lower Barremian), *Paracoskinolina maynci, Montseciella arabica, Palorbitolina lenticularis, Praeorbitolina cormyi* (upper Barremian-Bedoulian), *Mesorbitolina parva, M. subconcava* and *M. texana* (Gargasian). A rich assemblage of dasycladalean and bryopsidalean green algae is associated. Among these, the *Boueina*- and *Arabicodium*-dominated banks have an important role, especially within the external platform domain. The Urgonian deposits from the Kučaj zone are generally characterized by open shelf (or platform exterior) facies, dominated by bioclastic and bioclastic-ooidic wackestone and wakestone-packstone, with grainstone-rudstone intercalations. The bioclasts consist of bivalve (mostly rudists), gastropod, echinoderm, bryozoans and brachiopod fragments, and more rarely coral and sponge fragments. Among the identified foraminifers *Paracoskinolina*? *jourdanensis*, indicate the lower Barremian. Other orbitolinid foraminifers (*Montseciella arabica, Orbitolinopsis* cf. *buccifer, Palorbitolina lenticularis*) are indicative for the upper Barremian-lower Aptian, while *Mesorbitolina minuta* and *M. texana* indicate upper Aptian (most probably Gargasian). A rich assemblage of other benthic foraminifers and calcareous algae is associated to these orbitolinids. A special mention could be made for the *Bouiena* banks near Pirot, the type locality of *B. hochstetteri*. The lithological and facies characteristics (dominance of the open shelf carbonate facies with clay-marl intercalations) as well as the micropaleontological assemblages make the studied deposits from the Kučaj zone quite similar with the Valea Minişului Formation of the Reşiţa-Moldova Nouă zone of late Barremian-Aptian (Gargasian) age. A distinct trait of the succession in the Kučaj zone is represented by the occasionally more abundant terrigenous quartz within some sequences.

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Geodynamic and sedimentary evolution of the Atlas domain during the Alpine cycle, Morocco

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On the geodynamic and sedimentary level, the evolution of the Atlas domain is part of a global framework that begins with the dislocation of the Pangea and the opening of the Atlantic rift expressed in North Africa by the Atlasic rifting from the Trias/Lias (CAMP: Central Atlantic Magmatic Province).

This rift aborted in the Lias forming a structure that is commonly called an aulacogen. It is followed by the installation of a carbonate platform extending from the Sinemurian to the Bajocian. The beginning of the oceanic expansion is synchronous with the movements of Africa towards the east and the transpression regime in the High-Atlas.

The opening of the South Atlantic to the Upper Jurassic - Early Cretaceous announces the translation of Africa to the north-east.

This movement is confirmed from the Upper Cretaceous to the present (Alpine phase). It results in a globally developed compression directed N-S causing the uplift of Alpine chains such as the High-Atlas and the Middle-Atlas (initiating in Morocco). The uplift and the relief of the Atlasic chain are also influenced by an asthenospheric rise.

3D estimation of fabric domains in the eclogitised continental crust of the Sesia-Lanzo Zone (Eclogitic Micaschists Complex; Mombarone-Mt. Mucrone-Mt. Mars area)

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The reconstruction of the tectonometamorphic evolution of lithospheric slices affected by fabric reworking and metamorphic transformation is possible through a multidisciplinary approach based on multiscale structural correlation of superimposed metamorphic and structural imprints, generally heterogeneously recorded in polydeformed tectonites (Spalla et al., 2005; Gosso et al., 2015). A quantitative 3D estimation of rock volumes characterized by homogeneous fabric evolution and metamorphic reaction progress is applied to reconstruct the textural heterogeneities (Salvi et al., 2010) during Alpine deformation partitioning in Mombarone-Mt. Mucrone-Mt. Mars (Sesia-Lanzo Zone). This area, within the HP metamorphic belt of the Western Alps, includes Permian intrusive and metasediments characterized by igneous features and granulitic/amphibolitic Variscan imprints, respectively. The multiscale structural analysis reveals seven groups of superposed structures, showing metamorphic imprints developed under eclogite facies (D1 to D3) and successively under lower-P blueschist facies (D4) during oceanic crust subduction, to greenschist facies (D5 to D7) throughout the continental collision (Zucali et al., 2002). D1 and D2 stages are the dominant imprints and are characterized by isoclinal folding associated with pervasive foliations (Delleani et al. 2012). In this work, we summarize and integrate with new structural field-work the petro-structural mapping and multiscale structural analysis performed by Zucali et al. (2002) and Delleani et al. (2013), to evaluate structural and metamorphic heterogeneities and realise "fabric and metamorphic transformation domain maps". The contouring of domains that show homogeneous fabric evolution (FE) is based on the estimation in the percentage of volumes occupied by successive planar fabric (0-20 %; 21-60 %; 61-100 %). Whereas, the individuation of the domains with homogeneous metamorphic transformation (MT) is determined on the basis of the modal amount of successive mineral assemblages (0-20 %; 21-40 %; 60-70 %; and >70 %). These domains are georeferenced and stored in a geo-database using geographic information system (GIS) to handle and export the petro-structural data. The fabric and metamorphic transformation domain maps linked to twenty interpretative cross-sections are used to constrain 3D volumes using Move 2016.2 software, that allow defining the size and shape of rock volumes showing homogeneous structural and metamorphic records. The results demonstrated that this approach can be a powerful tool to unravel the variation in the size of rock volumes, homogeneous in structural and metamorphic evolution (Tectono-metamorphic units), involved in subduction-collision system.

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Depositional sequences in clastics Triassic of Crmnica and surroundings (in Montenegro)

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In this paper, terrigenous clastics from different depositional areas were examined. In Olenekian age Clastics Brčela and Bioturbated Formation and in Anisian age Tudjemili Flysch and Conglomerates Crmnica (Čadjenović et al., 2014). Clastics Brčela are marine deposits comprised of graywackes, very fine grained micaceous sandstones, micaceous calcarenites, and quartz oosparites. In Olenekian stage, the first Triassic succession of sediment of the 3rd order of depositional sequences, consisting of transgressive/ regressive cycles and parasequences has been registered. The appearance of Lower Triassic ooid layers involves the following sequence of events: (1) high sea level and siliciclastic deposition (2); decreasing of the sea level and the partial erosion of previously deposited siliciclastites (3); recovery of sea level, when oolites with other clasts (after the erosion) cover the sea floor, and (4); repeated high sea level growth and the emergence of siliciclastic deposition. More detailed research has revealed that the oolitic facies are formed at the top of shallowing upward sequences. Bioturbated Formation is the product shelf, younger of the previous unit, with a thickness of about 200 m Later contains well expressed bioturbation (issues Rhizocorallium sp.). Clastics Bujaka appear as a separate package within the bioturbatne units. Tudjemili Flysch is equally developed in both Dinaric zones (between Budva and Bar, Crmnica and the Adriatic coast). Dimitrijević (1967), among other things, distinguishes three unequally expressed fan systems (system of Crminica, Budva and Bar). Tudjemili Flysch is typical turbidite deposited in the middle and lower submarine fan and in the basin. The thickness registered within the type locality is about 300 m. Most of Bouma Sequence types are Tc and Td containing cross and planar lamination in greywackes, calcarenites, calcareous sandstones, and siltstones which contain diverse fauna. Conglomerates Crmnica were transported to debris flow in a complex system of shallow channels with an uneven bottom. The thickness of the unit ranges from 180 m (Crmnica) to a few m (Stari Bar). Channel sequences are as follows: A-amalgamated sequences of disordered rudites; B-partially separated disordered to poorly sorted sequences of the rudites; C – separated sequence partially sorted to well sorted rudites; the D-complete sequence of channel fills. The main sediment is rudite which is built from carbonates and subordinated siliciclastic clasts. The macrofauna is most synchronous, transported with turbids flows, channels or traction. Filling of the channels and Bouma sequences are of short duration, the 4rd and 5rd order cycle. The stratigraphy of terrigenous clastics cycles and cycle-stacking patterns are related to the sea level changes and driven by orbital forcing and subsidence. The depositional sequences of terrigenous clastics, in the specified age in transgressive/regressive cycles of the third and a shorter orbital order, are characteristic. Deposits are under the constant control of the strong tectonic activity. These terrigenous clastics as well as carbonate formations share similar characteristics with other calcareous sediments of the Mediterranean region. The sea-level curve shows similarities in transgressive/regressive impulse during Olenekian and Anisian stage. With significant sea-level increase at the end of Illyran, the final destruction of a space consisting of the Dalmatian-Herzegovinian zone and Budva Zone and the opening of Neotethys Ocean has occurred.

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Facies and biostratigraphy of the Jurassic to Lower Cretaceous succession in the Danubian nappes (Eastern Serbia)

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The Danubian nappes have been studied along three structurally superposed sections of Jurassic – Early Cretaceous deposits along the valley of the Danube River. These sediments had been previously dated with ammonites. In order to determine the age of the Danubian nappes in eastern Serbia more precisely, we have revisited some of the “well-known” geological sections and have dated the radiolarians and dinoflagellates content of Jurassic – Early Cretaceous deposits.

In the studied area, Jurassic sedimentation began with clastic deposits that transgressively overlie Permian rocks. Three considerably different successions were studied above the Lower Jurassic transgressive sequence made up of quartz sandstone and conglomerate.

The first (structurally the highest) succession, exposed between tunnels 17 and 21, is over 150 m thick and typical of a deep-water basin. The following units occur in stratigraphic order: red shale with intercalations of thin beds of nodular limestone; white marly limestone that transits upwards into well-bedded limestone with subordinate marly interlayers; thin-bedded green and upsection red calcareous radiolarite; poorly bedded grey marly limestone; well-bedded reddish limestone with chert nodules and interlayers of dark red shale. Several breccia and calcarenite beds are interstratified in the last unit.

The second succession (exposed at tunnel no 10) indicates deposition on a pelagic plateau. This section is much more condensed, not exceeding 20 m in total thickness. The predominant facies is red nodular limestone of Rosso Ammonitico type. Rare chert nodules and layers exist only in the middle part of the section. Slumped beds and intraformational conglomerates occur in the upper half. Both sections continue with a thick succession of light grey micrite with chert nodules that closely resembles the Maiolica limestone of the Southern Alps. Up to several meters thick slumped levels are common in this Lower Cretaceous limestone.

The third succession (exposed at tunnel 13) is also condensed (total thickness 17 m) and indicates deposition on a pelagic plateau. This section is characterized by a thin, but rather a conspicuous interval of alternating green, violet and red radiolarites.

The first section (tunnels 17 – 21) represents deeper basin, while the other two (tunnels 10 and 13) were deposited on a pelagic plateau. These successions indicate a typical horst-and-graben topography, well known from other domains of the Alpine Tethys. The topographic difference was apparently diminished by the Early Cretaceous when Maiolica type limestone became ubiquitous as is now confirmed also with radiolarians.

Late Triassic ribbon radiolarite components from the Middle Jurassic ophiolitic mélange: Age, microfacies and provenance (Zlatibor Mt., Serbia)

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Triassic ribbon radiolarites are of special interest for the reconstruction of Neo-Tethys oceanic domain, the Jurassic geodynamic history of the western Tethyan realm and the palaeogeographic evolution of the Inner Dinarides. Newly detected Late Triassic oceanic ribbon radiolarite clasts in the late Middle to early Late Jurassic ophiolitic mélange (Gawlick et al. 2016) between Trnava and Rožanstvo (Zlatibor Mt.) were investigated to reconstruct their provenance and depositional setting. Besides a lot of outcrops of the ophiolitic mélange south of the study area, the outcrops between Trnava and Rožanstvo provide the rather seldom possibility to study Late Triassic ribbon radiolarite components from the ophiolitic mélange which occur in fissures in the underlying limestone blocks, fill depressions between the different limestone blocks or lie directly on top of them. We studied more than ten different radiolarite pebbles for the microfacies characteristics and the biostratigraphic age. Six radiolarian samples yielded determinable and moderately preserved radiolarian assemblages. Samples SCG 48a (Upper Carnian to Middle Norian) and SCG 48b (Upper Norian – Rhaetian) derive from the ophiolitic mélange overlying a Late Triassic fore-reef to reefal block (reefal Dachstein Limestone). The samples SCG 50, SCG 51 (uppermost Carnian - Lower Norian) and SCG 52 (Carnian to Middle Norian) derive from the ophiolitic mélange filling a depression between the Late Triassic fore-reef to reefal block and an Early Carnian reefal limestone block (Wetterstein Formation). The sample SRB 207 (Upper Norian – Rhaetian) derive from a fissure infilling in Late Triassic lagoonal to back-reef lagoonal Dachstein Limestone. Practically all radiolarite components are violet-greyish, violet-reddish or red, in cases manganese-rich, as typical for condensed oceanic ribbon radiolarites (Baumgartner 2013). The radiolarites are completely bioturbated and therefore massive, in cases clay-rich. All Late Triassic radiolarites show more or less a similar microfacies. Dominant are carbonate-free radiolarian wackestones to packstones in a clayey, in cases completely silicified matrix. Filaments or crinoids, as typical for shelf or continental slope near radiolarites are completely missing in these radiolarite components, even they occur not as chertified ghosts. This microfacies resembles undoubtedly oceanic ribbon radiolarites. Our new data strengthen the still not commonly accepted one ocean reconstruction for the western Tethyan realm in Triassic-Jurassic times and provide new insights into the Late Triassic depositional history of this oceanic domain. In the Late Jurassic in the course of westward directed ophiolite obduction (Gawlick et al. 2008; Schmid et al. 2008) the limestone blocks with the overlying ophiolitic mélange were transported to its actual position west of the Drina-Ivanjica unit. The ophiolites of the Dinaridic Ophiolite Belt including the ophiolitic mélange derived as far-travelled oceanic sheets from the Neo-Tethys Ocean to the east.

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The role of Paleogene larger foraminifera and plankton in the subdivision of carbonate platforms on the Adriatic plate – the example of Herzegovina

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Paleogene strata in Herzegovina are exposed from Livno in the north to Metković in the south, and west and east of the river Neretva. They occur in folded structures as isolated patches within Cretaceous rocks and in a hanging-wall of bauxite deposits. Their outcrops are NW-SE oriented and tectonically deformed. Their northern part is exposed in the southern slopes of the Čabulja and Velež Mountains, the eastern part along the Neretva, and the southern part in the south and central Herzegovina with bauxite deposits (Hrvatović, 2006, Jungwirt, 2001). In Herzegovina, the authors have a long experience in the study of large foraminifers, especially alveolinas and nummulites, conical foraminifers, large miliolides, planktonic foraminifera and nannoplakton (Slišković et al., 1978, Babić et al., 1985, Drobne & Šikić, 1986, Sakać et al., 1987). Research localities with a rather complete succession of beds were chosen from initiation of deposition to deepening and overlying by flysch beds. A special role was played by alveolinas that were traced from the NW part of Paleogene Adriatic carbonate platform. They appear separately in two phylogenetic lines as Alveolina histrica > Alv. septentrionalis > Alv. rakoveci, only in Cuisian (Up.Ypresian) E1 = Lower Eocene), in the northern part of the platform. The second line belongs to Alveolina levantina > Alv croatica > Alv. hottingerina from Mid. Cuisian to Low. Lutetian, in the southern part to Greece. Their assemblage is quite uniform in the whole western part of the Central Tethys. We established in selected profiles: 1. Start of sedimentation: in the north and east of Neretva in Paleocene, and in southern Herzegovina in Cuisian - E1. 2. Alveolinas from the Alv. histrica line only in the northern arc, and alveolinas of the Alv. levantina line only in the southern part. 3. Gradual passages from platform regime to flysch occurred first in the north already in E1 after Ilerdian in Cuisian time, later in the southern part in E2 in Mid. or Up. Lutetian. In view of the common paleontological, stratigraphical and facial characteristics of strata on platforms, the model of BioZ 1-5 biosedimentary zones was introduced (Drobne et al. 2009). It enables a chronological zonation of the uniform platform into distinct units, their spatial delimitation, origin and subsidence through deepening. The model was applied for SW Slovenia and NE Italy. Accordingly it can be established in Herzegovina BiosZ 1 – in the north in the POTOČANI traverse with nannoplakton proving Paleocene, Selandian-Thanetian (after Ćorić), BiosZ 2 – in the north GORANCI traverse, east of Neretva GUBERAČA, PODVELEŽJE (Paleocene and Ilerdian), followed by flysch in the Cuisian, BiosZ 3 – in the north DOBRINJ, GRABOVA Draga and east of Neretva Stolac – HRGUD and Metković – SJEKOŠE traverses (Paleocene, Ilerdian and Cuisian), following by the flysch at the end of the Cuisian and in the Lower Lutetian (Charvet, 1978, Drobne et al., 1986, Trutin et al., 2000), and BiosZ 4 – in the southern part, at KADIM, POSUŠJE with surroundings and ZAMAČE traverses (Mid. Cuisian to Mid. Lutetian), carbonates, followed by the transition to flysch are of Up. Lutetian and partly Bartonian age. With these BiosZ zones the Herzegovina Paleogene can be connected to the Dalmatian region and Adriatic islands toward Istria and Slovenia, and belongs to the common Paleogene Adriatic carbonate platform (PgAdCP), marked A on the tectonic map by Hrvatović (2006), being exotic part of the Dinaric carbonate platform.

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Chladocrinus basaltiformis (MILLER) and *Zeilleria mutabilis* (OPPEL) from the Pliensbachian oolitic limestone of the Rumija Mt. (Southern Montenegro)

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Pliensbachian rocks of the Rumija Mt. (marginal part of Dinaric Carbonate Platform), in southern Montenegro, are represented by oolitic grainstones with cross-stratification, with rare fossil fauna. In these layers echinoderm fragments (crinoids ossicles and echinoid spines), rare foraminifera *Lituolipora termieri* (HOTTINGER), and algae *Palaeodasycladus mediterraneus* PIA and *Thaumatoporella parvovesiculifera* (RAINERI) are found. The Liassic succession (Hettangian-Sinemurian) starts with micritic limestones, only a few meters thick, which are overlaying Upper Triassic Dachstein limestones. Above the micrites are thick bedded coarse-grained grainstones with ooids, about 100 m thick. Pliensbachian grainstones with ooids are covered by late Pliensbachian-early Toarcian marls and marly limestones. In these deposits, from an outcrop in the village of Kostanica, a fauna of crinoids and brachiopods was collected. Mentioned fossils build coquinas that occur in several levels in a layer that is a few meters thick. Crinoids are represented with stem fragments and individual ossicles of the species *Chladocrinus basaltiformis* (MILLER). Disarticulated brachiopod valves of the species *Zeilleria mutabilis* (OPPEL) are determined. The composition of the fauna indicates Pliensbachian age. The palaeobiogeographic distribution of these two species has been enlarged. Oolitic grainstones with cross-stratification represent sediments deposited in a high-energy environment of an open platform. The way that fossil fauna is preserved (crinoids stem fragments, isolated brachiopod valves) indicates that they were transported by sea currents or storm events.

A geophysical study of the Eastern Vardar Zone ophiolite: An overview

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The Vardar Zone is one of the main geotectonic units of the central part of the Balkan Peninsula. It represents relics of the former oceanic lithosphere, which remained after the closure of the Tethys Ocean. The easternmost part of the Vardar Zone (hereafter: Eastern Vardar Zone) shows significant differences from the rest of the Balkan ophiolites. It is a rather narrow ophiolite belt elongated in NNW-SSE direction, displays the most pronounced supra-subduction geochemical signatures and its spatial position and mode of emplacement is still matter of debate. In this study, we applied geophysical methods in order to investigate the subsurface distribution and, thereby to better constrain the mode of emplacement of the Eastern Vardar Zone ophiolite.

A combination of magnetic/aeromagnetic and gravity observations in Serbia and FYR of Macedonia was applied. All previous geophysical researches within the study area were discussed and incorporated in this study as an important part. Two approaches were used: local and regional approach, both of which involved qualitative and quantitative analysis. The local approach was based on 2D models at three representative sites (Kuršumlija, Ždraljica and Demir Kapija / Gevgelija). The regional approach included the analysis of compiled data for the entire Serbian and Macedonian part of the Eastern Vardar Zone, which resulted in Bouguer Anomaly Map and Total intensity of the Earth's magnetic field Anomaly Map. The accuracy of the inferred position of the Eastern Vardar Zone ophiolite at different levels was evaluated within the whole study area according to filtered and transformed geophysical data.

These two approaches resulted in a 3D model for the almost entire area of the Eastern Vardar Zone. The obtained results were considered and compared with the previous views on its position, such as geological observations, field data, paleomagnetic data, seismic data, etc. Generally, 2D models show that the Eastern Vardar Zone lies below the Serbo-Macedonian Massif with a variable slope angle that is steeper towards the south. Based on analysis of transformed geophysical data it is concluded that the cause of anomaly represents single body elongated in NNW-SSE direction. The Western border of the East Vardar zone ophiolite is sharp and clearly determined, while eastern border is diffuse. It is, however, evident that below the surface this ophiolite dips to the east below Serbo-Macedonian Massif. Obtained results suggest that not all Tethyan ophiolites were emplaced via a typical Tethyan emplacement style. In this study, we propose accretion mechanism as a mode of emplacement of Eastern Vardar Zone ophiolite, which is more related to the Cordilleran emplacement style.

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Polycyclic Alpine orogeny in the Rhodope Metamorphic Complex: The record in migmatites from the Nestos Shear Zone (N. Greece)

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The Rhodope Metamorphic Complex (RMC) is a high-grade crystalline massif located at the northern margin of the Aegean region. Numerous scenarios have been proposed for the evolution of the RMC during Alpine times. A debated issue is whether there has been a single protracted orogenic cycle since around the mid-Mesozoic or whether Alpine orogeny involved distinct episodes of subduction and crustal accretion.

We describe a key outcrop located on the Nestos Shear Zone (NSZ), a major NNE-dipping top-to-SW shear zone characterized by an inverted metamorphic sequence. Structural and petrological data document the existence of two anatectic events. The first event, best preserved in decametric structural lenses, is pre-kinematic with respect to top-to-SW shearing and involved high-temperature "dry" melting. The second event is syn-kinematic and involved lower-temperature water-assisted melting. Zircon, monazite, and rutile LA-ICPMS U-Pb dating indicates that the first event occurred at ~140 Ma and the second event at ~40 Ma. During ongoing top-to-SW shearing and as late as ~36 Ma, the rocks from the outcrop were at higher temperatures than the peak temperatures experienced by lower levels of the NSZ. This confirms the existence of the inverted metamorphic sequence and demonstrates that the NSZ was a major thrust at 36-40 Ma. The ~100 Myr time laps between the two anatectic events encompasses the period from ~115 to ~70 Ma characterized by a gap in the geochronological record on the scale of the RMC (the Eastern Rhodope excluded). This ~45 Myr gap likely reflects a period of tectonic quiescence between the mid-Mesozoic orogen and the Cenozoic one, attesting for polycyclic Alpine orogeny in the RMC. Unlike assumed in several geodynamic scenarios, the Alpine evolution of the RMC did not consist of a single orogenic cycle of Mesozoic age followed by Cenozoic crustal-scale extension triggered by mantle delamination.

Polycyclic orogeny has resulted in a two-loop P-T-t path for the hanging wall unit of the NSZ. The Cenozoic P-T paths of this unit and the footwall unit merged while both units were being exhumed, a feature attributed to the syn-thrusting extensional spreading of the main mass of the hanging wall unit above the NSZ. Fast exhumation of the thrust zone likely explains why the inverted metamorphic sequence has been preserved instead of being erased during post-thickening thermal relaxation.

The late Middle to early Late Jurassic overlooked Hallstatt Mélange (Pavlovića Ćuprija, Zlatar Mélange) in the Dinaridic Ophiolite Belt

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In the Dinaridic Ophiolite Belt (SW Serbia) hemipelagic Triassic sediments (Hallstatt Limestone succession), which were deposited originally on the outer passive margin of the Neo-Tethys Ocean, occur only as components of different size (mm to square km) in mass transport deposits of Middle Jurassic to early Late Jurassic age, forming a sedimentary mélange. Hallstatt Mélanges are interpreted to be formed in front of advancing nappes in the outer shelf region due to ongoing ophiolite obduction in the late Middle Jurassic. This late Middle to early Late Jurassic Hallstatt Mélange in the Inner Dinarides plays a crucial role in the reconstruction 1) of the Triassic-Jurassic passive margin configuration of the western Neo-Tethys Ocean, 2) of the Middle to Late Jurassic geodynamic history of the Dinarides, and 3) for the correlation of the tectonic units in the Circum-Pannonian realm. In the Zlatar Mountain, especially in the area of Pavlovića Ćuprija below the Middle to early Late Jurassic ophiolitic mélange and their overlying ophiolite sheets of the Dinaridic Ophiolite nappe occur mass transport deposits and slide blocks in a radiolaritic-argillaceous matrix. The components of the mass transport deposits and the slide blocks consist of Triassic to Early Jurassic carbonates and Middle Jurassic radiolarites, and the matrix is late Middle to early Late Jurassic radiolarites, siliceous claystones and siliceous marls. The slide blocks in the Zlatar (Hallstatt) Mélange reach several tens to hundred metres in size, occasionally even kilometres. Several olistoliths and blocks contain well preserved parts of the Triassic sedimentary succession. Their stratigraphy and facies evolution allowed the reconstruction of complete sedimentary successions originating from a distal continental margin setting (Hallstatt facies zone), located originally east of the preserved facies belts of the Inner Dinarides. Sedimentary features, the litho- and microfacies of the Hallstatt Limestone sequences clearly indicates, that the whole Hallstatt Mélange area in SW Serbia (Zlatar Mélange) represents a far-travelled nappe from the Triassic-Jurassic distal passive margin facing the Neo-Tethys Ocean to the east. The clasts and slides of the Hallstatt Mélange in the Zlatar Mountain (Zlatar Mélange) and adjacent areas derive from the outer shelf region and resemble the known situations in the Eastern Alps or the Albanides. The Zlatar Mélange resembles the (Late) Bathonian to Early/Middle Oxfordian Sandlingalm Formation (Hallstatt Mélange) in the Northern Calcareous Alps and equivalents in the Inner Western Carpathians and several units in the Pannonian realm or the Albanides. This age of the Zlatar Mélange clearly indicates that the formation of deep-water trench-like basins in front of the obducted ophiolitic nappe pile started in Middle Jurassic times and not in the latest Jurassic). The situation of the Zlatar Mélange below the obducted ophiolite sheets in the Dinaridic Ophiolite Belt corresponds perfectly to the situation known further to the south in the Albanides and to the north of the Eastern Alps and Western Carpathians, where identical mélanges were formed in Middle to early Late Jurassic times. The Zlatar (Hallstatt) Mélange is therefore part of the Neotethyan Belt in sense of Missoni & Gawlick (2011).

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Retroward extrusion of the Pelion Blueschist Nappe (Hellenides, NW Aegean)

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Detailed structural analysis/mapping in combination with microtectonic and amphibole chemistry analyses enabled us to produce a new structural map and to unravel the Alpine deformation history of the Hellenides in Pelion area (Thessaly region). The main finding emerged from in this study is that the Pelion Blueschist Nappe is tectonically sandwiched between gneisses-marbles of the Pelagonian Zone and is bounded by two major ductile shear zones, a Basal thrust and an Upper normal-sense detachment. This nappe is the lateral equivalent of the Cycladic Blueschists and has been affected by Eocene blueschist-facies metamorphism followed by greenschist-facies overprint of presumably Oligo-Miocene age.

The Pelion Blueschist Nappe has a structural thickness of *c*. 4 km and is made up of quartz-micaschists, calcite schists and marbles, and lenses of meta-mafic and meta-ophiolitic rocks. The main ductile deformation is expressed by a penetrative foliation and a pronounced ENE-trending mineral lineation. Ductile deformation is mainly localized along the Basal thrust and the Upper detachment producing 20-30 meters thick mylonitic zones. Kinematic analysis revealed a dominant top-to-the-ENE sense of shear recorded in the Basal thrust mylonites and in the main bulk of the Pelion Blueschist Nappe. In the structurally uppermost 500 meters of the nappe, a top-to-the-WSW shear sense that becomes stronger towards the Upper detachment was observed. Chemical analysis of the syn-kinematically grown amphiboles, which define the mylonitic foliation and lineation, showed a progressive passage from blueschist-facies to greenschist-facies conditions in both NE- and SW-directed mylonites. These structural relationships indicate that the exhumation of the Pelion Blueschist Nappe, from c. 7-8kbar to c. 3-4kbar, was achieved by an ENE-directed ductile extrusion at late Eocene-Oligocene times. This finding is in contrast with the prevailing view that the Hellenides is a unidirectional, SW-vergent orogenic belt.

Based on the fact that the Pelion Blueschist Nappe is sandwiched between Pelagonian rocks, we suggest that the protolith of the nappe should have been formed in an intracontinental basin within the Pelagonian. This basin was probably formed in a back-arc setting triggered by the SW-vergent subduction of the Pindos Ocean beneath the Pelagonian microcontinent at pre-Cenozoic times. The consequent continent-continent collision between the Apulian and the Pelagonian microcontinents possibly triggered the basin inversion that led to a proward-dipping intracontinental subduction and the high-pressure metamorphism of the Pelion Blueschist Nappe during early-middle Eocene. During late Eocene-Oligocene, the induced lateral pressure gradient possibly led to the retroward (ENE) ductile extrusion/exhumation of the Pelion Blueschist Nappe under a compressional tectonic setting.

The boundary of the eclogite belt in the Western Alps: an example from the Susa Shear Zone

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Western Alps is a collisional belt, where nappes of different paleogeographic origin are stacked. Here the tectonic evolution juxtaposed volumes of rock who registered different metamorphic peaks, and crossing the orogen is possible to distinguish various domains. Detailed geological mapping and structural analysis in the Susa Valley (Inner Western Alps) allowed the recognition of a first-order shear zone (i.e., the Susa Shear Zone, SSZ; Gasco et al., 2011), which separates the Internal Piedmont Zone (IPZ) and Dora-Maira Massif (DM) from the External Piedmont Zone (EPZ). In the investigated area, IPZ and DM correspond to the eclogitic belt, whereas the EPZ is part of the so-called frontal wedge (Malusà et al., 2011). The IPZ is a remnant of the Mesozoic Alpine Tethys, and consists of meta-ophiolites and related meta-sedimentary cover, whereas the DM was part of a continental margin wherein a composite Paleozoic basement was covered by an older siliciclastic succession and a younger carbonate one. The EPZ consists of minor meta-ophiolites and a thick supra-ophiolite metasedimentary cover (i.e., the Schistes Lustrès). IPZ and DM, during subduction, reached eclogitic metamorphic conditions, while EPZ reached just blueschist metamorphic conditions. Structural evolution of the SSZ and its hanging wall and footwall was characterised by four main ductile regional phases (D1 to D4), that deformed the stacked units with distinctive styles and at different crustal levels. D1 show some relics of S1 foliation and some A1 axes in strong rheologically lithotypes (metabasite, grey marble, metagabbro). Few syn-S1 folds are rarely recognisable in some volumes saved by subsequent deformation. D2 is a W-verging phase, who develop a very pervasive S2 foliation (regional foliation), axial plane of D2 isoclinal non-cylindrical folds, with A2 W dipping, sub-parallel to the L2 stretching lineation. D3 developed at higher crustal deep, showing open-to-close cylindrical folds, with a long hinge-short hinge, N-verging. This phase didn't develop a pervasive S3 foliation, just an intense crenulation, with axes oriented almost E-W, gently dipping to E and W. Locally, D3 develop box folds. D4 show W-verging open folds, with long hinge-short-hinge geometry. A4 are directed almost N-S, without developing axial plane foliation. Inside the eclogitic belt, the tectonic contact between DM and IPZ, responsible for their coupling, is a pre-D2 shear zone, strongly deformed in D2 and re-crystalized in greenschist facies metamorphism. The geological meaning of the phases changes across the eclogitic belt and EPZ: before coupling, these units followed strongly different evolution in the alpine history, and structural elements gain different sense in geodynamic evolution. The first activation of SSZ is a post-D2 and pre-D3 mylonitic event, related to the early coupling between the lower eclogitic belt and the upper EPZ, with a Top-to-E extensional kinematism, during exhumation. The second activation of SSZ is a late-metamorphic syn-D4 mylonitic event, occurred when the eclogitic belt developed a dome structure, with a Top-to-W extensional kinematism, related to the latest doming phases in the ductile environment. Kinematic indicators of the first mylonitic event, now on the field, show an apparently reverse shear sense, because of the subsequent doming which overturned and re-oriented the first mylonitic shear zone and their related kinematic indicators.

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Middle Triassic deep-water sediments on a transect across the Dinarides

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The Dinarides are an excellent study area to restore the rift topography of the western continental margin facing the Meliata-Maliac branch of the Neotethys Ocean. The cross-section through different facies belts extends from the proximal to the distal margin and includes remnants of the oceanic crust. This cross-section is much more complete than in the Southern Alps, where only the proximal Triassic margin is preserved. On the other side, the Hellenides south of the Scutari-Peć line preserve the relatively distal margin but lack the proximal part with the High Karst Carbonate Platform.

We are currently investigating Upper Anisian to Ladinian syn- and early post-rift sediments on a transect through the External and Central Dinarides in Croatia and in Bosnia and Herzegovina. Previously published regional studies provided a general stratigraphic framework and demonstrated the horst-and-graben paleotopography of the continental margin. Our studies focus on precise dating with radiolarians and conodonts, and on facies analyses at four localities. The pre-rift sequence of all localities ends with Middle Anisian platform carbonates. The study localities are:

1) Mt. Svilaja in Dalmatia, High Karst Zone; restricted intra-platform basin. The syn-rift succession starts with dolomitic breccia and is followed by a 150 m thick succession of pelagic silica-rich carbonates, with pyroclastic rocks ("pietra verde") in the lower part. In addition to conodonts and radiolarians, rare ammonoids and some excellently preserved silicified calcareous algae, foraminifers, corals, gastropods, brachiopods and crinoids were found. The entire succession is characterized by high content of organic matter.

2) Two sections along Varoški potok, Herzegovina, Prekarst Zone; subsided blocks at the edge of the High Karst Platform. In the first section, the pelagic interval is reduced to a few meters and overlies a several tens of meters thick unit of platform limestone, which is cross-cut with fissure fillings of red pelagic limestone. In the second section, platform limestone is overlain first by a meter of polymictic carbonate breccia and then by a pelagic unit, which is considerably thicker than in the first section and includes tuffaceous layers. The pelagic limestone in both sections is light to vivid red, in places greenish or light grey to pink. This lithology is perfectly comparable with the Buchenstein Formation of the Southern Alps but contrasts significantly with dark grey rocks of the Svilaja section.

3) Ulog – Kalinovik, Bosnia, Bosnian Zone; deep-water sediments ranging in age from the Middle Triassic to the Cretaceous flysch (=the Bosnian Flysch). Red nodular limestone and radiolarite with tuff interbeds occur in the lower part, pelagic limestones with cherts prevail in the Upper Triassic and Lower Jurassic. In contrast to other sections, no platform carbonates younger than the Anisian occur.

4) East of Kalinovik, Bosnia, Treskavica Nappe (NW continuation of the Durmitor Nappe); topographic high with a few meters thick unit of red siliceous limestone and chert between platform carbonates.

The horst-and-graben geometry inferred from variations in thickness and facies of the syn-rift sequence is remarkably similar to the proximal North Atlantic margin. The Bosnian Basin is a good example of a deeply subsided basin on a thinned continental crust between the High Karst Platform and the Durmitor continental ribbon. The continuation to the distal margin can be reconstructed based on recent studies in the Drina-Ivanjica and Kopaonik units.

Primary magnetization in the Berriasian of the Northern Calcareous Alps (Salzburg area)

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Berriasian succession in the central part of the Northern Calcareous Alps (NCA) consists of ca. 150 m hemipelagic sediments of the Oberalm and Schrambach formations. The rocks are dated with calpionellids and ammonites (Krische et al., 2013; Bujtor et al., 2013), however due to low frequency of calpionellids and long barren intervals the stratigraphic divisions are not as precise. Magnetic stratigraphy in the Berriasian is a widely applied tool. When integrated with calpionellid and/or nannofossil stratigraphy, it permits for construction of high resolution chronostratigraphic framework correlated directly to Global Polarity Time Scale (e.g. Grabowski et al., 2016). Despite widespread remagnetization documented by Pueyo et al. (2007) in the Triassic to Lower Cretaceous of the NCA, a detailed paleomagnetic study of the Oberalm and Schrambach formations was undertaken in the Leube quarry (Salzburg area) following other successful studies of the Berriasian deep marine sediments in Alpine – Carpathian fold-and-thrust belt (e.g. Ogg et al., 1991; Grabowski, 2011).

Natural remanent magnetization (NRM) intensities were mostly weaker than 1 mA/m, while magnetic susceptibility fluctuated between 10 and 70 x 10^{-9} m^3/kg. Magnetite is the most important magnetic mineral, occasionally magnetization is carried also by hematite. NRM consists of three components which have been isolated using thermal demagnetization. The component with highest unblocking temperatures (above 500 ^{o}C) of mixed, normal and reversed polarity, is interpreted as primary. Basing on results of microfossil stratigraphy, the magnetozones from M17r to M14r (close to the Berriasian/Valanginian boundary) were identified. General clockwise rotation of paleodeclination is confirmed. In the next step, an attempt will be made to reconstruct an influx of lithogenic material into the basin and correlate it with orogenic processes as well as global and regional paleoclimatic and eurybathic trends.

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Variscan to Eoalpine tectono-metamorphic history of the Austroalpine Units south of the Tauern Window (Kreuzeck Mountains, Eastern Alps, Austria)

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The Austroalpine Units of the Eastern Alps are derived from the continental crust of the northern Adriatic continental margin. They consist of several basement and/or cover nappes, which were affected differently by Phanerozoic tectono-metamorphic events. This work presents new age and PT data from the Kreuzeck Mountains located to the south of the Tauern Window.

The investigated area consists of two nappe systems, namely the Koralpe-Wölz Nappe System (KWNS) in the footwall and the Drauzug-Gurktal Nappe System (DGNS) in the hanging wall. They are separated by the several hundreds of meters wide newly defined Wallner Shear Zone, representing an Eoalpine (Cretaceous) South-dipping normal fault.

The KWNS is composed of monotonous paragneiss with intercalations of mica schist and amphibolite (Prijakt-Polinik Complex). Eoalpine peak conditions reached eclogite-facies further in the North and amphibolite-facies in the study area. Rb/Sr biotite ages indicate cooling below c. 300 °C at 75-80 Ma.

The DGNS consists of 3 complexes, which experienced different metamorphic conditions during the Variscan orogeny. The lowermost Strieden Complex is built up by intensely folded, locally garnet-bearing mica schist and amphibolite recording Variscan upper epidote-amphibolite-facies conditions. Structurally above, the Gaugen Complex is dissected by an EW trending, steep North-dipping thrust fault – the Leßnigbach Shear Zone – which is interpreted to be linked to the Wallner Shear Zone and therefore also Eoalpine in age. The Gaugen Complex comprises mica schist and paragneiss and minor amphibolite. Kyanite and staurolite identified in thin sections suggest amphibolite-facies conditions, which is confirmed by PT-pseudosections revealing peak conditions at 600±50 °C and 0.8±0.1 GPa. Sm/Nd garnet isochron age suggest peak conditions around 306±5 Ma. Rb/Sr biotite ages gave 292±3 Ma and 273±3 Ma in the area to the South of the Leßnigbach Shear Zone and 221±2 Ma to the North of it. These ages are interpreted to reflect Variscan cooling with a Cretaceous thermal overprint, which is very weak in the South and more intense in the northern block reflecting the tectonic history of the northern block, which was exhumed from greater depths during the Late Cretaceous activity of the Wallner and Leßnigbach shear zones. The uppermost Goldeck Complex, in contrast, consists of phyllite and marble, which only reached Variscan greenschist-facies conditions.

Taking all together, the DGNS came in contact with the underlying KWNS along the Wallner Shear Zone during the Eoalpine event in the Late Cretaceous. Within the DGNS the individual complexes show a different Variscan imprint. The Gaugen Complex is divided into two blocks, separated by the Leßnigbach Shear Zone. Both blocks reached amphibolite-facies conditions during the Variscan orogeny, but the northern block was exhumed from greater depth by the activity of two shear zones in the Upper Cretaceous.

Structural and petrologic investigation of the subduction-exhumation history of the Modereck nappe system, central Tauern Window

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The central part of the Tauern window contains Tertiary high-pressure (HP) rocks derived from the former Alpine Tethys (Glockner nappe) and the distal European continental margin (Eclogite Zone, Modereck nappe). The HP rocks are strongly sheared and heterogeneously retrogressed, such that they only locally retain the HP fabrics and parageneses. In past work, this heterogeneity was interpreted to reflect a mélange-type structure, with blocks of eclogites surrounded by calcareous schist (Bünderschiefer) and metabasite (Prasinite) with greenschist-facies parageneses. The apparent absence of HP assemblages in these surrounding rocks was believed to support the notion that the HP rocks were tectonically injected into a lower-grade matrix that never experienced HP metamorphism.

Here we report the first evidence that HP metamorphism affected the whole Modereck nappe in the central Tauern Window. The HP assemblages occur in lozenges of less-sheared rock surrounded by a highly sheared, mylonitic calcschist and prasinite, which we found to also contain relicts of HP metamorphism. These include lawsonite pseudomorphs in garnet within early Cretaceous pelitic metasediments (Brennkogel Fm). Raman spectroscopy of quartz inclusions in garnet and on carbonaceous matter, as well as thermodynamic modelling of co-existing mineral parageneses in other Mesozoic metasediments from different parts and lithostratigraphic formations of the Modereck nappe, indicate peak-metamorphic conditions of ca. 20 kbar at 400-500 °C. Similar metamorphic conditions are also obtained in lithologies of the oceanic Glockner nappe, indicating that both distal continental and oceanic units were subducted.

Both the Modereck and Glockner nappes were affected by a multi-km-scale recumbent sheath fold, the Seidlwinkl fold, as indicated by the consistent N-S trend of stretching lineations around its entire, arcuate hinge on the map scale. The contact between these two nappes is a thrust which is affected by and therefore predates the Seidlwinkl fold. The axial plane foliation of this fold syn- to post-dates the HP metamorphism and is associated with top-N shear sense indicators parallel to the aforementioned stretching lineations. Therefore, we suggest that the formation of the sheath fold was related to the exhumation of the Modereck nappe and the overlying Glockner nappe as a composite fold nappe from ca. 60 km depth to shallower levels corresponding to greenschist-facies conditions.

HP metamorphism occurred throughout the Modereck nappe and the nappe displays a well-ordered stratigraphic succession. This indicates that it is not a mélange but a coherent HP nappe that is interpreted to have been introduced into the lower-grade neighbouring tectonic units during thrusting of the Penninic nappes beneath the Austroalpine units. During continued subduction and subsequent exhumation, they underwent extensive retrogression and structural overprinting during exhumation.

Sheath folds like the Seidlwinkl fold may be characteristic of subduction-exhumation channels, where high strain rates and temperatures favour low viscosity contrasts among the constituent continental and oceanic lithologies; this, in turn, maintains the coherence of the original passive-margin sequence. We propose that crustal-scale sheath folds nucleate along pre-orogenic structural heterogeneities of the passive margin (e.g., thickness variations in the vicinity of rift-related low-angle normal faults), then undergo explosive growth followed by homogeneous, noncoaxial shearing on their way back up. We speculate that the Seidlwinkl fold may provide an analogue for anomalous structures at the tops of downgoing slabs imaged with high-resolution seismic tomography using receiver functions.

Did the Adula nappe (European basement) endure UHP metamorphism during the Alpine Orogeny?

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The mafic-ultramafic rocks in the Adula nappe, and its western extensions Alpe Arami and Cima Lunga units (hereafter Cima Lunga), preserve the only record of regional high- to ultrahigh-pressure metamorphism (~13-35 kbar) in the Central Alps. These rocks are hosted within felsic country rock gneiss that is up to 25 kbar lower in peak-pressure conditions. The Adula-Cima Lunga nappe is traditionally interpreted as a tectonic mélange of the European continental basement, metasediments and metavolcanics of Valais Ocean and mantle-derived ultramafic rocks. The exhumation and emplacement of ultrahigh-pressure (UHP) rocks into lower-pressure units remains enigmatic; even more so is the subduction of a large piece of continental crust to mantle depths.

This study investigates the kinematics of (U)HP eclogite and the surrounding country rocks in the Cima Lunga unit through structural mapping and a microstructural and textural analysis. Structural mapping allows for a re-interpretation of the lower Cima Lunga nappe boundary. Paired with structural, textural and geochemical observations, the mafic-ultramafic (U)HP rocks are presented here as a nappe separating lithology rather than lenses within a basement nappe unit.

We examine the lattice preferred orientation in omphacite using electron backscatter diffraction to determine the deformation regime active under (U)HP conditions. Our microstructural observations reveal limited evidence for simple shear; instead, textural data of eclogite rocks show affinity for a flattening strain geometry. When comparing our textural observations with published data from the Cima Lunga and the main Adula nappe, we consistently observe a contrast in omphacite texture between the two areas. Geochronological and thermobarometric data from published studies show similar contrasts: the main Adula nappe has experienced two orogenic cycles of (U)HP subduction and exhumation, while the Cima Lunga unit has only experienced one cycle during the Alpine orogeny.

U-Pb and REE analyses of metamorphic zircon inclusions from garnet in the Alpe Arami eclogite rocks gave individual U-Pb spot ages of ca. 40-30 Ma and all spots show typical “eclogite” REE distribution patterns. The Ti-in-zircon temperatures on the same analytical spots apparently increase with time. Zircons in two eclogite samples from Cima di Gagnone, separated in the traditional way, gave similar results although larger scatter in grain shapes and composition. Zircons from granitoid gneisses beneath and above the layer containing mafic and ultramafic rocks gave very consistent rim ages with mean and lower intercept ages at ca. 31.6 Ma. Age depth-profiling on zircon prism faces yielded ages of 30-33 Ma on the outer one micron.

Major and trace-element whole rock analyses of most mafic eclogite samples from Adula and Cima Lunga units are indicative of MORB origin. While samples from the Cima Lunga and Alpe Arami units are very similar, they bear consistent differences to the samples from the Adula nappe suggesting a different geodynamic setting of the protoliths.

Structural position, age, and compositional discrepancies between the main Adula nappe and the Cima Lunga unit leads us to suggest that these two units experienced different geodynamic histories and can be considered as two separate lithotectonic units. In summary, we suggest that only the ultramafic rocks of the Cima Lunga domain have endured UHP metamorphism (> 30 kbar), while the Adula nappe was subducted during Alpine orogeny as a coherent body to maximum depths of “only” 24 kbar.

Self-consistent shear zone formation with applications to thermochronological dataset interpretation

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Crustal-scale shear zones are generated by strain localization, which in turn has several controlling mechanisms. We perform two-dimensional numerical simulations of shortening a viscoelastoplastic lithosphere to investigate the strain localization due to thermal softening. Furthermore, inversion of thermochronometric data using three -dimensional thermokinematic modelling constrained by independent geological and geophysical observations was performed to evaluate the contribution of slip partitioning, duplex development, and relief growth on the evolution of the thermal structure of the Himalaya during the last 12 Ma.

Our modelling results demonstrate that orogenic wedges develop spontaneously in response lithospheric shortening in a basic thermo-mechanical framework. The modelled orogenic wedges are characterised by the presence of (i) a first order deeply rooted shear zone, and (ii) a sequence of second-order shear zones in the upper crust. All shear zones are caused by thermal softening and result from local temperature increase due to shear heating and the temperature-dependence of viscosity. Continental underthrusting takes place along a first-order shear zone that initiates spontaneously. Whereas a sequence of second-order shear zones dissects the upper crust in a series of tectonic nappes altogether forming an orogenic wedge. The depth of the upper/lower crust boundary controls the lateral spacing of upper crustal shear zones. In the models, the second order shear zones are typically active for a duration between ~1 and ~4 My, while the first-order shear zone is active during the entire simulation (10 to 20 My).

The changes in rate of exhumation cause the underlying temperature field to change; the shear zones strongly deflect the isotherms by heat advection during the orogenic event and the rapid thermal relaxation towards a conductive geotherm that follows. The high temporal resolution of our experiments demonstrates that such shear zones are transient in time so that the resulting shear heating is also transient. These thermal processes have an effect on the techniques used to determine exhumation rates in the upper crust and consequently on the techniques used to determine the age of the faults and shear zones. To include the effect of a transient temperature field requires solving the heat equation numerically. Examples of natural temperature histories will be discussed in the terms shear zone histories by comparing false interpretations using traditional techniques and their reinterpretation based on numerical predictions.

Slab rollback and Neogene deformation at the Dinarides-Hellenides junction

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The Dinarides-Hellenides junction on the Adria-Europe plate boundary is the site of post-middle Miocene extension and block rotation that are linked to out-of-sequence thrusting and transfer faulting along the Hellenic arc. The main structure at this junction is the Skhoder-Peja Normal Fault (SPNF), which accommodates orogen-parallel extension and clockwise rotation of its hanging wall about a vertical axis near the city of Shkoder in northern Albania. The onset of normal faulting is constrained by mid-Miocene clastics in the hangingwall of the SPNF in the Kosovo-Metohia Basin (Elizaj 2009). Recent-to-ongoing fault activity is indicated by offset Holocene strata, earthquake focal mechanisms (Pondrelli et al., 2006) and GPS motion vectors (Jouanne et al., 2012) indicating SE-directed, clockwise motion of the hanging wall block towards the Hellenic arc in map view. North of the Shkoder rotation axis, post-Paleogene shortening in the Dinarides is minor (Bega, 2015), whereas south thereof, young thrusts affect Mio-Pliocene sediments and imbricate the Paleogene fold-and-thrust belt of the Hellenides. This Neogene shortening increases SE-ward, i.e., away from the rotation axis, as indicated by a SE-ward increase in elevation of Miocene sediments in thrust hanging walls, as well as increased folding and backthrusting of Mio-Pliocene strata in the Tirana foredeep basin. This shortening is linked via an oblique-dextral transfer zone (Elbasan-Vlora) to Mio-Pliocene thrusts at the orogenic front along the coast of central-southern Albania. The activity of this transfer zone is documented by dextral focal plane solutions (op cit); this zone has been interpreted as the surface exposure of a SE-dipping lateral ramp that accommodated 75 km of shortening (Vilasi et al., 2008). Regarded on the plate-boundary scale, the SE-ward increase in Neogene shortening away from the SPNF coincides with a southeastward increase in the length of subducted Adriatic lithosphere as imaged by body-wave tomography (e.g., Spakman and Wortel 2004) and receiver-function studies (Pearce et al., 2012). Moreover, the amount of subduction rollback measured in lithospheric cross sections increases progressively to the SE, from 90 km just south of the SPNF, to c. 200 km and 400 km on either side of the Kefalonia transfer fault. We therefore propose that the entire system of Neogene faults described above is an integral part of the highly mobile Adria-Aegean plate boundary at the NW end of the Hellenic arc. Since mid-Miocene time, the Shkoder-Peja Normal Fault system has served as a hinge to accommodate clockwise rotation and arc-parallel extension of the crust towards the apex of this arc during rollback subduction of the Adriatic lithosphere. In addition, the fault system may have transferred shortening from the Hellenic subduction to internal parts of the Dinarides, where this shortening is masked by Neogene orogen-normal extension in the upper plate of the retreating Dinaric and Carpathian orogens. We speculate that extension and block rotation at the SPNF were triggered by slab tearing and detachment beneath the Dinarides, then accommodated bending and rollback of the Hellenic slab segment in Neogene time.

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Variscan and Eo-Alpine eclogites of the Schober Group (Austroalpine)

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The Schober Group is located in the Lower Central Austroalpine, which comprises pre-Permian basement rocks with Variscan metamorphism, partly overprinted by Cretaceous metamorphism.

At the Prijakt Mountain in the western part of the Schober Group, a several hundred meters thick eclogite body occurs. The protolith age is 590 ± 4 Ma obtained by Pb-Pb zircon dating (Schulz and Bombach, 2003). The age of the high-pressure metamorphism, Variscan vs. Alpine, is controversial. Based on petrology and structure, Schulz (1993) proposed early-Variscan high-pressure metamorphism for the eclogites with P/T conditions of 1.4-1.6 GPa and 550-650 °C. Linner (1999) obtained a garnet-whole rock Sm-Nd age of 115 ± 33 Ma for the Prijakt eclogites and therefore proposed Eoalpine metamorphism at 1.6-1.8 GPa and 660 ± 30 ˚C.

We performed Lu-Hf geochronology on two eclogite samples from Prijakt. In both samples, two garnet generations occur. In one sample (PRI 4), the older generation (grt 1) is predominant with thin rims of grt 2, whereas in the other sample (PRI 3), grt 1 is only present as relics and grt 2 dominates. Lu-Hf ages are Late Carboniferous for PRI 4 (also confirmed by Sm-Nd) and Late Cretaceous for PRI 3. We interpret that these rocks experienced eclogite-facies metamorphism twice, in the Variscan and in the Eoalpine orogeny. While the Variscan eclogite paragenesis of PRI 3 was almost completely retrograded before the Eoalpine eclogite-facies metamorphism, PRI 4 preserved its Variscan high-pressure assemblage and therefore yielded a Variscan age. Thus our study confirms that the basement of the Schober Group was subducted twice, in the Variscan and in the Eoalpine orogeny.

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The tectonic window of Oberhof (Carinthia, Austria): A key area to understand the tectono-metamorphic evolution of the upper part of the Eo-Alpine nappe stack

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The Upper Austroalpine Unit in the Eastern Alps represents a nappe-stack that formed during the Eo-Alpine (Cretaceous) event. It is dominated by crystalline rocks that experienced several metamorphic imprints, specifically during the Variscian, Permo-Triassic, Eo-Alpine and Neo-Alpine events. While the central eclogite-bearing nappes (Koralpe-Wölz Nappe System) are well studied, a good understanding of the upper parts (Ötztal-Bundschuh and Drauzug-Gurktal Nappe Systems) is still missing. The tectonic window of Oberhof represents a key area to study the structure and evolution of the upper part of the Eo-Alpine nappe stack since the succession extends over units corresponding to three nappe systems.

In this contribution, we present a revised lithotectonic map of the Oberhof window. The core of the window is occupied by the middle-grained Late Ordovician “Oberhof orthogneiss” which is overlain by dolomite marble, both representing the easternmost outcrop of the Bundschuh Nappe. The overlying unit is composed of garnet bearing quartzite and garnet-chloritoid-bearing graphite schist. Commonly referred to as metasediments of Pennsylvanian age, their tectonic affiliation is still a matter of debate. These units are overthrusted by garnet-micaschist, amphibolite, hornblende-garbenschist, calc-micaschist, interpreted as the uppermost parts of the Koralpe-Wölz Nappe System. The uppermost units are comprised of micaschist, phyllite and quartzite corresponding to basal nappes of the Drauzug-Gurktal Nappe System. A unique feature compared to the rest of the Upper Austroalpine Unit is the reversed position of parts corresponding to the Koralpe-Wölz Nappe System overlying the Bundschuh Nappe.

From structural field observations and petrographic analysis of thin-sections we can distinguish four deformation events. The first one is preserved in relict isoclinal folds of quartz layers. It is postdated by ductile, top-to-the-E shearing, visible only in the upper parts of the section. The most dominant imprint all over the profile caused flattening and is represented by tight folds with E-W/SE-NW trending fold-axes. A corresponding axial plane schistosity is shallowly dipping to the N/NW. It becomes the dominant schistosity especially in the lower part and obscures the previous deformation events. As the latest deformation event at the brittle-ductile transition shallow eastwards dipping normal faults with top E/SE kinematics are identified. Biotite Rb/Sr ages varying around 75 Ma suggest a Late Cretaceous cooling and imply a maximum age for the latest brittle-ductile shearing event.

To constrain the metamorphic history, peak Temperatures are derived from Raman spectroscopy on the carbonaceous material, which vary around 520°C in the lower units. This indicates epidote-amphibolite facies peak conditions which is in accordance with P-T information gained from thermodynamic modelling using pseudosections. Based on petrographic observations the metamorphic grade decreases to middle greenschist facies conditions towards the higher structural part of the section. Microstructural relations allow correlation of the P-T path with the deformation events, proposing a tectono-metamorphic evolution history of this region.

Towards a new lithostratigraphic and tectonic model for the "Innsbruck Quartzphyllite Zone" within the Upper Austroalpine nappes (Oberpinzgau, Salzburg, Austria)

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The "Innsbruck Quartzphyllite Zone" (IQZ) extends over 80 km in Austria from Innsbruck (Tirol) in the west to Mittersill (Salzburg) in the east. Tectonically, the IQZ is bound (1) to the north by Eoalpine thrusts, in footwall position below the Höllengebirge-Staufen Nappe (Tirolic-Noric Nappe System, including the "Western Greywacke Zone"), (2) to the west by Eoalpine (Cretaceous) shear zones and faults, in a footwall position below the Ötztal-Bundschuh Nappe System and (3) to the south by a series of Neoalpine thrusts, in a hangingwall position above Penninic, Subpenninic and Lower Austroalpine nappes. These tectonic contacts have been partly overprinted or crosscut by Neogene faults triggered by the exhumation of the Tauern Window and the eastward extrusion of the Eastern Alps (Brenner-Silltal Fault System, Innsbruck-Salzburg-Amstetten Fault System and Salzach-Ennstal-Mariazell-Puchberg Fault System).

Lithologically, the IQZ is dominated by Paleozoic low-grade metamorphic siliciclastic sedimentary rocks intercalated with marble and mafic schist marker horizons as well as Ordovician orthogneisses and Permian metarhyolites. The peak mineral assemblages indicate greenschist facies metamorphic conditions. Additionally, garnet-bearing micaschist, paragneiss and orthogneiss are found as consistent rock assemblages in the hangingwall of the "Patscherkofel Crystalline Complex" (Ötztal-Bundschuh Nappe System), in the Tux Alps and in the vicinity of the Steinkogel, respectively in the western, central and eastern parts of the IQZ.

The internal lithologic and tectonic outline of the IQZ, as well as the correlation of its lower- and higher-grade parts to orogen-scale nappe systems, are still a matter of debate. Furthermore, the limited amount of mapping, structural, petrological and geochronological studies make any attempt for correlating and defining lithostratigraphic and/or tectonic units as well as understanding their deformation and metamorphism uncertain.

In this contribution, we present a new lithological map as well as new structural, petrological and geochronological data for the easternmost part of the IQZ (BMN-map sheet 121 Neukirchen am Großvenediger, Operpinzgau, Salzburg). This data allows us to propose a new lithostratigraphic and tectonic model. We distinguish the lower-grade Salzachgeier Nappe consisting of the Kröndlhorn Complex and the higher-grade Wildkogel Nappe consisting of the Steinkogel Complex. The latter corresponds to the previously defined "Steinkogelschiefer-Komplex", with a wider extent revealed by our new mapping. Stacking of these two nappes as well as the contact to the Höllengebirge-Staufen Nappe was controlled by top-to-the-WNW shearing, most likely during the Eoalpine event. In addition we discuss a new model with a possible correlation of the Salzachgeier and Wildkogel Nappes to orogen-scale nappe systems (Silvretta-Seckau, Koralpe-Wölz nappe systems). Our new model is still in development and has to be tested in the light of further field, geochronologic, petrological and structural studies.

Chloritoid-bearing phyllites of the Upper Austroalpine nappes: Are these rocks that low grade?

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Chloritoid is a common mineral of the Upper Austroalpine nappes. There, it is mostly found in Al- and Fe-rich phyllites and fine grained micaschists that are dominated by fine grained phyllosilicates, stained by graphite and/or oxides and deformed in the dissolution-precipitation creep regime. Chloritoid frequently occurs oblique to the main schistosity and is hence interpreted as a post-tectonic phase. For these reasons, the chloritoid from the Upper Austroalpine nappes has long been considered as a lower greenschist facies mineral that cannot be used for determining P-T conditions precisely.

In this contribution we present examples of chloritoid-bearing phyllites from the Schöckel Nappe (Hirschkogel Lithodem) and Gschnaidt Nappe (Raasberg Formation), both belonging to the "Graz Paleozoic", from the Bundschuh Nappe ("Carboniferous of Oberhof", Gurktal Alps) and from the Salzachgeier Nappe ("Innsbruck Quartzphyllite Zone", Kitzbühl Alps). Microstructural observations indicate that even if chloritoid overgrows the main schistosity, it is either parallel to it and often boudinaged, or oblique to it and folded or used as the cross-cutting element of flanking structures. Therefore, it cannot be considered as post-tectonic.

SEM observations combined with EMP analyses allow us to characterize the mineral chemistries, the phase relations and the prograde metamorphic reactions between chloritoid, white mica, chlorite, rutile, ilmenite as well as staurolite, garnet and biotite. Thermodynamic modelling and RSCM thermobarometry is used for determining the conditions of the observed equilibrium assemblages, showing that the chloritoid-white mica-chlorite assemblage without garnet and/or staurolite can theoretically be stable up to 550 °C. Our study also highlights the role of detrital ilmenite as an important Fe-source for chloritoid growth and the relevance of the bulk-rock chemistry for the nature of the prograde reactions. Metamorphic regional isogrades based on the occurrence of chloritoid, garnet and staurolite are therefore ambiguous even in the simple system of Al- and Fe-rich metapelites. We finally emphasize that chloritoid-bearing phyllites are good targets for determining P-T conditions with pseudosections in units lacking garnet.

Genesis of Permian pegmatites and spodumene bearing pegmatites during regional scale, high temperature/low pressure metamorphism in the Austroalpine unit

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Thousands of Permian pegmatites in the Austroalpine unit (Eastern Alps) form a more than 400 km wide pegmatite field. They formed during the Permian event that is characterised by lithospheric extension, causing crustal basaltic underplating, high temperature-low pressure metamorphism (HT-LP) and intense magmatic activity within the crust (Schuster and Stüwe, 2008). Fieldwork and detailed mapping revealed that Permian pegmatites are restricted to distinct complexes with typical lithological associations and petrological features. Three different domains can be distinguished. (1) In structurally lower parts, pegmatitic patches, narrow pegmatitic dykes and larger feldspar dominated pegmatites occur in aluminosilicate bearing, garnet-rich mica schists and paragneisses. Metamorphism in the surrounding mica schists and paragneisses indicate that during the Permian event this domain experienced upper-amphibolite facies metamorphic conditions (c. 0.4 GPa and 650°C; e.g. Stöckert, 1987; Habler and Thöni, 2001), corresponding to a depth of c. 15 km. (2) Structurally higher domains are characterized by frequent concordant barren pegmatites of several meters thickness. In some places (e.g. Martell valley, Uttenheim valley, Geißrücken near Judenburg) associated inhomogeneous leucogranitic bodies with pegmatitic and aplitic striae parts occur. (3) Higher evolved, spodumene bearing pegmatites are present as partly discordant dykes in the structurally uppermost levels. According to the presence of contemporaneously formed garnet in surrounding mica schists and paragneisses these pegmatites intruded in upper greenschist facies (~0.3 GPa at 500°C) crustal levels, corresponding to c. 10 km depth. Sm/Nd garnet ages on barren pegmatites are in the range of 247 to 288 Ma (e.g. Thöni and Miller, 2000). New age data on three spodumene pegmatites yielded 263±8, 265±3 and 268±2 Ma whereas for leucogranites ages of 259 to 287 Ma were determined. Magmatic muscovites from more than 450 samples of barren pegmatites, spodumene pegmatites and leucogranites as well as cm-sized single muscovite crystals from migmatic mica schist were investigated with respect to their chemical composition. With respect to the pegmatite classification diagrams of Černý and Burt (1984) muscovites from barren pegmatites and migmatitic mica schist mostly plot in fields of muscovite bearing (MSC) and muscovite barren (MSCB) pegmatite classes. Leucogranites plot together with higher evolved barren pegmatites, whereas spodumene pegmatites reach the fields of moderately evolved pegmatites. Even though the spodumene pegmatites are far away from highly fractionated pegmatites. All in all pegmatitic melts formed by regional anatexis during the Permian event. Melt accumulation and fractionation via crystallization of barren pegmatites and leucogranites lead to the formation of spodumene pegmatites. The quantification of Li enrichment from Al-rich metapelites to the pegmatite forming melt is going to be the topic of further investigations.

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Lithostratigraphy of Lower Miocene (Ottnangian-Karpathian) clastic-carbonatic shelf of south-eastern part of Central Parathetys, Formation Sirakovo (Drmno depression, Stig district, Serbia)

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Petroleum deposit «Sirakovo» is located 80 km east of Belgrade in Drmno depression, Stig District, Serbia. Petroleum system is in Lower Miocene, Ottnangian-Karphatian clastic and carbonate rocks deposed in south east part of Parathetys. According to general geotectonic zoning and setting in Europe, Formation Sirakovo belongs to the cover of Serbian-Macedonian Composite Terrane.

For this lithostratigraphic investigation are applied basic principles and procedures of classification, definition, nomination and special requests for establishing subsurface lithostratigrafic units.

The results of lithostratigraphical investigations are presented in the questionnaire of answers and with figures composed of descriptions, interpretations, graphics, diagrams, photos and citations.

The rank, name and code of unit is Formation Sirakovo, SirM1. Formation Sirakovo is a new informal unit (not yet adopted). Type locality and representative cores are saved and confidential because the exploitation of petroleum (oil and gas) deposit «Sirakovo» is still in progress.

In paper are described lithology, thickness and their variation, fossils, relationship&boundary criteria, and distinguishing&identifying features of the type locality. It is presented evidence of age and correlation with other units, general geologic description and aspects, regional geographic extension and geomorphological expressions. The major textures and structures are marked by graphic symbols and in photos. The geophysical and geochemical expressions are described and interpreted. The genesis, depositional environments and tectonic setting are explained and interpreted. On the end is presented comments, graphic documentation, photos and references.

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3-D Surface-wave tomography of the European Alpine lithosphere from ambient-noise and earthquake two-station measurements

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Some first order questions concerning the slab geometries at the junction between Adriatic, European and Pannonian domain are still open in spite of numerous geophysical attempts to image the deep part of the orogen. Different interpretations have been proposed to explain the along-strike transition of the Adriatic plate from its upper plate position in the Central Alps to its lower plate position in the Dinarides. This switch is inferred to involve slab break-off of the European plate allowing for the reversal of slab polarity below the Eastern Alps, where the Adriatic Plate would subduct below Europe after 30 Ma (Schmid et al., 2013; Handy et al., 2015). However, in these models that link the East-Alpine slab to the Adriatic plate, it is difficult to reconcile the length of > 250 km of the inferred slab to the amount of only 50 km of post-30 Ma shortening in the Adriatic plate (Eastern Southern Alps: Schönborn, 1999; Nussbaum, 2000).

We compile a dataset of surface-wave phase-velocity measurements using more than 25,000 station pairs around the European Alps, combining ambient-noise and earthquake-based two-station correlations. This allows us to constrain the structure from the shallow crust to 150 km depth. This shallow mantle zone is insufficiently resolved by body-wave tomography although it is crucial to our understanding of slab polarity and potential slab detachments in the Alps.

Both Love and Rayleigh waves are extracted from the data. We determine phase velocities from ambient noise in the frequency domain using an automated algorithm. In the best-sampled regions we achieve a lateral resolution of 20 km close to the surface. We create high-resolution images of sedimentary basins and the crustal thickness in the Alps and map the subduction slabs under the Alps, the Apennines and northern Dinarides.

Our models show a pronounced contrast between central Alpine mantle structures and the ones underneath eastern and western Alps. We infer that the European slab is detached both under the western and the eastern Alps. In the eastern Alps we argue that a deep slab is present below 150 km and that it is of European origin. Above this depth, in the area between 12° and 15° longitude our models show no clear signs of Adriatic subduction.

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Crustal structure at the contact of the northern Dinarides and southwestern Pannonian Basin from local earthquake tomography

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The aim of this research was to determine the crustal structures on the contact area of the northern Dinarides and the southwestern part of the Pannonian basin, based on the P-wave velocity model, obtained using the seismic tomography method. Events used in this study were recorded on 15 temporary seismic stations which were deployed in Croatia (in period November 2005 – May 2007) within the ALPASS-DIPS project and several Croatian and Slovenian permanent seismic stations. 12 temporary seismic stations within ALPASS-DIPS project were deployed along the Alp07 profile which was oriented nearly perpendicular to the Dinarides, 2 stations were situated in Istria and one was in the northern part of Croatia (Šumanovac et al., 2016). First arrivals from 70 earthquakes were used in analysis. The area of study is characterized with complex structures, so travel-time tomography technique was used to obtain a three-dimensional (3-D) velocity model. Detailed models can be provided using local earthquake tomography, but depth of model is limited with the maximum hypocentral depths. In the investigated area, hypocentres are located in the crust. The deepest earthquakes used in analysis, occurred at depth of 30 km. For inverse problem, in order to determine V_p, code designed to solve the coupled velocity-hypocentre problem in three-dimensional model subdivided into layers and nodes, which was provided by Kool et al. (2006), was used. The code provides implementation of the multistage fast-marching method for calculating arrival times and ray paths of multiple phases in complex layered media (Rawlinson and Sambridge, 2004a, b). The results obtained by local earthquake tomography were compared with 2D velocity model on the Alp07 profile based on active seismic refraction data and receiver functions (Šumanovac et al., 2009, 2016). The velocity model on the part of the profile which is sufficiently covered with seismic rays, is comparable with the model determined along the Alp07 profile. The shape of the Moho discontinuity is similar with the shape of the refraction model, but the Moho depths are 10 to 15 km larger. The greatest Moho depth of 45-50 km is under the Dinarides. The structure of the upper crust is characterized by strong lateral and vertical velocity changes. There is positive velocity anomaly (≈ 6 km/s) in Sava depression and negative velocity anomalies in the Karlovac (4.5-5.5 km/s) and Drava depression (≈ 5.5 km/s) areas. The discrepancy from the refraction model exists in Istria where smaller velocities were obtained with earthquake tomography method. In the lower crust, seismic velocities are in range 6.0-7.2 km/s with lower and more uniform velocities in the Pannonian crust.

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Differential uplift in the northernmost kink area of the Periadriatic fault system – a 4D kinematic model

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The Brenner Base Tunnel is a core infrastructure facility within the Scandinavian-Mediterranean Trans European Network railway corridor and is scheduled to be built between Innsbruck (N, Austria) and Fortezza (S, Italy) until 2026. Crossed Austroalpine nappes (N-S) are allocated to Silvretta-Seckau System, Ophiolite-bearing units (Penninic nappes) and Subpenninic nappes of Venediger Duplex and its hanging wall, the southernmost part cuts across Southern Alpine rocks. Amongst the entirety of pierced fault zones between separated tectonic units the overtilted Pustertal fault and the Maulsertal fault, each part of the Periadriatic fault system, provide a unique opportunity to examine differential vertical movement attributed to the intensely compressed transition zone between the northernmost Southern Alpine head and the southwestern Tauern Window.

Specification of regionally distinguishable relative uplift rates valid for fault-delimitated tectonic units along a set of sections will increase fundamental understanding of local tectonic history. Therefore, quantification of relative vertical movement within delimitable periods is derived from differential cooling rates of recent adjacent blocks. Subsurface samples have been collected in the course of Brenner Base Tunnel excavation. Cooling path modelling assembles three age-temperature pairs per sample: Zircon and Apatite fission track as well as (U-Th)/He analysis cover an adequate temperature range. Model-derived calculation of distinguishable relative uplift rates valid for fault-delimitated tectonic units is modelled considering compiled thermochronologic surface data published by several authors (Pomella et al., 2012, and citations therein) as well.

We are currently working on an enhancement of the geometric, tectonic and kinematic understanding of this very complex zone and aim for a refining of polyphase fault behaviour resolution and corresponding kinematics. Latest acquired ages show that expected results will represent a substantial spatial and chronological record of fault behaviour within the uppermost crust. All data will be visualised in terms of a 4D evolution model.

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Metamorphic gradients in the Adula nappe and their potential significance for the nappe's kinematic history

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The Adula nappe in the Central Alps is one of the Penninic units derived from the former European margin that experienced high-temperature (HT) and high- (HP) and even ultrahigh-pressure metamorphism during the Eocene. Petrological studies firmly established peak-pressure and -temperature gradients with increasing PT records in a southward direction, i.e. the direction of underthrusting. A major problem, especially concerning the pressure gradient, is that peak pressures, if converted into depth assuming realistic lithostatic gradients, give a greater former vertical extent of the nappe than its present horizontal length, although the nappe was even stretched horizontally upon exhumation by top-N shearing. Two end-member scenarios were proposed that potentially resolve this problem. Nagel (2008) proposed that the Adula nappe had a very steep subvertical orientation in the subduction zone and was exhumed from mantle depth into a top-N shear zone where several subnappes were sheared off to the north one after another. Such alternating ortho- and paragneiss-dominated subnappes can indeed be mapped out and substantiate a nappe-internal geometry of a foreland-dipping duplex. Pleuger and Podladchikov (2014) argued that peak pressures reported from the Adula nappe may have been reached at the base of thickenned orogenic crust and have a significant proportion of tectonic overpressure.

We present new data concerning the temperature gradient constrained by the very robust Zr-in-rutile method (Ferry and Watson, 2007) based on electron microprobe measurements on HP-HT eclogites. Samples collected from a north-south cross section along the nappe yielded a temperature gradient that is lower, but comparable to earlier studies (c. 3°C/km; c. 620 °C in the north to c. 750 °C in the south). We will combine these robust temperatures with the Raman-based SiO_2-inclusion in garnet barometry (Ashley et al., 2014) on the same sample set, to archive pressure estimates that are basically purely based on physics rather than an interpretation of domains of thermodynamical equilibrium.

If the northernmost sample, that is likely to preserve a Variscan metamorphic peak, is excluded, our data can be interpreted in terms of a steady north-south T gradient. On closer inspection, however, they may also give rather homogeneous peak-temperatures for each individual subnappe from which the eclogites were collected; c. 620 °C for the highest eclogite-bearing (Fanella) subnappe, c. 640 °C for the middle (Trescolmen) subnappe, and c. 740 °C for the lower subnappe. Thus, they may reveal the burial of these subnappes to different depths. In this case, the T gradient would only be an apparent one resulting from the particular nappe-internal geometry where structurally lower subnappes occur more to the south. This interpretation is compatible with the model of Nagel (2008) but needs to be supported by further temperature and pressure determinations, including Raman barometry of SiO_2 inclusions in garnet.

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The Alpine granitic rocks of the Western Carpathians: Petrology & tectonics

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The Western Carpathians as a part of the Neo-Europa form a piece of the extensive Alpine orogenic belt. Present-day structure of the Western Carpathians was derived from the Late Jurassic to Tertiary (Alpine) orogenic processes connected with the evolution of the Tethys Ocean, in a long mobile belt sandwiched between the stable North European Plate and continental fragments of the African origin. The Alpine orogeny has produced granitic rocks during the Late Cretaceous (Eo-Alpine) and the Miocene (Late-Alpine) periods in the Western Carpathians. Two different types of granite rocks have originated due to different geodynamic conditions and/or melting of diverse rock sources. The Late Cretaceous – Rochovce granitic body is located in the contact zone between two principal tectonic units Veporicum and Gemericum. The Rochovce granites (RG) are formed by two intrusive phases: ***1st*** – coarse-grained biotite monzogranites with the pink K-feldspars phenocrysts, locally with mafic microgranular enclaves, and granite porphyries, generally resembling banatites; ***2nd*** more evolved type is representing by medium- to fine-grained biotite leucogranites and leuco-porphyries. The RG have normal to elevated SiO_2 = 66 ~ 77 wt. %, typical calc-alkaline, subaluminous to peraluminous character ASI = 0.9 ~ 1.4, high concentrations of Ba, Rb, Li, Cs, Mo, Nb, Y, V, W, Cr, F, Th, U and low concentrations of Sr, Zr and Be. The low I_{Sr} = 0.708 ~ 0.713, together with negative epsilon $Nd_{(i)}$ = -3.0 ~ -2.4, zircon, epsilon$Hf_{(i)}$ = -5.2 ~ +0.2, and stable isotopes delta^{18}O = 8.0 ~ 8.3‰; delta^{34}S = -2.1‰; delta^{7}Li = 4.7‰ suggest a lower crustal meta-igneous protolith. Their Cretaceous magmatic age 81.5 Ma was proved by SHRIMP zircon U-Th-Pb and Re-Os molybdenite dating (Kohút et al., 2013). The Miocene calk-alkaline granitic rocks are presented only in the Central Slovakian Neovolcanic field (CSNF). The massive granodiorites consist of intermediate plagioclase, quartz, K-feldspar, biotite, amphibole, and accessory magnetite, titanite, pyroxene, apatite and zircon. The rock's texture is evengrained and porphyric in marginal parts, locally with mafic microgranular enclaves. The granitic rocks are often altered – sericitized, chloritized and propylitized. These granodiorites have standard values of SiO_2 = 59 ~ 66 wt.%, higher contents of CaO, FeO, MgO and lower content of TiO_2. Generally, they have enriched Ba, Cr, V and F, whereas values of Sr, Rb and Zr are standard compared to other Western Carpathians granites. The initial Sr values of 0.706 ~ 0.710 and/or isotopic characteristics of CSNF en bloc suggest a lower crustal source affected by the lithospheric mantle and its I-type character. New SHRIMP zircon and ZHe & AHe dating proved their age at 13 Ma (Kohút and Danišík 2017). The Cretaceous Rochovce granites with typical Mo-W mineralization are unique in the Western Carpathians and represent the northernmost continuation of mineralization associated with the Cretaceous calc-alkaline magmatism within the Alpine-Balkan-Carpathians-Dinaride metallogenic belt. Crustal thickening together with some heat input from the mantle triggered partial melting and generation of RG in the lower crust. During the middle Cretaceous, shortening and crustal stacking continued and prograded outwards. Shortening in the rear of the Veporic wedge triggered its exhumation and orogen-parallel extension. During the final stages of exhumation, the RG were emplaced into the extensional shear zones. The Neogene evolution of the Carpathian-Pannonian area was controlled by gravity driven subduction of lithosphere under the Outer Carpathians flysch basins with the arc-type magmatism. The rapid exhumation rate of the CSNF granitic rocks (5 mm/yr) was related to active tectonism at 13 Ma, and the extreme cooling rates (678 ± 158 °C/Myr) may have resulted from the cessation of volcanic activity.

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Conodont zonation of the Lower Triassic strata in the Dinarides

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Conodont research in the Dinarides started back in the sixties, during the time of the elaboration of the Basic Geologic Map of Yugoslavia 1: 100.000 and was carried out by the team of the Federal Geological Survey in Belgrade. The first significant Early Triassic conodont fauna was collected from the Smithian *Parachirognathus / Furnishius* zone in sections in Slovenia and Serbia. In the following decades intensive conodont research of the lowermost Lower Triassic successions contributed to the definition of the Permian-Triassic boundary interval, first in Slovenia, and later in the broader area of the Dinarides of Croatia and Serbia.

Conodonts were recovered from Lower Triassic marine sedimentary rocks in the area of Slovenia, Croatia, Bosnia and Herzegovina, Serbia and Montenegro. The Permian-Triassic boundary interval containing conodonts is preserved only in the Idrija-Žiri area in Slovenia. The Lukač section near Žiri in the External Dinarides represents a key section to define the PTB interval strata in Slovenia due to the presence of the conodont species *H. parvus* which is used as a marker according to an international criterion of the IUGS. Therefore it is taken also as a standard for conodont zonation for the entire Dinarides.

A succession of seventeen conodont zones can be identified in the Lower Triassic strata of the Dinarides: *H. parvus* Z., *Isarcicella lobata* Z., *I. staeschei – I. isarcica* Z., *H. postparvus* Z., *Hadrodontina aequabilis* Z.*, Ha. anceps* Z., *Eurygnathodus costatus* Z., *Neospathodus planus* Z., *N. robustus* Z., *Platyvillosus corniger* Z., *Pl. regularis* Z., *Pachycladina obliqua* Z., *Foliella gardeane* Z., *Triassospathodus hungaricus* Z., *T. symmetricus* Z.*, N. robustispinus - T. homeri* Z. and *T. triangularis* Z.

Certain Early Triassic faunas in the Dinarides show very low diversity marked by shallow water and/or euryhaline genera (i.e. *Hadrodontina, Pachycladina*) that are an important regional biostratigraphic tool in the western Tethys, whereas some other taxa have a limited geographic distribution confined to the European sections (*Foliella, Platyvillosus*), which suggests they were ecologically restricted and probably adapted to shallow water environments. Most Dienerian and Smithian conodont faunas recovered in the Dinarides markedly differ from the contemporaneous conodont faunas of North America and Asia.

The introduced Early Triassic conodont zonation of the Dinarides can be applied also to the shallow shelf environments of the western Tethys.

A reinterpretation of the geological map of northwestern part of the Lece Volcanic Complex

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The Lece Volcanic Complex (LVC) is the second large volcanic province in Serbia. It is located along the contact between the Serbo-Macedonian Mass (east) and the Vardar Zone (west). The LVC is predominantly composed of andesite volcanic and volcaniclastic rocks.

The studied area is located in northwestern part of the LVC, 12 km south from Kuršumlija. Actually, it encompasses a roughly E-W oriented section from Brankova Kula, through Rudare up to Prolom Banja. On the Basic Geological Map 1:100000 – Sheet Kuršumlija, Malešević et al. (1974) interpreted the volcanic succession in this area as multiple interlayers of lava flows and pyroclastic material and recognized two petrographic types of the lava flow facies: amphibole and amphibole-pyroxene andesite. Our volcanological observations revealed the presence of the same petrographic varieties, however, we found evidence of different relationships between the occurring volcanic facies. First, we argue that all non-coherent volcanic rocks in this area belong to various volcaniclastic deposits, because we did not find *in situ* pyroclastic deposits. In general, we distinguish two volcanic events during which this part of the LVC formed. During the first event emplaced amphibole andesites, most likely as coherent and autoclastic lava flow facies, which underwent reworking and redeposition soon after eruption. This is shown by several outcrops from Brankova kula to Rudare, which display numerous characteristics of debris flow and, subordinately, debris avalanche deposits. The U-Pb zircon age of this rock is 33.56 Ma. These volcaniclastic rocks sometimes contain meter- to tens of meter large blocks of coherent volcanic rocks, which, most likely, were misinterpreted as continuous lava flow facies during the mapping in the seventies. These volcaniclastic facies are overlain by the products of the second event represented by hornblende-pyroxene andesite. These rocks emplaced as coherent or autobrecciated lavas and rarely as redeposited volcaniclastic deposits. A shallow dyke-like intrusion of these lavas, which exhibits impressive columnar jointing, is exposed at Brankova Kula, where it apparently cuts into the volcanic pile of hornblende andesites produced during the first event. The hornblende-pyroxene andesite is also dated on zircons with U-Pb method and it revealed an age of 32.67 Ma.

This new volcanological information allows for establishing a new interpretation of the field relationships of volcanic facies in this part of the LVC. It may help in better understanding the evolution of the entire complex, with special regards on the succession of events that ultimately led to caldera formation. Moreover, this study argues that there is a growing need for revisiting other Serbian Cenozoic provinces and for better understanding the true nature of their volcanic facies.

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Structural characteristics of Supragetic basement (Serbian Carpathians, eastern Serbia): preliminary results and implications for late Early Cretaceous nappe-stacking

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Supragetic is one of the highest nappes of the Dacia mega-unit in South Carpathians and Serbian Carpathians (Schmid et al., 2008). Structural characteristics of Supragetic metamorphic basement in eastern Serbia are not well constrained. Here, we present preliminary results of the structural analysis of Supragetic basement at map-, outcrop-, and thin section-scale, between Danube and Pek rivers.

Low grade metamorphic basement of the lower Supragetic unit (sensu Kräutner and Krstić, 2002) in studied area includes various volcano-sedimentary rocks with protolith age interpreted as Ordovician-Silurian (Iancu et al., 2005). Mineral assemblages of the two studied sequences imply low greenschist metamorphism with temperatures reaching 300-350˚C and pressure reaching 0.3-0.5 GPa. Under these conditions quartz and albite demonstrate dominantly bulging and locally subgrain rotation recrystallisation, while chlorite, sericite and muscovite define spaced to continuous foliation recognized both at outcrop- and thin section-scale. Statistical analysis based on the data collected during geological mapping in the area (Kalenić and Hadži-Vuković, 1973) shows low to high angle west-dipping foliation. This can be interpreted either as east-vergent tight to isoclinal folding, or as ramp-flat internal geometry of Supragetic basement. At thin-section scale C' planes cutting previously recognized foliation and forming C'-S structures were indentified, demonstrating top to ESE reverse tectonic transport, especially in the lower of the two studied metamorphic sequences. Both S and C' planes are deformed by younger reverse kinking recognized both at outcrop- and thin section-scale. Those kink bands are results of ESE-WNW compression and could represent the later stage of continuous deformation event during which C'-S structures formed. The youngest, brittle, deformation is represented by subvertical joints with no offset recognized in thin-sections.

Structural characteristics of Supragetic low grade metamorphic basement in the studied area combined with tectonothermal events recognized elsewhere in Dacia mega-unit (Gröger et al., 2013; Antić et al., 2015, and references therein) could imply possible initiation of late Early Cretaceous nappe-stacking in ductile to semi-ductile/semi-brittle domain. However, further research is needed to better constrain the age of deformations presented in this study.

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Permian high-temperature metamorphism in the Western Alps (NW Italy)

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Following the Variscan orogeny the Adriatic margin underwent lithospheric thinning accompanied by asthenospheric upwelling, causing a high thermal regime within the continental crust. This produced high-temperature, low- to medium-pressure metamorphism and partial melting in the lower crust as well as extensive magmatic activity affecting all crustal levels.

Evidence for a late Palaeozoic regional metamorphic imprint is extensively recorded and well established in the Southern Alps and in Austroalpine units of the Eastern Alps. In the Western Alps, Permian metamorphism has been repeatedly inferred for Adria-derived units, but the age of this metamorphism has been established in very few locations. The present study fills this gap. Our focus lies on the Sesia Zone (EMC, 2DK), Dent Blanche nappe (Valpelline Series) and the Mt. Emilius Klippe. The 2DK and Valpelline Series preserve mainly Permian metamorphic assemblages, their Alpine metamorphic imprint is minor, whereas EMC and Mt. Emilius Klippe show a strong, pervasive Alpine high-pressure overprint preserving only relics of pre-Alpine metamorphism.

An extensive dataset of U-Pb ages for metamorphic zircon is presented. Age data are complemented by *P–T* estimates for this metamorphism, based on mineral thermometry (Ti-in-Zrn, Zr-in-Rt) and *P–T*-information derived from mineral assemblages. Clastic metasediments (mostly metapelites) were investigated to ensure sufficient amounts of zircon and to facilitate comparisons within the dataset.

The studied zircons show discrete growth zones with textural features typical of metamorphic growth. Those related to Permian metamorphism define an age range between 286 and 266 Ma. Ti-in-Zrn-thermometry yields temperatures between 580–890 °C, whereas Zr-in-Rt temperatures are slightly higher, 630–850 °C. Taken together with preserved mineral assemblages (Grt + prismatic Sill + Bt + Pl + Qz + Kfs + Rt + Zrn + Fe-Ti oxides) these temperature estimates suggest upper-amphibolite to granulite facies conditions for the Permian metamorphism. Kyanite is absent in the mineral assemblages, and cordierite formed on retrogression; these observations indicate a pressure range between 0.5–1.1 GPa.

The data presented show that Permian high-temperature metamorphism is abundant and widely distributed also in the Western Alps, in units derived from the Adriatic margin. U-Pb-ages from this study are similar to Permian ages reported for the Ivrea Zone in the Southern Alps and Austroalpine units in the Central and Eastern Alps.

Western Vardar zone, Danubicum and Timok magmatic complex (Serbia): Coordinated or independent CW rotation

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The Vardar zone which is a wide megasuture between the Eurasian and Gondwana margins comprises remnants of the oceanic lithosphere (ophiolite and ophiolitic mélange), distal parts of the ancient Gondwana margin (the Drina–Ivanjica and the Jadar-Kopaonik units) and the sedimentary and igneous representatives of post-closing times. The Timok magmatic complex and the Danubicum are situated east of the Vardar zone, in the Carpatho-Balkanides. The Danubicum is built up of the Neoproterozoic basement, Palaeozoic rocks and Carboniferous to Late Cretaceous cover sediments and is considered by some as autochtonous and by others as a nappe system. The Late Cretaceous volcano-sedimentary Timok magmatic complex belongs to the Getic nappe system.

We studied the paleomagnetism of a large number of samples drilled and oriented in situ from 38 localities/sites of Late Cretaceous sediments representing an overstep sequence and Oligocene–Early Miocene igneous rocks from the Western Vardar zone, 8 localities of Late Jurassic and Early Cretaceous limestones from the Danubicum, and 13 localities/sites of Late Cretaceous sedimentary and igneous rocks from the Timok magmatic complex. After measuring the natural remanent magnetisation and the anisotropy of the magnetic susceptibility, the samples were subjected to standard paleomagnetic measurements and demagnetizations. The demagnetization curves were analysed for linear segments which were used for statistical evaluation on locality/site level. When applicable the fold/tilt test on locality and regional level was carried out.

The obtained results from the studied areas of the Western Vardar zone (Kopaonik, Rudnik and Struganik areas) point to about 30°CW uniform rotation in post-Early Miocene time. The Timok magmatic complex is characterised by about 25°CW rotation, which must have taken place after the Late Cretaceous. Our results from the Danubicum are clearly of post folding age, similarly to those obtained for the same tectonic unit on the Romanian side of river Danube (Panaiotu et al., 2012). The results from both sides of the Danube river are consistent and indicate about 65°CW rotation.

The CW rotations are clearly of regional significance and affect different tectonic units, possibly simultaneously. Based on the upper K/Ar age limit for the igneous rocks, still exhibiting rotation, the most likely time is after 20Ma. The significantly larger CW rotation in the Danubicum than further in the West can be explained by repeated CW rotations after the Early Cretaceous or by oroclinal bending around the Moesian platform.

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Application of the Ti-in-Bt-Geothermometer to regional and contact metamorphic rocks of the Motajica-Inselberg, northern Bosnia and Hercegovina

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The oceanic suture of the Sava Zone between the Adriatic and European plates hosts numerous metamorphic core complexes that were exhumed in the Late Oligocene to Middle Miocene, concomitant with the opening of the northerly adjacent Pannonian Basin. One of the best studied of these core complexes is the Motajica Inselberg in northern Bosnia and Hercegovina. The exposed part of the Motajica metamorphic core complex (MCC) is part of a much larger E-W-striking and N-dipping extensional low-angle detachment, which forms the structural bottom of a supra-detachment basin with up to several km of Early Miocene to Pliocene syn- to postrift sediments in the Sava Depression. The low-angle detachment that exposes the MCC initiated in Maastrichtian times as a suturing thrust between Adria-derived units in the footwall and European-derived units (Tisza-Dacia) in the hangingwall, sandwiching remnants of Neotethys oceanic lithosphere and trench fill sediments.

The Motajica MCC is composed of a central granitoid (26.72 ± 0.1 Ma), enveloped by regionally metamorphosed rocks up to amphibolite-grade conditions (amphibolites, mica schists and paragneisses). Up-section, these rocks are overlain by greenschist-facies phyllites. Metamorphism in the envelope is related to suturing between Adria and Europe in the Maastrichtian and clearly predates emplacement of the central granitoid. The pluton created a hitherto ill-defined contact metamorphic aureole. Mineral assemblages observed in the dominantly metapelitic envelope provide an excellent target to investigate the applicability of the Ti-in-Bt mineral thermometer of Henry et al. (2005) in terms of its sensitivity to regional and contact metamorphism.

The Ti-in-Bt-geothermometer of Henry et al. (2005) is based on the relationship between the Ti-content and the χ_{Mg}-value (Mg/(Mg+Fe)) of biotite. For a specific χ_{Mg}, the Ti-content increases as a function of temperature and decreases with increasing χ_{Mg}. The geothermometer is calibrated for peraluminous metapelites containing additional Ti-phases such as ilmenite or rutile that equilibrated at 4-6 kbar.

The composition of biotites from the metamorphic envelope in Motajica was determined by EMPA and temperature estimates were subsequently obtained following the method of Henry et al. (2005). In combination with the overall mineral assemblages and micro-textural criteria of each sample, two metamorphic imprints were distinguished: (1) regional metamorphism of up to T ≈ 650°C for the amphibolite-facies rocks with the occurrence of garnet and (2) contact metamorphism related to the intrusion of the pluton. The contact metamorphic overprint is indicated by temperatures of 650°C for a phyllite sample adjacent to the pluton, whereas a temperature of 550°C was obtained for a phyllite located structurally 500 m above the pluton. These observations hence suggest a strongly elevated temperature gradient of about 200°C/km in the contact aureole enwrapping the pluton. This temperature gradient was very likely 'telescoped' by vertical shortening related to the buoyancy-driven emplacement of the pluton, concomitant with unroofing along the extensional detachment. Numerous magmatic dikes that were emplaced into the metamorphic envelope and later deformed provide independent evidence for the synchronicity of extensional unroofing and igneous activity.

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New constraints for the tectono-metamorphic evolution of Zermatt-Saas Zone, Western Alps

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Multiscale structural analysis and detailed mapping (1:20 scale) integrated with petrological investigation was applied to Zermatt-Saas serpentinites outcropping in upper Valtournenche, Zermatt-Saas Zone (Italy). The analysis resulted into a map with foliation trajectories that allowed recognizing the transposed original litostratigraphy of serpentinites comprising magnetite layers and rare, decimeter-thick, pyroxenite layers. Locally veins of Ti-clinohumite, layers and lenses of dunites, veins of olivine, and layers of dark clinopyroxenes are embedded in serpentinites. Serpentinites record three stages of ductile deformation: D1 consists of rare folds and S1 foliation; D2 produced isoclinal folds and a very pervasive foliation (S2) that is the dominant structure; D3 includes crenulation and shear zones affecting S2. The meso- and micro-structural observations revealed that the structural evolution is equivalent to that proposed by Rebay et al. (2012) with the addition of pre-D2 paragenesis. Dark clinopyroxene layers are interpreted as evolved melt percolations in oceanic lithosphere such as gabbro veins (Rebay et al., 2017) as also suggested by the augitic core. The oceanic/metasomatic evolution of the serpentinites is also suggested by the proximity of gabbro bodies and rodingite dykes (Zanoni et al., 2016 and refs. therein). The microstructural analysis supported by extreme detailed structural survey allowed to clearly define pre-D2 mineralogical and textural relicts that are preserved regardless the pervasive S2 HP-UHP foliation. Pre-D2 parageneses, in serpentinites, dunites and clinopyroxene layers, allow to better constrain metamorphic conditions predating D2 for Valtournenche serpentinites. Furthermore the P-T conditions for D2 are similar to those of the surrounding serpentinites (Rebay et al., 2012) that were dated at 65 ± 5.6 Ma (Rebay et al., 2017). These results, coupled with P-T peak condition proposed in this work, lead to consider that the ZSZ was already buried at depth before 70 Ma and dramatically widen the time span under which ZSZ recorded P-T peak conditions. Such observations support the idea that ZSZ is a mosaic of ophiolitic tectono-metamorphic units, recording P-peak conditions in different times (Mahlen et al., 2006; Skora et al., 2015; Rubatto et al., 1998, and references therein), and that were coupled during Alpine exhumation.

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Formation of ophiolite-bearing tectono-sedimentary mélanges in the Alpine-type mountain belts: Insights from analogue models and the Apenninic Casanova mélange case study

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Orogenic wedges locally present chaotic tectonostratigraphic units that contain exotic blocks of various size, origin, age and lithology, embedded in a sedimentary matrix. The occurrence of ophiolitic blocks, sometimes huge, in such “mélanges" raises questions on i) the mechanisms responsible for the incorporation of oceanic basement rocks into an accretionary wedge and ii) the mechanisms allowing exhumation and redeposition of these exotic elements in “mélanges" during wedge growth.

To address these questions, we present the results of a series of analog experiments performed to characterize the processes and parameters responsible for accretion, exhumation and tectonosedimentary reworking of oceanic basement lithospheric fragments in an accretionary wedge.

The experimental setup is designed to simulate the interaction between tectonics, erosion and sedimentation. Different configurations are applied to study the impact of various parameters, such as irregular oceanic floor due to structural inheritance, or the presence of layers with contrasted rheology that can affect deformation partitioning in the wedge (frontal accretion vs basal accretion) influencing its growth (Fig. 1). Image correlation technique allows extracting instantaneous velocity field and tracking of passive particles. Using the particle paths determined on models the pressure-temperature path of mélange units or elementary blocks can be discussed.

The experimental results are then compared with field study and Raman spectroscopy of carbonaceous material (RSCM) observations from the ophiolite-bearing mélange in the northern Apennines (Casanova mélange). A geological scenario is proposed following basic observations (Fig. 2). The tectonic evolution of the retroside of doubly vergent accretionary wedges is mainly controlled by backthrusting and backfolding. The retro wedge is characterized by steep slopes that are prone to gravitational instabilities. It triggers submarine landslides inducing huge mass transfers. This erosion combined with backthrusting could favour exhumation of the ophiolitic fragments formerly accreted at the base of the wedge along the rough seafloor-sediments interface. Such an exhumed material can be reworked and deposited as debris-flows in proximal basins located at the foot of the retrowedge slope forming a tectono-sedimentary mélange. These syntectonic basins are continuously deformed and involved in prograding backthrusting-induced deformation.

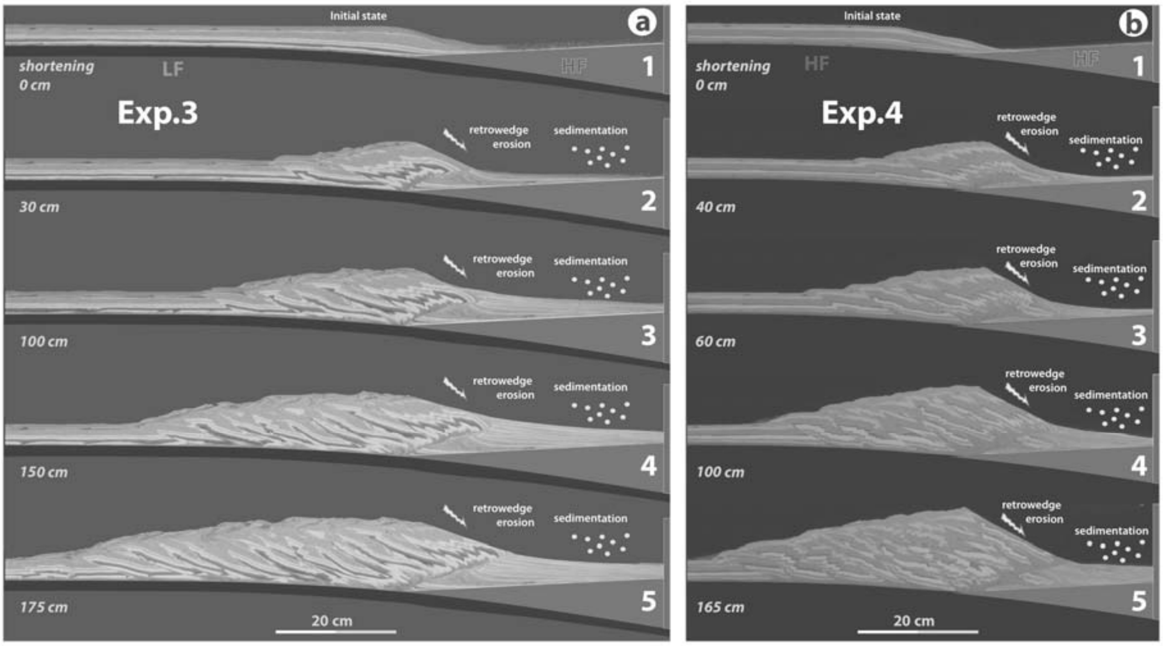

Figure 1: Evolutionary stages of experiments 3 and 4 outlining the impact of basal friction on wedge dynamics and exhumation.

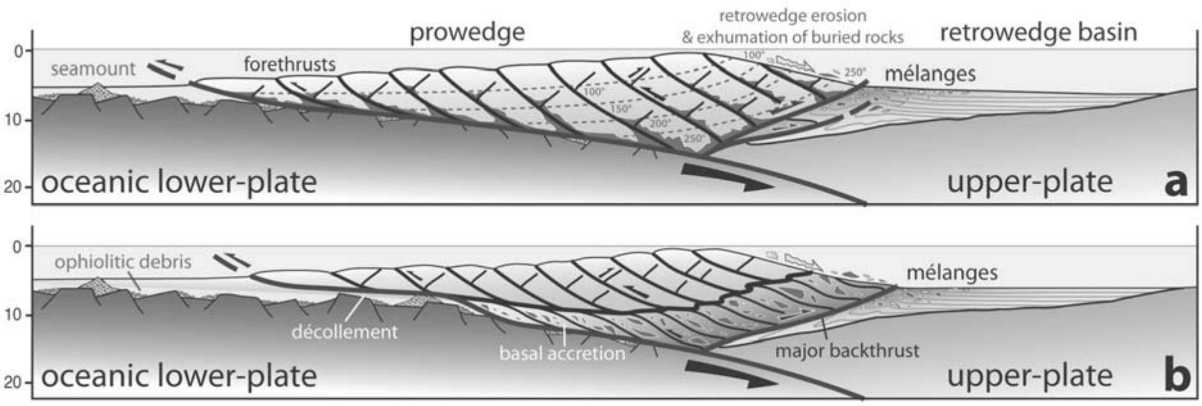

Figure 2: Cartoon illustrating the proposed model for exhumation and redeposition of ophiolitic debris and wedge rocks as tectonosedimentary mélanges in the retrowedge setting. Major backthrusting and gravity driven submarine erosion allows exhumation and deposition of exotic blocks in the syn-tectonic retrowedge basin. a) First setting, the wedge grows by frontal accretion of imbricated thrust units. The red dotted lines suggest the shape of isotherms registered by peak temperature thermometry. b) Second setting, deformation partitioning occurs, the wedge grows by frontal accretion and basal accretion at depth.

Timing of detachment of continental slices from the downgoing slab in a subduction zone

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In the Gran Paradiso Massif (Western Alps), the Money Unit crops out as a tectonic window below the Gran Paradiso Unit. In both units, four stages of deformation and metamorphism have been identified (Manzotti et al. 2015). Stage 1 reflects the phase of continental crust subduction (~18-20 kbar, 480-520 °C and ~13-18 kbar, 500-530 °C for the Gran Paradiso and the Money units, respectively). This yields a maximum difference of ~20 km in the depth reached by these two units during the early Alpine history. Thrusting of the Gran Paradiso Unit over the Money Unit (stage 2) led to the development of the main foliation (~12.5 kbar-14.5 kbar and 530-560 °C), identical in both units. The thrust contact was folded during stage 3 together with the entire Money Unit, and then both units were exhumed together (stage 4). Accessory phases (i.e. monazite, allanite, and xenotime) have been studied in key samples from the Money and Gran Paradiso Units. Their relative timing of growth and dissolution have been assessed by combining thermodynamic modelling, inclusion, textural and chemical (major and trace-element) data from both major and accessory phases. (U-Th-Pb) ages of allanite, monazite, and xenotime will be presented and tied with the evolution of the studied samples. The new data constrain (i) the age of the high pressure in the Money and the Gran Paradiso Units, (ii) the timing of the thrusting of the Gran Paradiso Unit over the lower pressure Money Unit and (iii) the exhumation rates in the Gran Paradiso Massif. Preliminary data indicate at most 3 to 5 Ma between the peak pressure (stage 1) and the thrusting event (stage 2), i.e. a displacement of the order of 2 to 4 mm/year.

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Inconsistent tectonic trends, consistent paleomagnetic directions: An example from External Dinarides

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The Central Dalmatian islands between Split and Dubrovnik are of special interest, since their orientations and structural trends are WNW-ESE, instead of the general NW-SE Dinaric trend. For this reason we made an extensive paleomagnetic study on more than 600 oriented cores from 43 localities. The samples represent shallow-water platform carbonates of Lower Cretaceous through Campanian in age from Mljet, Korčula and Hvar islands and also Upper Jurassic age from Mljet island. Hand samples were taken for a biostratigraphic determination from the sampled beds in the outcrops. Based on the stratigraphic ages a Campanian – Santonian (only Hvar island), a Cenomanian – Turonian (all islands), an Aptian – Albian plus a Tithonian – Barremian (Mljet and Korčula islands) paleomagnetic overall mean directions could be defined. For the first two groups, positive tilt test constrained the age of the magnetisations as of pretilting age, for the last two the tilt test is indeterminate. Earlier published coeval paleomagnetic directions from the Northern Adriatic islands and Vis (Márton et al., 2014) suggest exactly the same magnitude of CCW rotation as the islands of the present study, at least from the Cenomanian on. Thus, the above-mentioned difference in tectonic trends can not be attributed to differential mass rotations but considered e.g. as the consequence of deformations at different times (Korbar, 2009).

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Permian through Paleogene northward shift, CW and subsequent CCW rotations affecting the Hronic Nappe system of the Central Western Carpathians in the Nízke Tatry Mts

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The Hronic units form the highest cover nappe system of the Central Western Carpathians which was emplaced over the Fatric nappe system during the Late Cretaceous. The pre-Late Cretaceous rocks were affected only by diagenetic or very low-grade, burial-related recrystallization and were tilted and transported together. The Hronic nappes are overlapped by Paleogene sediments.

Earlier obtained paleomagnetic results from Permian red beds and paleobasalts from the Hronicum indicated large rotations of uncertain sense (Krs et al., 1982). We started a new project with the aim to give a definite answer to this dilemma. In this paper, we are presenting new results, not only from the Permian but also from the Triassic of the largest outcropping areas of the Hronicum, the Nízke Tatry Mts.

Three laboratories (Bratislava, Budapest and Warsaw) were involved in standard paleomagnetic processing and AMS measurements of the samples, while Curie-points were determined in Budapest. The site/locality mean paleomagnetic directions obtained were significantly different from the local direction of the present Earth magnetic field, indicating the long term stability of the paleomagnetic signal.

The new results suggest that the Hronicum must have travelled from near-equatorial position (Late Permian) to around 20°N (Middle-Late Triassic) while rotating in the CW sense. Additional CW rotation must have happened during nappe emplacement. Finally, the area rotated CCW during the Miocene, as the Paleogene cover sequence of the Hronic units, close to the Nízke Tatry (present study) as well as further to the north and east (Márton et al., 2009) exhibit large CCW rotations.

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Paleomagnetically indicated rotations in the Sava Zone and in the active European continental margin, Belgrade area

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This paper presents new paleomagnetic results from Upper Cretaceous to Oligocene rock sequence located in the wider Belgrade area (Northern Šumadija). The area belongs to the suture between units of Adriatic and European affinities, which originated from the closure of the Neotethys Ocean during Cretaceous to Paleogene (the Sava Zone, sensu Schmid et al., 2008). After the early Paleogene continental collision, the entire area underwent post-orogenic deformations, namely extension in the Miocene and inversion during the latest Neogene–Quaternary (Bada et al., 2007). In the study area, a complex reverse fault, the Bela Reka fault (BRF) separates the Upper Cretaceous to Paleogene Sava turbidites in the footwall from the Europe derived for-arc contents of the hanging wall (Toljić et al., submitted). The paleomagnetic samples were collected in Upper Cretaceous deposits from both footwall and the hanging wall units, while the Oligocene sites exclusively belong to the latter.

During two short field campaigns (2016 and 2017) we collected a total of 230 oriented samples from 13 Upper Cretaceous localities, one Upper Cretaceous (?) and five Oligocene dykes. The samples were drilled in the field, oriented with magnetic/sun compass, cut into standard-size specimens and subjected to standard paleomagnetic measurements, including AMS and demagnetizations. Results from the hanging wall suggest about 30° CW rotation, after the intrusion of the dykes. Those from the Sava zone, all representing turbidites, are definitely of post-tilting age, yet are far from exhibiting consistent rotations. The angles mostly vary between 38°CCW and 31°CW. The geographical distribution of the localities with different senses and magnitudes of rotations do not show a pattern. CW rotated localities from the Sava zone are probably remagnetized during the intrusion of the Oligocene quartz latite. Localities exhibiting CCW rotation have composite remanences, suggesting that CCW rotations could have taken place in the Sava zone before the general CW rotation affecting both the foot and the hanging walls. The CCW rotation can be associated tentatively with the phase of contraction and thrusting in the NE Dinarides (e.g. Djoković, 1985). The subsequent post-Oligocene CW rotation in the Belgrade area can be correlated with the rotations observed in the West Vardar zone, which was documented further south in Rudnik and Kopaonik Mts (Lesić et al., 2017). This suggests that during Neogene the entire northern segment of the Adria-Europe suture underwent rotations in the CW sense following the process of oroclinal bending of the South Carpathian–Balkan mountain belt around the Moesian promontory.

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High-pressure micaschist as indicator of an exhumation channel between colliding continental plates

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Eclogite and blueschist are the metamorphic rock types that are typically used to define high-pressure (HP: ≥10 kbar) units (or terranes). The occurrence of such a unit in an orogenic belt is related to a suture that resulted from subduction of oceanic crust and subsequent collision of continental plates. This long-lasting collisional process has led to numerous Alpine-type belts in Phanerozoic times. Frequently, eclogite and blueschist (of true mafic protoliths) occur only as small bodies in country rocks (= felsic metamorphic rocks). Thus, the question arises if the country rocks experienced a similar metamorphic evolution as the metamafic ones. An answer is very rarely given, but the assumption of extended HP if not even ultrahigh pressure (UHP: ≥30 kbar) terranes with dominating felsic country rocks and little metamafics seems to prevail in the recent literature. As a consequence of such assumptions, deep subduction of continental crust is favoured at the moment.

Important rock types of the aforementioned HP terranes are metapelite and metapsammite representing former relatively immature clastic sediments deposited at continental margins. It can be demonstrated by thermodynamic calculations, resulting in pressure(P)-temperature(T) pseudo-sections, that an average sediment of this type is metamorphosed at medium T (500-550 °C) and P of 10-15 kbar to a micaschist containing (besides quartz and albite) considerable amounts of potassic white-mica (30±10 vol%) with Si contents around 3.3 per formula unit and almandine-rich garnet (5-10 vol%) but virtually no biotite. Such simple characteristics can help the geologist to recognise such type of HP rock already before further detailed studies. The evaluation of chemically zoned garnet leads then to clockwise P-T loops characterised by a slight temperature increase during early exhumation (T peak at 6-10 kbar; e.g., Massonne and Toulkeridis, 2012; Massonne, 2016a). Accessory monazite, which can be easily dated with the electron microprobe, is a common phase in such rocks and, thus, can contribute to the understanding of the timing of the metamorphic processes.

The geodynamic scenario that caused the formation of the HP micaschist is probably the following (e.g., Massonne, 2016b): At the beginning of a continent-continent collision, the sediments at the continental margins are buried to depths of 35-50 km (10-15 kbar) where they are involved in a subhorizontal channel flow (exhumation channel) resulting in long-lasting exhumation along the top of the downgoing continental slab with opposite direction compared to the movement of this slab. A major reason for the development of the exhumation channel is the high H_2O-release capacity (Massonne, 2016b) of the involved sediments. The occurrence of small eclogite bodies, that have experienced much higher pressures during subduction than the metasediments in the exhumation channel, is due to their involvement in a subduction channel which brings rocks from the subduction zone into the exhumation channel. Thus, pressures derived from rocks exhumed in the subduction channel cannot be taken as being relevant for the downgoing continental slab.

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Calcareous nannoplankton from Lower Cretaceous deposits of the Northern Near-Sivash region

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Lower Cretaceous deposits of the Northern Near-Sivash region stripped by the drilling for oil and gas were studied by many researchers (O.K. Kaptarenko-Chernousova, L.F. Plotnikova, A.M. Voloshina, V.F. Gorbenko, I.M. Yamnichenko and others (Gevorkyan, 1971)), which allowed one to draw the detailed stratigraphic schemes of this region. The processing and interpretation of the new data on calcareous nannoplankton gave the possibility to stratigraphically supplement and to refine the separate horizons of sections of the wells and to implement the correlation with the International stratigraphical scheme (Ogg, 2008). In clays in the interval 2431.0-2604.0 m of the Ust-Salgirskaya-1 well, the complex of calcareous nannoplankton is represented by the species *Watznaueria britannica, W. biporta*, *Tranolithus orionatus*, *Zeugrhabdotus xenotus*, *Eiffellithus hancockii, Helicolithus trabeculatus*, *Crucibiscutum hayi, Cretarhabdus striatus,* and others. Since the first appearance of the zonal Upper Albian species *Eiffellithus* aff. *turriseiffelii* was revealed only in the upper part of the clay stratum (about 2599.0 m), the age of these deposits was dated by calcareous nannoplankton as the Middle-Late Albian – Early Cenomanian. A depleted complex of nannoplankton is found in clays in the interval 2665.0-2670.0 m (*Eprolithus floralis*, *Watznaueria britannica*, *Manivitella pemmatoidea*, *Corollithion* sp*., Staurolithites* sp.), which allows us to refer them oтly to the deposits formed not earlier than the Early Aptian. In aleurolites in the interval 2495.0-2512.0 m of the Genicheskaya-5 well, we determined the complex of calcareous nannoplankton of the Middle Albian – Early Cenomanian age: *Tranolithus orionatus*, *Zeugrhabdotus xenotus*, *Watznaueria britannica*, *Braarudosphaera africana*, *Rhagodiscus asper*, *Nannoconus truittii* subsp. *rectangularis*, *Manivitella pemmatoidea*, *Flabellites oblongus* and others. The Albian deposits are overlapped by marls, sandstones, and aleurolites of the Cenomanian Period. The following Cenomanian complex of calcareous nannoplankton is revealed in dark-grey aleurolites in the interval 2069.0-2074.0 m of the Genicheskaya-5 well: *Watznaueria britannica, W. biporta, Tranolithus orionatus*, *T. gabalus*, *T. minimus*, *Eiffellithus turriseiffelii*, *E. gorkae*, *Microrhabdulus belgicus*, *M. decoratus*, *Corollithion kennedyi*, *Zeugrhabdotus xenotus*, *Z. bicrescenticus*, *Z. embergeri, Z. diplogrammus*, *Braarudosphaera bigelowii*, *Retecapsa crenulata*, *Prediscosphaera cretacea*, *Rhagodiscus asper* and others. The simultaneous presence of the zonal species *Watznaueria britannica* and *Corollithion kennedyi* in it allows one to refer these deposits to Early Cenomanian (subzone UC1a of the zone UC1) (Bown, 1998). The deposits of Lower Cenomanian are inaccordingly overlapped by Santonian-Campanian limestones and marls characterized by microfauna and nannoplankton. The great amount of nannoplankton (25 species) in the absence of zonal species can testify to the start of a transgressive cycle of the Upper Albian – Early Cenomanian period. Probably, the connection with the open basin was hampered in the Middle Albian period, which is indicated by the absence of planktonic foraminiferas (Voloshina, 1966). In the deposits of Early Cenomanian, the nannoplanktonic subzone UC1a of the zone UC1 in the bulk of the ammonitic zone Neostlingoceras carcitanense is clearly determined by calcareous nannoplankton (Ogg, 2008).

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Blueschist facies radiolarites in the Meliatic Superunit (Western Carpathians)

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The Meliatic Superunit of the inner Western Carpathians includes rock complexes directly related to the geological evolution of the Triassic–Jurassic oceanic basin termed as the Meliata Ocean. However, rocks with a real oceanic provenance occur only in a part of these complexes, forming olistoliths of ophiolitic rocks as constituents of former oceanic floor embedded in the Jurassic accretionary mélanges. Ophiolites are represented by basic igneous rocks belonging to the uppermost part of ophiolite sequence (basalts, dolerites) in association with red deep-sea Triassic (Ladinian) radiolarites, cherts and siliceous shales, frequently enriched in products of submarine Fe-Mn hydrothermal mineralization. Besides the red Triassic radiolarites, the grey or greenish Jurassic radiolarites are present as well, forming small fragments in the mélange matrix. These radiolarites contain a considerable terrigenous admixture. During the Upper Jurassic closure of the oceanic basin, a part of the Meliatic rock complexes, inclusive some mélanges underwent subduction metamorphism in the blueschist facies conditions. They are regarded as components of an independent tectonic unit designated as the Bôrka Nappe. As a result of differences in exhumation rates, some formations of the Bôrka Nappe were affected by retrogressive metamorphism under the greenschist facies conditions. Radiolarites metamorphosed in the blueschist facies conditions have been found in the Hačava Fm. of the Bôrka Nappe near village Honce. They form blocks (from centimetres to several metres in diameter) in the black phyllitic matrix, but they have been found also as individual blocks together with metabasalts transformed to glaucophanite. Macroscopically dark reddish-brown colour and conchoidal fracture are typical for these rocks. In the mélange they are accompanied by blocks of various types of pelagic sediments transformed to phyllites with paragonite and/or chloritoide and HP/LT metamorphosed basalts with well-preserved hyaloporphyric, intersertal or ophitic phantom textures, and strongly depleted N-MORB geochemical signatures. Radiolarites metamorphosed in the HP conditions are microscopically very fine-grained rocks with the domination of quartz with dispersed Fe-Mn oxide ore pigment. Radiolarians are still discernible as oval-shaped phantoms. The presence of garnets, sodic pyroxenes and sodic amphibolites are typical features. Spessartite component is prevailing in the composition of garnets (75–78 mol %), andradite (15–19 mol %) and grossular (5–8 mol %) are present in less amount, whereas almandine (0–2 mol %) and pyrope (0–0.7%) are negligible. Na-pyroxenes have been found only as inclusions in garnets, ca. 5 µm in size. Aegirine or manganoan aegirine are prevailing components in the composition of Na-pyroxenes (Ae 62–75 mol %, Jd 5–22 mol%, Quad 15–20 mol %, Mn = up to 0.180 p.f.u.). Compositions of Na-amphiboles vary between magnesio-riebeckite and manganoan magnesio-riebeckite. Radiolarites originally metamorphosed in the blueschist facies conditions and thereafter retrogressed in the greenschist facies have been found in the Steinberg Fm. of the Bôrka Nappe in the surroundings of Dobšiná town. Besides prevailing quartz and pigment of Fe-oxides, some Na-actinolite, chlorite and epidote are present. HP/LT metamorphic stage is detectable by locally preserved glaucophane cores in Na-actinolite crystals or aggregates of green aegirine. Other radiolarites of the Meliatic Superunit, outside of the Bôrka Nappe and associated mélanges, do not bear any sign of HP/LT metamorphism with one exception – veinlets of magnesioriebeckite in radiolarite have been found near Jaklovce village as an indication of the short-acting effect of the high-pressure metamorphic conditions.

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Subduction erosion along the Caribbean-Cocos plate boundary off Costa Rica

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The convergent margin off Costa Rica is a textbook example of the process of subduction erosion. Based on high- resolution 3D seismic data and results from ODP drilling, it has been recognized that the Costa Rican forearc wedge on the upper plate at this convergent plate boundary is currently undergoing active subduction erosion rather than tectonic accretion by underplating. The model of subduction erosion implies that the forearc wedge of the upper plate is progressively reduced at its base and that the offscraped material is transported downward into the subduction zone. Removal of material from the base of the forearc causes extensional deformation of the upper plate, which results in subsidence of the forearc wedge and leads to landward migration of the coastline.

The remains of single-celled organisms (benthic foraminiferal faunas) can provide information on the history of changes in the ocean depth and other ocean features. Therefore, faunas from ODP Sites 1041 and 1042 located within sediments on top of the Costa Rican forearc basement have been sampled to test the hypothesis of subsidence of the forearc wedge as a result of subduction erosion. By comparing these organisms with their recent equivalents from similar environments, it was demonstrated that the forearc underwent strong subsidence, thus verifying the model of subduction erosion off Costa Rica. Sites 1041 and 1042 revealed an inverse bathymetric profile in time with species and sedimentary structures indicating shallow water conditions at the base of the holes and subsequently deeper water conditions in lower borehole depths.

Further to the south the convergent plate margin off the Osa peninsula in southern Costa Rica is characterized by the indentation of the aseismic Cocos ridge 4-5 Ma ago. The indentation causes the uplift of the Osa mélange which is interpreted to represent an exhumed major channel for the transport of tectonically eroded material down into the subduction zone. This situation is similar to the Nicoya segment of the subduction erosion dominated Costa Rica convergent margin. The composition of the Osa mélange is characterized by the tectonized material of the upper-plate Nicoya ophiolite complex (basalt, radiolarite, limestone). Strong deformation is concentrated in numerous discrete shear zones and produced the layered fabric of large rock volumes which partly experienced temperatures >200 °C. The interpretation of the Osa mélange as a product of subduction erosion at the base of the outer arc wedge structure is in line with stress coupling across the plate margin as indicated by paleostress data. We thus interpret of the Osa mélange as a product of subduction erosion at the base of the outer arc wedge structure.

Depositional environment of the Norian Hallstatt Limestones - an attempt to characterize the Late Triassic open-marine continental shelf sedimentation of the Western Tethyan realm

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Strong tectonic pulses triggered by Late Triassic (Norian) strike-slip movements destabilized the ancient topography and resulted in a new geometry of the western Tethyan passive margin. Lateral offset culminated in the late Middle Norian/Late Norian and decreased rapidly in the early Rhaetian. A widespread destruction of the submarine topographic relief with deep fractures into the underlying sedimentary succession, 'climatic cooling' with significant shifts in the stable carbon and oxygen isotopes, and eustatic pulses were coupled with changing palaeo-ocean environment proxies. This Late Triassic architecture can be proven in the open-marine continental shelf successions in the Eastern Alps, the Western Carpathians, the Southern Alps, distinct units in the Pannonian realm, the Dinarides/Albanides, in the Budva Zone, the Hellenides, and in Sicily. Depending on the palaeogeographic position in Early-Middle Lacian times, high sea-level with a (frequent) supply of carbonate debris and soluble carbonate from distant shallow-water environments influenced the diagenetic redox-reactions in the hemipelagic sediment with an in rare cases evolving microbial mat development. The sea-level fall in the latest Lacian and continental runoff from Pangea with the erosion of uplifted deeper continental crust in the hinterland resulted in an intense remobilization and in available erosional particulate material towards the Neotethys. Lowered sedimentation rates on the open shelf (Hallstatt facies), due to a decrease in the carbonate production, modified the depositional texture and promoted changes in the sediment accumulation rate that resulted in the Hallstatt Limestones in condensed environments. An order of dissolution and recrystallization reactions in the lithifying sediment caused interactions among the communities of symbiotic macro- and microorganism, fermentative decomposition of the organic matter, metal sorption onto clays and suspended particles, formation of authigenic minerals with diffuse pyritization and the emission of biogenic gas that can be traced on the continental shelf, by eg. cemented channels. Decreasing carbonate production in shallow-water areas combined with increasing continental runoff exhibit an increased relative abundance of biologically available elements. This triggered in stratified layers the selective sorption of metal and lanthanide cations and processed during the fossilization the replacement of calcium cations in the biomolecules of some deeper water organisms, which destabilized the equilibrium in the biological system and favoured crystalline effects on the (buried) skeletons. Changes in the pore-water pH fostered a microbial silicification of fragile compounds, the formation of biomineralized micrites, and a ferromanganese encrustation on organisms. The around the Alaunian/Sevatian boundary culminating tectonic motions destabilized the gas hydrates, and supported an ocean acidification expressed in silicifying the sediments on the distal continental shelf. This event marks the starting point for the stepwise extinction during Norian-Rhaetian times. Climatic warming yield to a transgression of the sea-level. Combined with a rapid subsidence triggered this the sudden 'recovery' of the Sevatian Dachstein Carbonate Platform, which is expressed in eg. rapid reef progradation or enormous carbonate production in lagoonal settings. Thus for the open-marine continental shelf sedimentation of the Western Tethyan realm, care should be taken in the geochemical correlation of the Hallstatt Limestones from the north with their time-equivalent series to the south despite the fact of their overall comparable tectonostratigraphy. Depending on the palaeogeographic and palaeoenvironmental setting, diagenetic mineralizations in the carbonates yield to regional differences that take place during the lithification.

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Seismotectonic characteristics of 2010 Kraljevo seismic sequence (Internal Dinarides, central Serbia)

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The Dinaric orogen hosts some of the strongest earthquakes in Europe. The studies of seismicity distribution, earthquake focal mechanisms and GPS shortening between the Adriatic microplate and the Pannonian basin show that most deformation is accommodated within the External Dinarides. Although this implies that the internal part of the orogen is 'locked' and seismically relatively inactive, several relatively strong earthquakes have been recorded in the Internal Dinarides, i.e. far from the area of the most active deformation. Albeit most were highly destructive and even caused fatalities, none of them gained much attention, hence, the seismogenic potential of these seismic zones remained very poorly constrained.

The main aim of this study was to determine and discuss seismotectonic characteristics of the 2010 Kraljevo seismic sequence, which started with a magnitude (mb) 5.3 Kraljevo earthquake on 3rd November 2010. We tried to constrain causative faults of the main shock and the strongest aftershocks and to propose a model of strain redistribution during this seismic sequence. The investigations involved using catalogue data about earthquakes as well as new focal mechanisms calculated on the basis of the polarities of first P-waves. A fault pattern of the wider research area was determined using stereoscopic SPOT images and digital elevation model. The timing of faults' activity and their kinematics were constrained by a combined approach of tectonic geomorphology and the analysis of reflective seismic profiles.

The results show that the main earthquake of the sequence is most likely released along the NW – SE striking sinistral fault referred to as the Sirča fault, situated about 5 km north of the city of Kraljevo. Deformation of geomorphological features indicates that this fault presumably consists of several strike-slip segments, with the cumulative displacement that does not exceed a few kilometres. With the assumption that the fault was active since the Late Miocene (~ 9 Ma), it appears that the maximal slip rate along the most active segment of the Sirča fault is no more than 0.4 mm/yr. Focal mechanisms of the strongest aftershocks suggest an important amount of vertical displacements along the causative faults of these earthquakes. This can be explained by the activation of shallower segments of the existing strike-slip faults; on seismic profiles these segments can be interpreted as flower structures. According to our model, the redistribution of strain after the main earthquake caused the activation of favourably oriented pre-existing faults. However, only those faults that had enough length (or area) of the activated segment, were the once that generated aftershocks of the studied sequence.

These results show a good agreement with our present day understanding of the active tectonic processes in the Dinarides, which describes the Adria – Dinaric convergence as the main factor controlling tectonic deformation within the entire orogen. However, we strongly argue that local strain redistribution along the pre-existing structures plays a significant role in earthquake generation in the Internal Dinarides, as well.

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Low angle normal faults and basement thrusts in the inner Northern Apennines (Italy): A surface and subsurface view

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The Northern Apennines of Italy are a classical site for studying relevant issues in orogenic wedges, such as ophiolite formation and emplacement, the interplay between tectonics and sedimentation, the role of in-sequence and out-of-sequence thrusting, syn- versus post-orogenic extension, along strike segmentation, etc. Accordingly, the Northern Apennines have been extensively studied since more than two centuries ago. Despite the huge amount of available data with different resolution, a 3D comprehensive regional view combining in a modern framework all available surface and subsurface information for contiguous sectors of the chain is still lacking. We performed such an attempt in the area framed between the Taro Valley to the north and the northern termination of the Alpi Apuane to the south. The region includes the main morphostructural zones of the North-West Apennines from the Tyrrhenian coast West-Northwest of La Spezia, through the main topographic divide of the Apennines, to the external frontal part of the chain. The area has been investigated through a multidisciplinary approach that integrated: 1) surface geological data collected during the last two decades of structural and stratigraphic field works in the internal as well as external sectors of the chain; 2) subsurface geological data including: a) interpretation of c. 1200 Km of seismic reflection profiles tied to surface geology and b) analysis of 39 boreholes stratigraphies. The construction of two regional NE-SW trending cross-sections (the Levanto-Pontremoli-Parma to the North and the La Spezia- Sarzana-North Apuane-Cerreto to the South), connected by the NW-SE trending Taro River-Lunigiana Area-Alpi Apuane composite section, allowed us to illustrate (i) the role of out-of-sequence blind thrusting in the basement, (ii) the presence of low angle normal faulting and its relationships with recent to active high angle normal faulting. Both extensional and contractional systems have relevant implications for the tectonics of the Northern Apennines as well as the seismotectonics of the studied region.

The influence of evaporites on the architecture of cover units in Eastern Alps: Middle-Late Triassic raft tectonics, Early Cretaceous thrusting and Neogene overprint

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Based on a new methodological approach (field structure and microfabrics of evaporites associated with Ar-Ar dating of K-sulphates polyhalite and langbeinite), a conceptual model is developed how different evaporite minerals react at changing temperature conditions and how the P-T conditions of these processes can be revealed in time. The model allows transfer to other orogenic belts.

Based on this methodology and study of magmatic and metamorphic blocks of all major evaporite bodies from the Northern Calcareous Alps (NCA; Permian-Lower Triassic Haselgebirge Fm.) reveal a number of hitherto processes not recognised before. These processes include: (1) Blocks of Permian magmatic rocks indicate the genesis in a Permian rift postdating thick Permian siliciclastic successions, which formed within syn-rift halfgrabens. Langbeinite of Hall indicates the first stage of a strong thermal overprint of evaporites at the Permian-Triassic boundary. (2) Numerous Ar-Ar ages of polyhalite mainly formed in extensional structures indicate a Middle-Triassic thermal overprint, pervasive fluid flow and lateral and vertical motion of the evaporite bodies. We explain this Middle-Triassic phase as ocean-ward directed gravity-driven raft tectonics directed to the oceanic Meliata-rift on the developing Austroalpine passive margin. (3) A few potentially Jurassic blueschists occur as blocks in the evaporites indicating Jurassic subduction (but not necessarily of the evaporites). (4) The evaporite bodies were emplaced during the latest Early Cretaceous NW-directed (present-day coordinates) thrusting, forming two different types of structural assemblages: compressional diapirs of halite-dominated evaporites and sheet-like decollement structures of sulphate-dominated evaporites. This phase of deformation also partly challenge the hypothesis of Jurassic gravity tectonics because of NW-directed continent-ward transport along ductile evaporite mylonite zones well preserved mainly in sulphates (anhydrite, polyhalite) and partly dated at ca. 110 Ma. (5) In other cases, these structures are overprinted by Late Cretaceous (?) ductile normal faults resulting in a break of the metamorphic profile. (6) Study of halite and gypsum fabrics indicates that these structures were strongly affected by Neogene and even recent tectonic processes modifying the previous structures, e.g., by strike-slip shearing. Similar very young (Pliocene?) structures of the Bellerophon Fm. were found in the Southern Alps, where the Fella-Sava strike-slip fault developed by shearing gypsum-rich evaporites.

Tectonic framework of the Balkan and Asia Minor: a preliminary work

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Based on the experience of the making of the maps of Mesozoic to Tertiary metamorphism in the Alps "Metamorphic Structure of the Alps" (Oberhänsli et al., 2004, Bousquet et al., 2012a) and "Tectonic Framework of the Alps" (Schmid et al., 2004, Bousquet et al., 2012b), where an interplay of data from structural geology and tectonics with metamorphism as well as age data and geophysical information was used to visualize the spacio-temporal geodynamic evolution of this complex orogenic system, we present a new tectonic frame for the continuation from the Alps to the Asia Minor. This map includes the Balkan, Aegean and Turkish realm in Asia Minor including the Carpathians, Dinarides, Rhodopes, Peloponnese, Aegean as well as Pontides and Taurides. The motivation for the compilation of this map is based on new metamorphic and age data especially for the Carpathians, Rhodopes, Aegean and Turkey. A tectonic map of the Carpatho-Dinaride realm that is consistent with a basic scheme of continental and oceanic realms and their structural relation as developed for the Alps was published by Schmid et al., (2008 and in prep.): However, the east ward continuation across Asia Minor is missing. With this new general map, we try to solve the problem of the continuation of the different continental and oceanic units from the Balkan over the Peloponnese and Aegean into Turkey and further to Iran. Due to intense neotectonic effects and movements and the Miocene to Neogene basins and volcanics that cover major parts of Turkey this is still speculative. Several small continental units (Menderes, Kirsehir) of Pan African origin, carrying along old metamorphism, are amalgamated along several Tethyan oceanic units and cannot simply be correlated with the Balkan setting. Our interpretation is based on work done in the realm of MEBE and DARIUS, two international joint ventures of academia and industry as well as many TÜBITAK projects in Turkey.

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Correlation of the geological maps 1:50 000 scale of the Albanian - neighbouring countries border area

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Geological structure of Albania and neighbouring countries has attracted the interest of several geoscientists since the 19th century. Several geological studies, including the geological mapping of various scales (1:2 000, 1:5 000, 1:10 000, 1:25 000, 1:50 000, 1:200 000, 1:250 000 and 1:500 000) have been carried out during this period. Some joint projects to unify the main data on the geological-tectonic structures, lithological composition and the ages of the formations on both sides of the border between the countries, have been undertaken these last years and the results are encouraging. The mutual cooperation between the respective scientific institutions is very important taking into account the participation of both countries in the compilation of the New Geological Map of Europe 1:500 000 scale. The implementation of the 1:50 000 scale mappings of the border area is indispensable. The correlation of these maps is realized through geological observations, sampling and other geological works. The implementation of the new geological maps 1:50 000 will serve as a good scientific basis for further studies in the field of earth sciences in the region. The common observations and geological investigations along the interboundary line have led to the correlation of the Ionian, Kruja (Gavrovo), Krasta-Cukali (Ollonos-Pindos), Mirdita (Subpelagonian) tectonic zones and Inner Depressions as well as the correlation of the geological and ore bearing structures and other formations along the respective inter-boundary line. The comparison of data on the stratigraphy, petrology, mineralogy etc., of different geological units, has been carried out as well. During this cooperation, it is worked with topographic sheets scale 1:50 000, on which were plotted the geological data in digital form. The final result is the publication of 38 geological sheets 1:50 000 scale and explanatory texts for each of them, for all the inter-boundary line between the countries. The following unified sheets 1:50 000 scales were published. Albanian-Montenegro border area - 1. Sheet 1 Vermoshi, 2. Sheet 2 Gucia, 3. Sheet 3 Stanet e Sublices., 4. Sheet 4 Rapsh-Starja, 5 Sheet 5 Tamara, 6. Sheet 6 Thethi, 7. Sheet 8 Kopliku, 8. Sheet 14 Shiroka, 9. Sheet 20 Velipoja:Albanian-Kosovo border area- 1. Sheet 7 Bajram Curri, 2. Sheet 12 Kruma, 3. Sheet 13 Kishaj, 4. Sheet 19 Morini: Albanian-Macedonia border area-1 Sheet 25 Shishtaveci, 2. Sheet 30 Mali i Korabit, 3. Sheet 35 Zerqani, 4. Sheet 36 Poçesti, 5. Sheet 41 Klenja, 6. Sheet 42 Trebishti, 7. Sheet 47 Librazhdi, 8. Sheet 48 Struga, 9. Sheet 54 Prrenjasi, 10. Sheet 60 Pogradeci., 11.Sheet 61 Bllaca: Albanian-Greece border area-1. Sheet 68 Pojani-Podgori Andartikon, 2. Sheet 69 Shueci –Andartikon, 3. Sheet 76 Korca-Hionades Gramos, 4. Sheet 77 Kapshtica- Korica Massapotamia, 5. Sheet 84 Vidohova – Hionades Gramos, 6. Sheet 90 Barmash-Hionades Gramos-Vassilikon Pogoniani, 7. Sheet 91 Hionades Gramos-Vassilikon Pogoniani, 8. Sheet 95 Libohova-Tsamantas, 9. Sheet 96 Leskoviku-Hioandes Gramos- Vassilikon Pogoniani, 10. Sheet 99 Jergucati-Tsamantas, 11 Sheet 100 Ksamili-Ishulli i Korfuzit, 12. Sheet 101 Mursia-Tsamantas, 13. Sheet 102 Sotira-Tsamantas, 14. Sheet 103 Konispoli-Sagiadha-Filatai.

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Significance of Jurassic early deformation structures in the SW-Bükk Mts.

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Field work in the quarry of Bükkzsérc and at the Patkó Cliffs (SW of Bükk Mts.) revealed several types of early, soft-sediment deformation structures in the Jurassic Bükkzsérc Limestone which was deposited in a subduction-related basin of the Neotethys ocean and now appears as olistoliths in the accretionary Mónosbél Complex. These structures include small syn-sedimentary normal faults, ductile shear surfaces and slump folds, both of which were not recognized by previous structural geological and sedimentological studies (e.g. Németh, 2007), although these structures have direct implications for the poorly known early deformation history of the Mónosbél Complex and possibly of the Bükk para-autochtonous unit.

The aim of our study was to estimate the Jurassic paleo-stress field for the Mónosbél Complex of the Bükk Mts. by measuring syn-sedimentary faults, and to estimate the paleoslope direction from the slump fold geometries.

In the case of the normal faults, the key observations in our interpretation were that the faults are characterized by rounded, curved shapes and that they don’t have discrete fault planes. This can be explained by syn-sedimentary deformation in case of which the deformation in soft sediments is limited, while the diagenetic processes may have further effects on fault geometries as well.

Data were rotated back to its paleoposition by the average paleomagnetic data attributed for the Bükk Mts. (e.g. Márton and Márton. 1996). Based on the back-rotated small-scale deformation structures we estimated a NE-SW extension as the Jurassic paleostress field, while the results of the slump fold analysis showed a SW paleoslope direction. Although these extensional directions match the previous broad estimations, we need to take into account that the olistolith itself could have had a further rotation, so in order to finalize our estimations, additional measurements in other olistoliths and direct paleomagnetic data from the Bükkzsérc olistolith are still needed.

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Crustal structure based on seismic and gravity datasets at the profiles in the northern Dinarides (Alp07) and central Dinarides (GP-3)

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The research was carried out along the profile GP-3 crossing the central Dinarides and extending from the Adriatic Sea towards Split and Banja Luka to the Hungary. Five permanent seismic stations (dataset from Orfeus; http:/www.orfeus-eu.org/data/eida) and two temporary seismic stations from ALPASS-DIPS project are located on the profile. The teleseismic data were interpreted by receiver functions method (RF). The main goal was to determine the crustal structure in the area of Dinarides and SW Pannonian basin, as well as the relationship between Adriatic microplate and Pannonian tectonic segment of Eurasia. The gravity model along GP-3 profile was defined within previous research (Šumanovac, 2015) using the calibrated set of densities obtained on the profile Alp07 in the northern Dinarides (Šumanovac et al., 2009), which stretches from Istra, continues via Karlovac and Bjelovar and ends in Hungary. The receiver functions analysis enabled more precise definition of the geological model along the profile GP-3. The RF is mainly used to map the velocity discontinuities. Moho layer can be usually very easy identified, but also discontinuities in the crust and sedimentary basement. The results correlate well with density model obtained by gravity modelling. There are two types of receiver functions: Dinaridic type with three discontinuities (Moho, intracrustal discontinuity and sedimentary basement) and Pannonian type with two discontinuities, Moho and sedimentary basement. Thus, under the Dinarides the crust is two-layered, while below the Pannonian basin is apparently one-layered. A wide transition zone is located between them, which includes ophiolite zones (Sava zone and Dinaridic zone; Pamić et al., 2002) and can be interpreted as a suture zone between Eurasia and Africa. Although, according to geological history this zone belongs to African units, in the present tectonic setting it can be considered as part of European units like the Pannonian crust. The general geological model along GP-3 profile was constructed, that correlate well with the geological model on the profile Alp07 (Šumanovac et al., 2016), which is based on all three datasets: gravity, seismic refraction and receiver functions. Along both profiles, GP-3 and Alp07, RF show thickening of the crust under the Dinarides (40-50 km) and significant thinning under the Pannonian basin (20-25 km). However, depths of the Moho under the Dinarides and suture zone obtained from RF are greater than the depths based on the refraction and gravity data. In the Pannonian basin, there are no significant differences in the Moho depths. The deviations are generally +15% compared to other data sets. The both geological models, GP-3 and Alp07, comprise the same tectonic units, similar crustal thicknesses under the Pannonian basin and similar dimensions of the transitional, suture zone. The thickness of the crust under the central Dinarides (GP-3) is greater than in the northern Dinarides (Alp07). In general, the Dinaridic structure can be considered as two-dimensional, which facilitates future research.

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Tectonic maps in areas of deposition of exotic olistolithes – application to the Northern Calcareous Alps of Austria

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A tectonic map shows the architecture of the upper portion of the earth's crust, and thus depicts the geometric relationship of tectonic units. Tectonic units are fault-bounded and transported relative to each other. In most cases, tectonic units are separated by faults. However, it gets more complicated in cases when deformation and deposition are contemporaneous. This is the case on continental margins. Many continental margins are subject to gravitative deformation, resulting in small- and large scale slumping and sliding. When “exotic”, (i.e. material derived from another unit as compared to the unit on which it comes to rest), and large (mountain-sized) slides are emplaced, and these slides are buried by sediments, the order of tectonic units in maps gets confusing.

In most cases, exotic olistoliths are interpreted to originate from another paleogeographic unit, however the sediments covering the olistoliths are part of the sedimentary succession of the underlying unit. To avoid confusion, slide planes at the bases of olistoliths should be distinguished from the top surfaces of olistoliths, that are unconformities after burial. Therefore I suggest to introduce a new type of tectonic boundary: (angular) unconformities between tectonic units. These are distinguished from “common” angular unconformities that may occur within tectonic units.

This new way of depicting tectonic contacts is applied to the central sector of the Northern Calcareous Alps of Austria. During the Early Upper Jurassic, huge olistoliths were mobilized on this deep-water continental margin. Middle to Upper Triassic pelagic limestones deposited on different parts of the continental slope, and platform limestones interfingering with pelagic limestones did slide onto the more internal part of the continental margin, creating a morphology that persisted into the Late Jurassic and was successively buried und thus unconformably overlain by Upper Jurassic and younger deposits.

Direct evidence of Upper Jurassic wrench faulting that could contribute to the mobilization of olistoliths is given by growth strata in Upper Jurassic deposits adjacent to a transpressive E-W fault in the area (Ortner, 2017).

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Jurassic normal faulting controls deformation style during Alpine Orogeny, external Northern Calcareous Alps, Tyrol, Austria

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The Northern Calcareous Alps (NCA) are a typical thin-skinned fold-and-thrust belt consisting of permo-mesozoic sediments derived from the northern margin of the Neotethys. During Alpine Orogeny, the sediments are sheared off their basement, transported over several hundreds of km and stacked in nappes. Fold architecture is mainly controlled by thick rigid carbonates, whereas low-strength stratigraphic horizons floor and core folds and are used as preferred detachment horizons. Contemporaneous thrusting and isoclinal buckle folding lead to often observed peculiarities, such as folds truncated on top or at the base, a carpet of slices of hanging-wall units immediately below a thrust and a patchy distribution of synorogenic sediments.

In the western part of the NCA, structural field work and interpretation of seismic sections were carried out at one of the major thrusts in the NCA, the Lechtal thrust, separating the lowermost and paleo-geographically most external unit of the NCA, the Allgäu nappe, from the next higher Lechtal nappe. The Lechtal thrust was active in Aptian/Albian times with a minimum displacement of 30km and mainly strikes NE-SW due to Top-NW thrusting. According to a general eastern dip of the NCA thrust belt in the study area, the Allgäu nappe appears in a greater extent to the west in (half)windows beneath the upper Lechtal nappe. Hence, deformation style and kinematics can be studied in good outcrop conditions.

In the Allgäu nappe, a normal-fault scarp can be mapped immediately below the Lechtal-thrust. Along this irregularly concave shaped normal-fault, Upper-Triassic lagoonal carbonates in the footwall are truncated obliquely to bedding by Lower-Jurassic syntectonic deep-marine marly limestones in the hangingwall, which show extensional Top-SW soft-sediment deformation. Hence the activity of normal-faulting is indirectly datable to Lower-Jurassic times, which correlates well with spreading of the Alpine Tethys oceanic system.

During Alpine shortening, this pre-existing Lower-Jurassic fault-scarp acts as a distinct morphological irregularity in the footwall and therefore also as a spatial irregularity in resistance for the approaching Lechtal nappe. As a result, the Lechtal thrust is forced to retrace this pre-existing morphological irregularity and is offset about 1,5km dextrally in NW direction. This offset produces non-noteworthy deformation in the footwall except of semi-ductile bending and rotation of structures immediately below the thrust. The hanging wall, however, is buttressed against the fault block in the footwall, resulting in the formation of two duplexes with drag folds accompanied by a NW-SE trending dextral tear fault.

Exceptionally preserved Early Tuvalian (Carnian, Triassic) radiolarian fauna from the Huğlu-Pindos succession in the Sorgun Ophiolitic Mélange (SE Turkey) and its role in the paleogeographic evolution of the Mesozoic Neotethys

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The Mersin Ophiolitic Complex in southern Turkey is a special area to study a very complicated tectonic mixture of an infra-ophiolitic mélange associated to South-Taurides ophiolitic belt. The Mersin Mélange is subdivided into two bigger independent units: the Late Cretaceous Sorgun Ophiolitic Mélange (SOM) and the Middle to Late Triassic Hacialanı Mélange. Both mélanges consist of a chaotic accumulation of blocks and rocks in a sedimentary mixture (olistostrome) of clastics, ophiolitic material, and oceanic and exotic blocks of various ages. Slide blocks in the mélanges typically range in size from a few meters to hundreds of meters. Broken formations are represented by elongated bodies ranging in size from hundreds of meters to kilometres. One of the most important and well developed tectonic blocks of the SOM is the Tavusçayırı block. This block contains several typical deep-sea sedimentary units (e.g., the Huğlu-Pindos succession), which are well-known from the Hellenides-Taurides belt, that provide important clues to the geodynamic evolution of Paleotethyan and Neotethyan series in the Eastern Mediterranean region. The classical Pindos-type series in Greece and the Huğlu-Pindos-type sequences in Turkey (the Köycegiz and Haticeana Dag series in the Lycian Nappes, part of the Antalya Nappes, the Beyşehir-Hoyran Nappes, broken-formations in the Mersin mélange, and the Köseyahya Nappe in Elbistan) show striking similarities in their successions. Both types of series are related to the latest extensional events leading to back-arc openings in the Variscan cordillera during the Late Triassic. These events are marked by widespread Triassic volcanism (e.g., Huğlu tuffitic series in Turkey) and by condensed Ammonitico Rosso horizons during the Liassic, leading to the onset of a passive margin setting that lasted until the Late Cretaceous obduction of supra-subduction type ophiolites. Similar Pindos-type units are also found in Crete and in several islands of the Dodecanese. Part of the investigated sequence contains one of the most diverse and best preserved radiolarian faunas of the world: the very well-preserved and particularly diverse early Tuvalian (late Carnian, Late Triassic) radiolarian fauna, which has been already described in a series of papers. The radiolarian fauna belongs to the *Spongotortilispinus moixi* radiolarian Zone (equivalent to *Paragondolella postinclinata - Paragondolella noah* conodont Zone), moreover the very similar late Julian-early Tuvalian radiolarian faunas from the Northern Calcareous, Alps through the Lagonegro Basin, Sicily, Rhodes Island, Greece and farther east in the Antalya nappes, in the Mersin Mélange and in Elbistan, Turkey and even in Oman may confirm that the Pindos-type succession found in different units of early Mesozoic oceanic basins formed in a single oceanic basin. We would like to summarize and present herewith the latest radiolarian results from the Huğlu-Pindos succession of the Sorgun Ophiolitic Mélange (SE Turkey) and discuss some implications for the geodynamic reconstruction of the Eastern Mediterranean region.

The Eocene-Oligocene climate transition in the Central Paratethys

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The Antarctic glaciation close to the Eocene-Oligocene boundary was one of the most significant events in the climate evolution of the Cenozoic Era. The principal cause of this climate transition is debated, although its consequences are indisputable: decrease in atmospheric pCO_2, the rapid expansion of continental ice volume on Antarctica and significant (>1 km) deepening of the global calcite compensation depth. All inferences are derived from deep-sea benthic foraminiferal oxygen and carbon isotope ($\delta^{18}O$, $\delta^{13}C$) records, which have been extensively studied, on the basis of the vast amount of Deep Sea Drilling Project (DSDP), Ocean Drilling Program (ODP) and Integrated Ocean Discovery Program (IODP) cores. However, significantly fewer studies have focused on the record of isolated marginal seas or terrestrial paleoclimatic changes from this interval. The stratigraphic record of marginal seas, such as the Paratethys in east-central Europe, may provide valuable new insights about the EOT. The paleoenvironmental consequences of the progressive separation of the Paratethys are reflected in radical changes in numerous marine proxies that imply unstable paleoceanographic conditions. The primary objective of this study is to reconstruct the paleoclimatic and paleoceanographic changes of the Central Paratethys during the EOT. Two continuous epicontinental Eocene/Oligocene boundary core sections (Cserépváralja-1 [CSV-1] and Kiscell-1 [KL-1]) from the HPB of the Central Paratethys have been investigated, including studies of their foraminifera and calcareous nannoplankton and high-resolution stable isotope geochemical analyses, which allowed paleoecological and paleoceanographic reconstructions. Assemblages of benthic foraminifera display a shift in dominance by epifaunal taxa in the late Eocene to shallow and deep infaunal taxa in the early Oligocene. Using the benthic foraminiferal oxygen index (BFOI), a decreasing trend of bottom-water oxygen levels is established across the Eocene-Oligocene transition (EOT), leading to the development of dysoxic conditions later in the early Oligocene. Trends in $\delta^{18}O$ and $\delta^{13}C$ values measured on tests of selected benthic and planktic foraminifera roughly parallel those of the global record of stepped EOT $\delta^{18}O$ increase and deviate only later in the early Oligocene, related to the isolation of the Paratethys. The overall similarity of the isotope curves and the presence of a planktic-benthic ecological offset suggest that the original isotope trends are preserved, despite the systematically more negative $\delta^{18}O$ values. Of different scenarios, a quasi-uniform diagenetic overprint by fluids with low $\delta^{18}O$ values, during burial or uplift, appears best supported. We conclude that the globally established isotopic expression of Antarctic ice sheet growth across the EOT may be recognizable in the Paratethys. Deviations from the global trends after the EOT were caused by regional paleoceanographic changes induced by the progressing Alpine orogeny and sea-level change, which led to a restricted connection with the open ocean, freshwater influx from increased precipitation and gradual development of bottom-water oxygen depletion.

Tethyan, Austroalpine and Pennine Western Carpathians – how do they relate?

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Considering the Mesozoic–Paleogene facies links, structural polarity and timing of principal tectono-metamorphic events, three major, mutually interrelated but autonomous thrust systems can be distinguished within the Western Carpathians (WC). The inner WC zones are built by units which were tectonized mainly during the Late Jurassic and Early Cretaceous in connection with the closure of the Tethyan Meliata oceanic branch. They include the Transdanubian and Bükk super units, both showing the Triassic to Lower Cretaceous facies links to the Upper Austroalpine–Southalpine and Dinaric domains, respectively. The latest Jurassic – earliest Cretaceous westward obduction of Jurassic ophiolite-bearing nappes and the mid-Cretaceous SE-vergent thrusting were the main deformation events. The northern boundary of these Tethyan Carpathians follows a complex, suture-like Rába–Hurbanovo–Diósjenő–Rožňava mobile zone. This zone is exposed only in its eastern part, where it includes the Meliatic-Turnaic accretionary complex, discordantly overlain by the Silica nappe. This thrust stack overrides the southernmost Austroalpine Gemeric sheet. The lowermost Meliatic Bôrka nappe (HP/LT metamorphosed at 160–150 Ma) includes Paleozoic formations that are akin to the underlying Gemeric complexes, thus indicating derivation from the distal southern Austroalpine margin involved in the Meliata subduction. On the other hand, the Turnaic nappes include some formations that show a striking affinity to the “southern”, Bükk-type units, i.e. they were likely derived from the opposite margin of the intervening oceanic domain. The Carpathian Austroalpine units form the core of the WC orogen, being composed of three thick-skinned thrust sheets (Tatric, Veporic and Gemeric) and three detached cover nappe systems (Fatric, Hronic and Silicic), all with a distinct NW-directed Cretaceous thrusting. Shortening propagated from the Early Cretaceous thrusting of the Gemeric over the Veporic to the main mid-Cretaceous events at the Veporic/Tatric interface that culminated by the expulsion of the Fatric cover nappes and their late Turonian emplacement over the Tatric foreland, followed by the Hronic nappes. During the Senonian, the Veporic metamorphic complex was exhumed by orogen-parallel unroofing in connection with underthrusting of the Fatric basement from the NW. The Carpathian Penninic units embrace the scarce remnants of the Piemont–Váh oceanic tract with their likely eastward continuation into the Iňačovce and Kričevo units that are wrapping up the eastern Austroalpine and Tethyan WC domains, and continue SW-ward into the Sava Zone, via the Szolnok Unit and the Mid-Hungarian Zone. The typical units of the Pieniny Klippen Belt were detached from the Oravic continental ribbon in the Middle Penninic position and were partly overridden by the frontal Austroalpine (Fatric and Hronic) nappes carrying the wedge-top, Gosau-type basins. The northern branch of the Alpine Atlantic is represented by two independent thrust wedges: the Rhenodanubian–Biele Karpaty accreted in the Senonian–Middle Eocene and the Magura accreted in the Late Eocene–Oligocene; these two wedges were unified during the Oligocene – Early Miocene in front of the eastward extruded AlCaPa. In terms of orogenic cycles, the Tethyan and Austroalpine Carpathians approached by the Late Jurassic subduction of the Meliata Ocean and merged by the ensuing Early Cretaceous collision of its former margins. On the other hand, the Pennine and Austroalpine thrust systems were joined by the stepwise accretion of the former in front of the latter during the Late Cretaceous to Paleogene subduction of the Alpine Atlantic oceanic branches. The mid-Cretaceous, outward prograding thrust stacking in the WC Austroalpine units was probably driven by subcrustal subduction of the lower crust and dense mantle lithosphere attached to the pulling Meliata slab and/or by the rear push of eastward advancing Adria.

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The Bjala Reka Dome (Rhodopes, southeast Bulgaria)

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The Bjala Reka Dome is the easternmost of four extensional metamorphic core complexes within the Rhodopes. The core of the dome is made up of large volumes of orthogneisses (Bjala Reka 1 Unit) that are overlain by “variegated” lithotectonic units. The Žulti Čal and Bjala Reka variegated (Bjala Reka 2) units are comprised of mostly amphibolite-facies para- and orthogneisses, metapelites, marble, ultrabasites, amphibolites, and eclogites that are often strongly retrogressed. The Krumovica unit, overlying the Bjala Reka 2 Unit to the north and west, consists of similar rocks, although with a higher proportion meta-ultrabasic and -basic rocks. To the east, the Bjala Reka 1 Unit is directly overlain by the Mandrica Unit that is dominantly composed of greenschists, phyllites, and partly garnet-bearing micaschists in its lower part, whereas its upper part is built up by Jurassic-Cretaceous slates and quartzitic sandstones and conglomerates.

According to previous works, the Mandrica Unit experienced greenschist-facies conditions below c. 400 °C and represents the Uppermost Complex. This complex, also known as Circum-Rhodope Belt, is essential to many tectonic models of the Balkan Peninsula because it is supposed to bear evidence for the obduction of Vardar oceanic lithosphere onto the European margin during Late Jurassic-Early Cretaceous initial stages of the closure of the Neotethys. In this tectonic scenario, all the tectonic units below the Mandrica Unit originate from the European margin and were exhumed in the footwall of the top-SSW Bjala Reka Detachment.

We carried out Raman spectroscopic analyses on the carbonaceous matter from slates and phyllites of the Mandrica Unit that yielded significantly different peak temperatures for the lower and upper part of this unit (500-530 °C and c. 280 °C, respectively). Raman barometry on quartz inclusions in garnets from micaschists of the Mandrica Unit gave peak preasures of c. 1.4 GPa. These findings indicate that what was hitherto called Mandrica Unit are two units with distinctly different tectono-metamorphic histories. We therefore propose the new names Gorno Lukovo Unit for the lower, high-grade metamorphic unit and Dolno Lukovo Unit for the upper, anchimetamorphic unit. Another important implication is that the greenschist-facies rocks of the Gorno Lukovo Unit did not form on a prograde metamorphic path (at least not all of them) but by retrogression of different formerly higher-grade basement units, most likely the Krumovica Unit in the north (Kulidžik area) and the Bjala Reka (2) unit in the southeast (Mandrica area).

We preliminarily propose the following tectonic scheme for the units exposed within and around the Bjala Reka Dome: The Bjala Reka (1) Unit represents former Adriatic or Pelagonian basement (Lower Complex), onto which the Žulti Čal and Bjala Reka (2) units that contain Vardar-derived ophiolitic rocks (Middle Complex) were thrust in SSW direction after c. 70 Ma. All these units form the footwall of the Late Eocene top-SSW Bjala Reka Detachment. The Krumovica Unit represents the former European margin (Upper Complex). The Gorno Lukovo Unit is part of the same Upper Complex but was strongly retrogressed during top-N extensional shearing below a detachment that somewhat predates the Bjala Reka Detachment. Units of the Uppermost Complex (obducted from the Vardar domain onto the European margin) form the hanging wall of the top-N detachment and are represented by the Dolno Lukovo Unit and Evros ophiolites exposed in Greece.

Syn- and post-obduction deformation of the Dinaric margin revealed by structural studies of the Drina block, Western Serbia

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Emplacement of oceanic crust on top of continental margins has been an object of particular interest since the observation of the large volumes of ophiolitic complexes. The understanding of ophiolite obduction has been developed by large amounts of geological works. On the other hand, the structural evolution of the lower plate in obduction systems has received less attention. How can we trace the propagation of deformation into the lower plate, and when does the lower plate reaches the maximal tectonic burial? A suitable place to answer these questions is the Internal Dinarides, where the Dinaric continental margin - that structurally underlies the ophiolitic nappe of the former Vardar ocean - is exposed in tectonic windows. We present a field study supplemented by K/Ar dating and Illite Crystallinity measurements that provide structural and timing constraints on the deformation history of Drina block (Dinaric margin) within the Zlatibor-Maljen region. The Drina block forms a map-scale, NW-SE anticline with low-grade Paleozoic rocks in the core, and Mesozoic successions on the limbs. Results: 1) The Drina-Ivanjica Paleozoic and the Northeastern Triassic unit have been affected by ductile deformation (D1) characterized by tight-isoclinal ductile folding. D1 was associated with high-temperature anchizone metamorphism evidenced by microstructures and Kübler Index values. The age of D1 deformation and metamorphism is 130-145 Ma based on K/Ar measurements. It probably represents the maximal tectonic burial of the Drina-Ivanjica and the WNW-verging propagation of deformation from the intra-oceanic phase of ophiolite obduction towards the Dinaric continental margin. 2) The Northeastern Triassic sequence is probably the original cover of the Drina-Ivanjica Paleozoic. The Southwestern Triassic sequence is not affected by D1 deformation and metamorphism, thus it cannot be the original cover of the Drina-Ivanjica Paleozoic. 3) D2 deformation phase represents a long-lasting (roughly late Early Cretaceous - Eocene) stage of the brittle fold and thrust belt evolution in the study area characterized by NE-SW shortening, that corresponds to the overall geometry of the Dinaric orogen. The emplacement of the Southeastern Triassic unit on top of the Drina-Ivanjica occurred during the D2 phase, most likely in latest Cretaceous or Paleogene times, transported by a NNE-verging backthrust. Map-scale NW-SE trending D2 thrusts are also present in the Triassic cover of the Drina-Ivanjica (Northeastern Triassic sequence). 4)D1 ductile deformation and metamorphism in the footwall of the internal Dinaric thrust system was followed by significant uplift and erosion in the hangingwall during the D2 thrusting phase. It resulted in the transgression of Cretaceous sediments onto all units from Paleozoic to the Jurassic ophiolites. 5) The stress field changed from NE-SW compression to roughly N-S transpression (D3) resulting in the development of strike-slip systems during the Oligocene-Early Miocene. The most remarkable features are major NNW-SSE striking dextral faults and related contractional structures. 6) Normal faulting and related development of small basins characterize the Miocene evolution of the region. Both orogen-perpendicular (NE-SW) and orogen-parallel (NW-SE) extension took place and formed the landscape during Neogene times. Neogene basin formation was most probably driven by the interplay between slab-rollback processes in the Carpathians and in the Dinarides.

Orogenesis and magmatism: A view from the Alpine-Himalayan belt

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The Alpine-Himalayan orogeny is one of the three major orogenic phases defining the geology of Europe and Asia, along with the Caledonian and the Hercynian orogenies. It generated accretionary orogen that occurs at a diffuse and long lived convergent zone between Eurasia and Gondwana, which has been active since Permian-Mesozoic times resulting in the consumption of major Tethyan ocean(s). The convergence varies in style involving accretion of small continental slivers and numerous oceanic island arcs in the west, to the world's most comprehensive continental collision in the east. It eventually gave rise to a complex collage enclosing continental crustal blocks intercalated with ophiolitic terrains of various sizes and ages forming superimposed mountainous belts.

Magmatism that occurs within these belts postdates final accretionary events forming the Alpine–Himalayan chain. It is diachronous with the most voluminous and widely distributed episode(s) beginning from the late Cretaceous. Associated with postcollisional magmatism occurs a global metallogenic unit including a number of world-class Cu-Pb-Zn-Au-Ag-Te deposits. The magmatism is derived from both the mantle and the crust, and is geochemically extremely heterogeneous, but dominantly potassium enriched. Its origin and relationship to the large-scale elevations in several massifs (Tibet, Menderes etc.) of the orogen is controversial, particularly the significance of the widespread geochemical signal typical for the recycled continental crust.

In my lecture I will draw conclusions about the geodynamic interpretation of orogenic lithospheric mantle within the Alpine–Himalayan combining the field, geochemical studies of K-rich post-collisional mantle-derived lavas from Spain, Italy, Balkans, Turkey, Iran and Tibet with high-pressure experiments. The composition of K-rich postcollisional lavas suggests that the orogenic mantle underwent much more intense and complex material recycling than anticipated only by fluid- or melt- dominated transport. This is based on several fundamental constraints: i) The lavas are strongly incompatible-element enriched with elevated $^{87}Sr/^{86}Sr$, $^{207}Pb/^{204}Pb$, $^{187}Os/^{188}Os$ and low $^{143}Nd/^{144}Nd$ and $^{176}Hf/^{177}Hf$ ratios. All these tracers represent a hallmark for continental crust; ii) The presence of an ultra-depleted component in the source of the K-rich lavas is identified by usual presence of refractory Cr-spinel, high Fo olivine and relatively low whole-rock FeO abundances; iii) Finally, extremely high Th/La is coupled with high Sm/La of potassic mantle-derived lavas points to a genetic relationship with the melange.

The above observations suggest that neither fluids nor melts alone can precondition orogenic mantle using known mechanisms that are active during material recycling within subduction zones, thus a new model is required. I will present a hypothesis that the orogenic mantle along the Alpine-Himalayan system is preconditioned during the previous episode(s) of "dirty" subduction. This process involves the formation of a new mantle lithosphere formed by accretion of suprasubduction fore-arc oceanic lithosphere plus trench sediments beneath older lithosphere during convergence within the Alpine-Himalayan system. The model demands conversion of the principally oceanic lithosphere (including melange) into the phlogopite-bearing continental lithospheric mantle and production of K-rich post-collisional lavas, which is a multi-component and multi-episodic process.

The Late Cretaceous Klepa basalts in Macedonia (FYROM)—Constraints on the final stage of Tethys closure in the Balkans

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The waning stage(s) of the Tethyan ocean(s) in the Balkans are not well understood (Prelević et al., 2017). Controversy centres on the origin and life-span of the Cretaceous Sava Zone, which is allegedly a remnant of the last oceanic domain in the Balkan Peninsula, defining the youngest suture between Eurasia- and Adria-derived plates. In order to investigate to what extent Late-Cretaceous volcanism within the Sava Zone is consistent with this model we present new age data together with trace-element and Sr–Nd–Pb isotope data for the Klepa basaltic lavas from the central Balkan Peninsula. Our new geochemical data show marked differences between the Cretaceous Klepa basalts (Sava Zone) and the rocks of other volcanic sequences from the Jurassic ophiolites of the Balkans. The Klepa basalts mostly have Sr–Nd–Pb isotopic and trace-element signatures that resemble enriched within-plate basalts substantially different from Jurassic ophiolite basalts with MORB, BAB and IAV affinities. Trace-element modelling of the Klepa rocks indicates 2%–20% polybaric melting of a relatively homogeneously metasomatised mantle source that ranges in composition from garnet lherzolite to ilmenite+apatite bearing spinel–amphibole lherzolite. Thus, the residual mineralogy is characteristic of a continental rather than oceanic lithospheric mantle source, suggesting an intracontinental within-plate origin for the Klepa basalts. Two alternative geodynamic models are internally consistent with our new findings: (1) if the Sava Zone represents remnants of the youngest Neotethyan Ocean, magmatism along this zone would be situated within the forearc region and triggered by ridge subduction; (2) if the Sava Zone delimits a diffuse tectonic boundary between Adria and Europe which had already collided in the Late Jurassic, the Klepa basalts together with a number of other magmatic centres represent volcanism related to transtensional tectonics.

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Neoproterozoic and Early Paleozoic complexes in the Variscan basement structure of the Western Carpathians constrained by U-Pb SIMS and LA-ICP-MS zircon ages

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Remnants of the south-vergent Variscan basement structure were recognized in the higher-grade complexes of the Cretaceous Tatric and Veporic units of the Inner Western Carpathians (Putiš, 1992). The Upper Variscan Unit paragneisses with emplaced bodies of orthogneisses, layered amphibolites, eclogites and serpentinites were thrust over the Middle Variscan Unit micaschists at ca. 356 Ma (^{40}Ar-^{39}Ar mylonitic amphibole ages; Dallmeyer et al., 1996). Neoproterozoic zircons of 700-550 Ma predominate in both, the micaschists and gneisses of the Middle and Upper Units. This age interval was unified by the Cadomian (Pan-African) metamorphic event to the concordia ages of ca. 565–560 Ma. The recycled zircons are Paleoproterozoic to Archean, up to 3,400 Ma. While the Middle Unit micaschists represent a flyschoid of the Gondwana northern passive continental margin, the meta-igneous members of the Upper Unit document the Middle Cambrian to Late Ordovician magmatic arc setting within the active Gondwana margin (Putiš et al., 2008, 2009). Igneous precursors of layered amphibolites and eclogites (478±3 Ma) were dated from 503 to 450 Ma. They are contemporaneous with the granitic protoliths of orthogneisses dated from 516 to 450 Ma. No oceanic crust of this age has been determined. The igneous precursor ages are consistent with the Gondwana margin extension, the South-Armorican branch of the Rheic Ocean opening and the Armorican–Galatian terrane microplate temporary separation at ca. 440 Ma. This rock-suite shows the early Variscan (Devonian) metamorphic ages at ca. 410–380 Ma due to the closure of the short-lived Prototethyan South-Armorican "Ocean" (Faure et al., 2005; von Raumer and Stampfli, 2008) and the northwards subduction. Meta-ophiolites of the Pernek Group (an N-MORB meta-gabbrodolerite dated at 371±4 Ma) in the Tatric basement, analogous to island-arc tholeiites and back-arc basin basalts, indicate a Late Devonian BAB setting north of a 410–380 Ma old northwards dipping subduction-accretion zone, dividing the Armorican–Galatian terrane microplate from the Gondwana margin. The SIMS dated gabbros from the Gemeric basement volcano-sedimentary Gelnica and Rakovec Groups showed pre-rift Cambrian–Ordovician ages. Gabbros with the Devonian ages occur in the Klátov Group gneiss–amphibolite complex thrust southwards over the Rakovec and Gelnica Groups. New geochronological data from the Klátov Group yielded magmatic ages of N-MORB-type gabbroic rocks ranging from ca. 410 to 380 Ma (Putiš et al., 2017), indicating an ocean rift zone evolution (Radvanec and Grecula, 2016; Németh et al., 2016a) of a peri-Gondwanan Paleotethyan basin, contemporaneously with the South-Armorican "Ocean" closure. This Group was partly incorporated into the North-Gemeric Carboniferous mélange-like tectonic zone (Németh et al., 2016b). Besides the rocks of the inferred sea-floor suite (gabbros, plagiogranites, basalts, ultramafics), the Klátov Group also encompasses continental margin rocks containing zircon of the various Neoproterozoic to Early Paleozoic (Cambrian to Early Devonian) sources. A part of the meta-sedimentary rocks shows clastogeneous texture rich in amphibole and plagioclase most likely derived from an active margin magmatic sources during the Devonian riftogenesis. The closure of the Paleotethyan Devonian–Early Carboniferous basins was accompanied by the MP/MT metamorphism of the Pernek Group (Putiš et al., 2004). Tectonic fragments or the high-pressure blueschist to eclogite facies meta-gabbroic rocks (Radvanec, 1999) occur within the Rakovec Group greenschists. Such kind of a clinopyroxene meta-gabbro shows zircon metamorphic age of 350±5 Ma. At that time, the Paleotethyan complexes of the Gondwana margin, as the Variscan Lower Unit, were northwards accreted to the Armorican–Galatian microplate, the latter being represented by the early Variscan Tatric and Veporic (Prototethyan) basement complexes. The West-Carpathian basement shared a common geological history with the terranes of the northern Gondwana margin from Neoproterozoic to Carboniferous times.

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The Eoalpine Orogen evolution from Permian–Triassic extension to Jurassic–Eocene accretion determined by Zrn U/Pb SIMS, microprobe Mnz and WhM Ar/Ar ages in the Western Carpathians and the Eastern Alps

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The Eoalpine orogeny segments are characteristic in Alcapia, Tisia, Dacia and Adria microplates (Schmid et al., 2004, 2008; Handy et al., 2010). The Eoalpine events were dated in the Slavonian Mts. (115–110/80 Ma; Balen et al., 2017), Apuseni Mts. (125–100/80 Ma; Dallmeyer et al., 1996, 1999; Reiser et al., 2016), Western Carpathians (135–100/70 Ma; Dallmeyer at al., 1996, 2005; Putiš et al., 2009; Vozárová et al., 2014) and Eastern Alps (100–90/70 Ma; Thöni and Jagoutz, 1993; Thöni, 1999; Dallmeyer et al., 1996, 2008). We searched these events in the Austroalpine-Inner Western Carpathian (AA–IWC) Block of Alcapia (ALCAPA sensu Neubauer, 1992) microplate separated from the Pelsó Block in the south by the Periadriatic-Rába-Hurbanovo-Diósjenö Fault. The IWC Eoalpine Orogen can be traced from the Meliatic–Gemeric–South Veporic (ME–GE–SVE) accretionary wedge in the S, to the North Veporic–Tatric–Infratatric (NVE–TA–IFTA) accretionary wedge in the N. The Eoalpine Orogen of the IWC yields white mica (WhM) ^{40}Ar–^{39}Ar plateau ages of 115–80 Ma or 50–45 Ma in the IFTA (Putiš, 1992) segment, 100–70 Ma or 50–45 Ma in the north-TA segment, 95–80 Ma in the NVE segment, or 125–85 Ma in the SVE and GE segments. Both wedges contain calc-alkaline and A-type volcanic, less plutonic acid to basic bodies of Permian, exceptionally Triassic age (Kotov et al., 1996; Uher and Broska, 1996; Poller et al., 2000; Putiš et al., 2000, 2016; Uher et al., 2002, 2004; Vozárová et al., 2009, 2012, 2015, 2016; Demko and Hraško, 2013; Spišiak et al., 2015) related to Pangea breakdown and the Neotethys opening. The Meliata Unit mid-Triassic silicites, interlayered with N-MORB, contain zircon (247–243 Ma) from a Lower Triassic acid source (Putiš et al., 2011).

The ME–GE–SVE accretionary wedge has formed between 135 and 85 Ma, due to the closure of the Neotethys Meliata BAB and southward subduction of its oceanic and marginal continental crust between 170 and 150 Ma that was dated on blueschist phengite (Dallmeyer et al., 1996; Faryad and Henjes-Kunst, 1997). The exhumation and cooling of the HP rocks between 150 and 130 Ma (rodingite perovskite U/Pb and zircon U–Th/He ages; Putiš et al., 2014, 2015; Li et al., 2014) was driven by the passive continental margin GE and SVE units underthrusting to about 20-30 km depth underneath the Meliata Unit being a part of the upper plate. The D1 burial stage of the GE Unit can be documented by Mnz microprobe isochrone age of 135 Ma from a Permian meta-rhyolite (Vozárová et al., 2014) and the WhM Ar/Ar ages between 130 and 120 Ma from the sheared basement metasediments, followed by the exhumation ages up to 85 Ma (Siman and Vozárová, in prep.). The SVE Unit underthrusting to about 30 km depth in this wedge achieved a higher medium-P greenschist- to lower amphibolite facies conditions (Putiš et al., 1996, 1997; Korikovsky et al., 1997; Janák et al., 2001). A trachyte dyke, crosscutting the Permian–Lower Triassic cover, yielded an older microprobe Mnz isochrone age of 130 Ma, consistent with the D1 WhM Ar/Ar ages around 125 Ma. The younger Mnz isochrone age of 100 Ma is coeval with the D2 WhM exhumation ages of 100 to 85 Ma. The buoyant underthrust continental crust, after mechanical weakening, was exhumed by the mechanism of top-to-the ESE/SE structural unroofing and sinistral transpression (Putiš, 1994). The (ME–)GE–SVE accretionary wedge of the IWC can be correlated with the Upper Austroalpine (UAA) structural complexes of the Eastern Alps (Schuster et al., 2004; Schmid et al., 2004), both representing the Meliatic passive continental margin (Putiš, 1991). We searched the UAA Kreuzeck Massif hanging wall HP Polinik complex overlain by Strieden, Hochkreuz and Steinfeld complexes, thrust over the Ragga complex (Putiš et al., 2002a; Michálek et al., 2012) of the Lower Austroalpine (LAA) position. Similarly, in the eastern Austroalpine margin, the UAA Sieggraben complex (Putiš et al., 1994, 2000, 2002b, 2017; Korikovsky et al., 1998) is overlying the LAA Grobgneis and Wechsel complexes. The eclogitic Sieggraben complex (analogous to the Polinik c. in the Kreuzeck Massif) forms isolated kilometer-size HP tectonic slices overlying the LAA Grobgneis Unit. It represents Variscan basement that underwent Cretaceous eclogite-facies metamorphism (e.g., Thöni, 1999; Schuster et al., 2004), now composed of mafic eclogites, meta-gabbros, amphibolites, ortho- and para-gneisses, marbles, less peridotites and pyroxenites. The eclogitized continental crust fragments contain Permian (256±2.8 Ma) gneisseous granite veins. A clinopyroxenite dyke in harzburgite, associated with eclogites, was dated on zircon at 252±2.4 Ma near Steinbach in Burgenland, Austria. The underlying Grobgneis granitic orthogneiss was dated at 265±2.2 Ma. These ages indicate a strong Permian crust-mantle extension and overheating during the Pangea breakdown and the Neotethys opening. The Cretaceous subduction was dated on an Ordovician gabbro (468.8±5.4 Ma) transformed to an eclogite lens at 89.8±4.2 Ma (Zrn U/Pb) of this complex at Sieggraben (ca. 80 km S of Vienna).

The NVE–TA–IFTA accretionary wedge was dated to 114±2.4 and 106±3.7 Ma from the newly-formed WhM in the Early Cretaceous cherty slates found as olistoliths in the Late Cretaceous flysch of the lower IFTA Belice Nappe (Putiš et al., 2006, 2008). The WhM ages from the higher IFTA Inovec Nappe basement micaschists and the Upper Paleozoic cover range from 105 to 83 Ma. The ages older than 100 Ma record the Inovec Nappe distal thinned Jurassic–Early Cretaceous continental margin underthrusting (ca. 250–300°C at min. 6–7 kbar) below the north-TA edge forming an Albian accretionary wedge most likely due to the closure of a Neotethyan (East-Vardar type?) Ocean north of this wedge. This might be supported by the IFTA foreland Albian Klape flysch blueschist pebble glaucophane Ar/Ar age of 155 Ma (Dal Piaz et al., 1995). The WhM ages of 90 to 70 Ma indicate the exhumation of the Albian IFTA/north-TA wedge due to the inferred Váhic (~South-Penninic) subduction underneath this wedge and opening the suprasubduction Belice fore-arc trough. The ages of 50–45 Ma are related to the closure of the Belice trough and the lowest anchimetamorphic overprint of the trough Late Cretaceous sediments, contemporaneously with the Magura (~North-Penninic) Ocean closure. The IFTA Unit was exhumed in the Miocene tectonic window (23–13 Ma Ap FT ages; Danišík et al., 2004). The Aptian to Cenomanian (ca. 115–95 Ma) flysch formations of the NVE–TA–IFTA wedge record the convergence-related exhumation of the Eoalpine segments often incorporating material from the Late Jurassic to Early Cretaceous Neotethyan mélanges. These can be traced from the IWC IFTA segment along the Main Tethyan Suture Zone (Săndulescu, 2009) up to the Romanian Apusenides nappe structure of Tisia with the Ar/Ar ages of 125 to 100 Ma (Dallmeyer et al., 1996). The eastwards thrusting of Transylvanian nappes over the Median Dacides Bucovinian nappes is most likely related to the closure of the Neotethys East Vardar Ocean (Savu, 2010). The Transylvanian nappes contain Triassic ophiolites and related sediments as olistoliths in Barremian to Albian wildflysch (Hoeck et al., 2009; Ionescu et al., 2009). They resemble the Triassic ophiolites, volcanics and sediments found in the Albian Klape flysch (cf. Mišík and Marschalko, 1986; Ivan et al., 2006). The NVE–TA–IFTA wedge is therefore tentatively correlated with the Eoalpine nappe system of Tisia Apusenides (Putiš et al., 2017). The IFTA segment seems to be a remnant of an Ultrapieninic ridge that almost completely disappeared during Cretaceous and Paleogene subduction-erosional processes when the inferred connection between the NVE–TA–IFTA wedge and the Tisia Apusenides was interrupted. The Tisia(–Dacia) Neogene clockwise rotation (Márton et al., 2007) may have diversed this block from Alcapia. A westward equivalent of this wedge could be the Arosa continental margin Walsertal zone (Winkler et al., 1988), where the Aptian to Albian flysch contains HP blue amphibole (Gln), lawsonite and Cr-spinel clasts, resembling the Klape wildflysch. These „pre-Gosau“ wedges and mélanges must have formed before the South-Penninic (~Váhic) closure. The Neotethyan East-Vardar suture (Mureş zone) could continue N-NW-W-wards and converge with the Atlantic (Alpine) Tethys suture from the Maramureş Mts. (northern E. Carpathians). Its westward pendants could be the peri-Klippen Belt IFTA segment and probably the Walsertal zone of the E. Alps, tracing a Permian–Triassic Neotethys intracontinental rift and detachment zone of a hypothetic „Alcapo-tisia“ micro-continent from the south-European Variscan basement.

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What drives Alpine Tethys opening: Suggestions from numerical modelling

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We discuss the results obtained for two subsequent numerical models that simulate the evolution of the European lithosphere from the late collision of the Variscan chain to the Jurassic opening of the Alpine Tethys. The first model accounts for the evolution of the crustal lithosphere after the Variscan subduction and collision (300 Ma) up to 220 Ma (Marotta et al., 2009). The second model accounts for the rifting of the continental lithosphere from 220 Ma up to reach the crustal breakup and the formation of the oceanic crust (Marotta et al., 2016). For both models, different initial geodynamic configurations have been tested and we compare the results with natural data of Permian-Triassic metamorphic rocks and Jurassic gabbros and peridotites, to evaluate which configuration best matches the observations. Natural data belong to different structural Alpine domains. Continental rocks are collected from Helvetic and Penninic domains (European paleomargin) and from Austroalpine and Southalpine domains (Adriatic paleomargin) and oceanic rocks are collected from Alpine and Apennine ophiolites. The comparison is made in terms of the contemporaneous agreement to lithology, pressure and temperature values, and ages. The comparison between Permian-Triassic to Jurassic natural data from the Alps and the Northern Apennines and two subsequent numerical models simulating the evolution of the lithosphere from the late collision of the Variscan chain to the Jurassic opening of the Alpine Tethys suggests that: i) a forced extension of the lithosphere results in a thermal state that better agrees the Permian-Triassic high temperature event(s) than a solely late-orogenic collapse; ii) a rifting developed on a thermally perturbed lithosphere agrees with a hyperextended configuration of the Alpine Tethys rifting and with the duration of the extension up to the oceanization. These results suggest that the Alpine Tethys rifting and oceanization developed on a lithosphere characterized by a thermo-mechanical configuration consequent to a post-Variscan extension affecting the European realm during Permian and Triassic. Therefore, a long-lasting period of continuous active extension can be envisaged for the breaking of Pangea supercontinent, starting from the unrooting of the Variscan belts (~300 Ma), followed by the Permian-Triassic thermal peak highlighted by HT-LP metamorphism and gabbros emplacement, and ending with the crustal breakup and the formation of the Alpine Tethys ocean (170-160 Ma). This process could be characterized by alternated period of active extension and stasis, as proposed for the Northern Atlantic rifting or as envisaged for the Ivrea-Verbano Zone based on three metamorphic ages.

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Sedimentary record of Norian to Middle Jurassic tectonic pulses in Slovenian Basin

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Slovenian Basin is a deep-water paleogeographic domain today located at the intersection between the eastern Southern Alps and the Dinarides. It originated due to the opening of the Meliata-Neotethys Ocean during the Ladinian and lasted until the end of the Mesozoic. It was bordered by the Dinaric (Adriatic, Friuli) Carbonate Platform to the south and by the Julian Carbonate Platform to the north. Within the Norian to Middle Jurassic succession of the Slovenian Basin, four pulses of intense synsedimentary tectonic activity can be recognised. The first, middle Norian in age, is recorded as dolomite-chert breccia megabeds within the Bača Dolomite formation. Synsedimentary normal faults, sealed by younger beds, were also observed. This tectonic pulse coincides with the formation of small-scale basins recorded in the Carnic Alps. The second pulse occurs at the Triassic-Jurassic boundary or slightly postdates it. In the western part of the basin, it is manifested by several-tens-of-meters thick horizons of limestone breccia megabeds that mark the base of the Hettangian-Pliensbachian Krikov Formation. These megabeds contain basinal, slope and platform margin clasts, the latter being dated to latest Triassic and also earliest Jurassic. Towards the east, these beds thin-out, but block tilting is still evident from the lateral variations in thickness and facies of the Krikov Formation. This pulse correlates with the initial rifting phase of the Piemont-Ligurian (Alpine Tethys) Ocean recorded in the western part of the the Southern Alps and other domains of the Adria margin. The third event is late Pliensbachian-Toarcian in age and is manifested clearly in the disintegration of the Julian Carbonate Platform, namely, in the formation of small-scale basins at the platform margin (e.g. Bovec Through). In the central part of the platform, neptunian dykes formed. The final manifestation of this pulse, however, is in the termination of shallow-water production on the Julian Carbonate Platform. This tectonic pulse is generally less evident in the Slovenian Basin but can be recognised in the change in the composition of calciturbidites at the top of Krikov Formation (from ooidal/peloidal to crinoidal/lithoclastic) and the highly variable thickness of the overlying, Toarcian marl-dominated Perbla Formation (from 0,5 to 130 m). Some synsedimentary slumps were also observed at the base of the Perbla Formation. This event coincided with the second rifting pulse recorded at the Adria western margin in the present-day Southern Alps. The fourth tectonic event is Bajocian-?Callovian in age reflected in thick limestone breccia megabeds that mark the entire southern margin of the Slovenian Basin. This breccia contains slope and basin litho/intra clasts and Late Triassic to Early Jurassic platform lithoclasts, whereas the matrix is dominated by ooides. Towards the central parts of the basin, these beds thin out to sporadic calciturbitites which are interbedded between radiolarian cherts of the Tolmin Formation. The slumping within the basal portion of radiolarian cherts can also be related to this event. This last prominent event coincides with the Piemont-Ligurian oceanisation, but is more probably related to the onset of thrusting (obduction) in the inner domains of Adria facing the Neotethys Ocean, which is well documented in the Internal Dinarides as well as in the Eastern Alps.

Tectonics and geodynamics of the Dinarides and Hellenides: Similarities and differences

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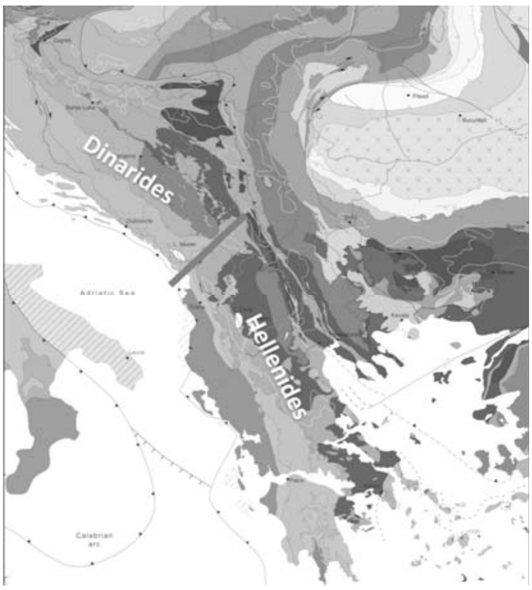
The NW-SE strike of the Dinarides abruptly changes across the Skutari-Pec Transverse Zone (red bar in map depicted below) in northern Albania into the NNE-SSE strike of the Hellenides typical for mainland Greece. At the same location the front of the obducted West-Vardar ophiolites is displaced towards the SW. Both orogens are basically made up of the same nappe units, the internal ones being composite nappes consisting of Adria passive margin sequences overlain by ophiolites obducted in the latest Jurassic. All these nappe units formed in Late Cretaceous to Early Cenozoic times (see figure below).

The change in strike between Dinarides and Hellenides was induced by massive slab pull associated with the roll back of the Aegean slab. In the Rhodopes slab retreat initiated already in Late Eocene times while it did not commence before the Oligocene in the Internal Dinarides where it was associated with slab break-off. The Aegean slab, however, persists until the present. Ongoing massive retreat during the Miocene not only led to the formation of the Kephalonia transform at the northern end of the curved Aegean trench but also affected external units in Albania further north (Ionian nappes) up to the Skutari-Pec transverse zone that hosts a normal fault, the Skutari-Pec normal fault, formed in the Late Miocene and accommodating the clockwise rotation of the Hellenides of mainland Greece. The activity of the Skutari-Pec normal fault is contemporaneous with Miocene shortening in the external Hellenides of southern Albania and mainland Greece. Such Miocene shortening is, however, very minor in the external Dinarides north of the Skutari-Pec normal fault. The formation of the curved Hellenic trench was associated with delamination of the 1800km long Aegean slab, leading to massive extension in the Aegean back-arc area amounting to some 400km arc-perpendicular extension and an equal amount of arc-parallel extension since the Miocene. It is the the slab pull exerted by the delaminated Aegean mantle slab that represents the driving force for the rotation of the Hellenides in respect to the Dinarides



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Regional-scale extension in the contractional External Dinarides, Montenegro and northern Albania. Does it document the onset of "Aegean-style" tectonics?

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With a Mw = 7.2 earthquake in 1979 off Montenegro, the southern Dinarides fold-and-thrust belt experienced one of the strongest instrumentally recorded earthquakes in Europe (Benetatos and Kiratzi, 2006). Coastal settlements like the historic towns of Bar and Budva, located within a few km of the 1979 epicenter, still show marks of recurring destructive events. The majority of the available earthquake focal mechanisms along the front of the Dinarides indicate reverse faulting (e.g. D'Agostino et al., 2008), suggesting ongoing NE-SW-convergence between Adria and Eurasia, in agreement with GPS studies (Bennett et al., 2008; Jouanne et al., 2012; Faccenna et al., 2014). However, this contrasts with new evidence for widespread active extension in the coastal areas of southernmost Montenegro and northern Albania.

The best documented example for such extension is a c. E-W-trending fault scarp, that can be traced at least for 7.2 km, running from Donja Poda, along the Rumija chain towards Bojke. It juxtaposes Mesozoic bedrock against colluvial slope scree. Very uniformly plunging fault striae on the undulating fault planes indicate SW-directed extensional movement. Varicoloured horizons of equal height are frequently found along the 2-42 m high exposed fault surface, representing former weathering horizons that were displaced by progressive (possibly seismogenic) normal fault motion. Three suitable sites along the scarp(s) were sampled for Cl^{36} dating of the exposed fault surface, which are expected to allow an estimation of fault slip rates and recurrence intervals of earthquakes.

Since the fault throw along the identified scarps is in the order of only a few meters presumably since the last LGM, we suspect that they represent embryonic faults. Their connection to active seismogenic faults, such as the causative fault of the 1979 earthquake, which accommodated horizontal shortening, is as yet unclear. Possibly, the embryonic extensional fault scarps document either a gravitational collapse or a recent transition from horizontal shortening to a horizontal extension in the frontal portions of the Dinarides fold-and-thrust belt. This "Aegean-style" tectonic behaviour, in which thrust faulting is confined to a narrow belt along the deformation front and where normal faulting dominates the internal portions of the orogen, develops as a consequence of continuing rollback of a subducting lithospheric slab (Burchfiel et al., 2008). Our findings hence document an important snapshot of transient kinematics in a continental fold-and-thrust belt behaviour, triggered by lithosphere-scale processes.

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Kinematics and age of the orogen-perpendicular Shkodër-Peja-Normal-Fault, northern Albania

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This contribution reports on preliminary results of an ongoing approach to constrain kinematics and age of the NE-SW-trending, orogen-perpendicular Shkodër-Peja-Normal-Fault (SPNF) at the transition from the Dinarides to the Hellenides fold-thrust belts in northern Albania. The SPNF juxtaposes pelagic units of the so-called Budva-Cukali zone in the footwall (spectacularly exposed in a half-window to the north) against the tectonically overlying Mirdita ophiolites. Fault-related fabrics can be identified in a zone of several tens of meters thick, affecting both footwall and hanging wall to varying amounts. Shear sense indicators in foliated cataclasites in both footwall and hanging wall lithologies across the SPNF, as well as brittle faults overprinting the cataclasites, consistently indicate a top-SE extension. The SPNF also truncates km-scale, SW- to locally S-facing folds affecting the entire footwall succession from the Triassic to the Eocene. This clearly implies that extensional movement along the SPNF postdates orogen-perpendicular contraction of Palaeocene to Eocene age. Apatite fission track (AFT) data from Maastrichtian (?) to Eocene siliciclastics in the footwall of the SPNF yielded central ages between 29.0 ± 8.8 and 20.8 ± 6.0 Ma (ZERTANI, 2015), i.e. younger than the depositional ages. This suggests that (1) the footwall succession saw a tectonic overburden large enough to reach the partial annealing zone of apatite and (2) its cooling was triggered by extensional unroofing below the SPNF during the Oligocene to lowermost Miocene. The findings of Zertani (2015) appear very feasible in the light of our measurements of the illite crystallinity from fault-related rocks, which indicate that anchizonal conditions were reached.

In order to improve timing constraints for the fault activity, we have dated illite fine fractions of fault gouges and cataclasites derived from both footwall and hanging wall of the SPNF by means of the K-Ar-method. Ages were determined on three size fractions (<0.2, < 2 and 2-6 microns). Fine fractions obtained from Maastrichtian (?) to Eocene siliciclastics in the footwall yielded ages between 106 and 47 Ma. A sample from the hanging wall, derived from tectonized Jurassic sandstones, gave K-Ar ages between 69 and 50 Ma. All these ages possibly represent mixed populations of both inherited and newly formed illites. The absence of any illite K-Ar ages in the range of the Oligocene AFT ages reported by Zertani (2015) is puzzling, but possibly best explained when recalling that extension along the SPNF was distributed across a shear zone of several tens of meters thickness. It is thus conceivable that rather than accommodating strain across the entire shear zone, faulting was most likely repeatedly switching between numerous smaller, anastomosing fault strands, leading to an incomplete rejuvenation of illite fine fractions in the fault zone despite favourable temperature conditions.

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Unrevealing the internal structure of Austroalpine basement nappes by using the mineral compositions and fractionation trends of Permian pegmatites (Eastern Alps/Austria)

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The Austroalpine Unit represents a complex nappe stack formed during the Eoalpine tectono-metamorphic event in Cretaceous time. In variable portions, the nappes consist of metamorphic basement rocks and Paleozoic and Mesozoic (meta)sediments. If slices of Mesozoic (meta)sediments are present it can be used to separate individual basement dominated nappes, but when they are missing the subdivision has to be based on the internal structure, metamorphic imprint and lithological composition of the basement rocks. Especially in the Cretaceous amphibolite to eclogite facies rocks of the Koralpe-Wölz nappe system in the Saualpe and Koralpe area, the subdivision is tricky. Recent studies reveal that the mineral compositions and fractionation trends of Permian pegmatites and newly found indications for initial migmatisation in the surrounding metapelites give an additional opportunity to determine the nappe boundaries more precise and give hints on the internal structure of the individual nappes. In the following three examples are given:
The basement in the area of St. Radegund (Styria) consists of two nappes with gneisses formed from Permian pegmatites only occurring in the lower Radegund nappe. In the southeastern part of the latter pegmatite gneisses composed of feldspar and quartz with minor muscovite and extremely scarce garnet and tourmaline appear. The surrounding mica schists are biotite rich, medium-grained and show indications of pre-Alpine migmatisation and andalusite/sillimanite bearing assemblages. In contrast, at the top of the unit along the tectonic contacts to the overlying nappes additionally spodumene and beryl occur in the pegmatite gneisses, which are situated in more fine-grained staurolite bearing mica schists. Chemical compositions (e.g. Li content, K/Rb ratio) of cm-sized magmatic muscovites from pegmatite gneisses indicate increasing fractionation towards the top of the unit and an upright position of the rock series with respect to the Permian situation.

The Plattengneis shear zone represents a major structural element within the eclogite bearing rock series of the Koralpe Mountains (Styria/Carinthia). It is still a matter of discussion with respect to its kinematics and geological significance. Rock series below the shear zone include schists with dm-sized kyanite pseudomorphs after Permian chiastolitic andalusite. Pegmatite gneisses therein contain frequent garnet and tourmaline and spodumene at one locality. Within the structural lower part of the Plattengneis shear zone pegmatite mylonites are rich in garnet and tourmaline, whereas those in the upper part are composed only of feldspar and quartz and even muscovite is extremely scarce. It seems that an important nappe boundary is situated within the shear zone.

At the southern slopes of the Koralpe Mountains the Plankogel Complex is overlying the eclogite bearing rock series. It is mainly formed by mica schists with intercalations of serpentinites, amphibolites and quartzites. Further Permian pegmatite gneisses containing cm-sized magmatic muscovite and scarce garnet and tourmaline are present. Based on the K/Rb ratios in muscovites they are moderately fractionated. The mica schists are characterised by complex textures which formed during Permian HT/LP metamorphism and a pressure dominated Eoalpine (Cretaceous) overprint. Textures of the mica schists indicate a first Permian assemblage including garnet1 + staurolite1. Still during the Permian HT/LP event staurolite1 broke down to andalusite. During the Eoalpine overprint garnet2 + staurolite2 formed, and in the lower part of the section, andalusite was transformed into fine-grained kyanite patches. The interpretation of the textures implies an upright position of the Plankogel Complex with respect to the Permian situation.

Miocene syn-rift lacustrine sediments in SW Hungary

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Mecsek Mts. in SW Hungary is the only area in Hungary within the Tisza Unit basement block, the SE half of the Pannonian Basin, where syn-rift sediments can be well studied on the surface. Above the widespread Lower Miocene fluvial clastics, the Budafa Formation contains the first stillwater deposits. It is traditionally considered to be of Karpatian age and partly heteropic sediments of varied lithologies are classified into its three members; however, the exact age, depositional environment and relationship of the members is debated. Recent work has provided new biotic, stratigraphic and tectonic data on the formation.

The older members of the formation are the Pécsvárad Limestone („*Congeria* unit"), mostly with coastal conglomerates, sandstones and bioclastic limestones, and the Komló Claymarl („fish-scale-bearing claymarl"), built up of calcareous silt, claymarl and fine sands. Macrofauna in both members is poor and indicates fresh or slightly brackish water. Molluscs are represented by *Congeria boeckhi* and *Ferebithynia* (*Bulimus*) *vadaszi* up to rock-forming quantities, additional macrofauna is composed of very few molluscs – *Gyraulus*(?) and *Stagnicola*(?) sp. – and fish remnants. The ostracod assemblage is low-diversity and indicates the littoral zone of freshwater or slightly brackish, permanent or intermittent lakes: *Heterocypris(?)* sp., *Heterocypris* cf. *salina*, *Cyclocypris*(?) sp., *Candona* sp., *Candona* (*Pseudocandona*) sp., *Candonopsis* sp., ostracoda indet. (probably gen. nov., sp. nov.). Recent collecting activity explored a rich macroflora in the western Mecsek Mts., with a strong presence of Lauraceae like *Daphnogene cinnamomifolia*, and further species – e.g. *Zelkova zelkovifolia*, *Zizyphus paradisiaca*, *Quercus kubinyii* or other evergreens like *Nerium* sp. – characteristic of warm, subtropical climate. Swamp plants like *Glyptostrobus europaeus* and *Myrica lignitum* occurred only sporadically, pointing to the restricted distribution of low-relief coastal plains.

Syn-sedimentary extensional movements are documented by pre-diagenetic (soft-sediment) deformations in both members and produced a rugged relief. Dissected topography is further supported by the vegetation, by the patchy occurrence of the two members and the spatial distribution and thickness of various lithofacies referring to gently sloping vs. steep shores. Due to the endemic fauna, dating could only be possible through the tuff interbeds; however, previous age data are highly uncertain. A new K/Ar dating gave a Karpatian age.

The uppermost member (Budafa Sandstone) overlies both previous ones and contains euhaline, (sub)tropical micro- and macrofauna. Neither new micropaleontological analyses nor the revision of archive data showed forms indicative of Karpatian age; the microfauna belongs to the upper part of NN4 zone, to the Lower Badenian.

The Pécsvárad Limestone and the Komló Claymarl Members can be interpreted as lacustrine sediments with endemic mollusc and ostracod species and are of Karpatian? age; more dating is needed to affirm this. Lake basin formation can be attributed to tectonic movements related to rifting of the Pannonian Basin. Paratethys flooded the area in the Early Badenian and deposited the Budafa Sandstone Mb. Considering both structural background and evolution history, the Mecsek area can be related to the Dinaric/Serbian Lake System.

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Paleocurrent Analysis as the Important Indicator of Paleogeography Determination at Bantarujeg, West Java, Indonesia

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Bantarujeg District is a well-known research area for geologists in Indonesia. Geological mapping sometimes conducted in this area, but detailed analysis of Paleocurrent have not been carried. Paleocurrent analysis itself is important for doing a geological reconstruction of a research area. The aim of this study is to gain detailed information about paleocurrent analysis in ripple-mark to determine paleocurrent direction and also paleogeography of Bantarujeg which is known from lithofacies analysis and the result of paleocurrent itself. The method is based on field data observation, acquiring azimuth dispersion of paleocurrent on ripple mark of the outcrops, then analyze the data in rose diagram. A total of 50 paleocurrent measurement on ripple marks surface is conducted at coordinates S 06^0 57’ 59’’ and W 108^0 15’ for the collection of data. Compass Tape and Traverse method of about 150 meters trajectory is also conducted to interpreted the depositional environment, so the paleogeography of Bantarujeg can be assumed. Based on paleocurrent data analysis in the rose diagram, it is known that sediment was transported from Northwest to Southeast. The pattern of incomplete Bouma Sequence mostly found in this area and interpreted as deep water deposit. The combination of paleocurrent analysis and lithofacies analysis shows that terrestrial environment was placed on the Northwest and marine environment was placed on the Southeast.

The late Cretaceous lamprophyres from Tešića Majdan (Belgrade) within the Sava Zone: Petrology, geochemistry and geodynamic significance

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The Sava Zone in the Balkans potentially represents a remnant of the most recent suture between European and Adriatic plates generated after the closure of the Neotethyan Ocean (Gallhofer et al., 2015, Prelević et al., 2017). Slightly metamorphosed terrigenous sediments and rare but widespread magmatic bodies of the Cretaceous age are the most important lithologies that occur along this zone. There are several magmatic centres outcropping along the Sava Zone, including Maslovačka Gora and Prosara in Croatia, Kozara in Bosnia and Herzegovina and Klepa in Macedonia-FYROM. In this contribution, we focus on geochemistry, petrology and the age data of the Tešića Majdan plutonic body in the Sava Zone south of Belgrade, for which our new data reveal a Late Cretaceous age. A decametre sized Tešića Majdan plutonic body represents a sill-like occurrence that intrudes the Upper Cretaceous flysch sediments. Our new Ar-Ar data measured on two samples of biotite separates gave the age of 86.80±0.5 Ma and 86.90±0.5 Ma. The rocks are phaneritic, medium to fine-grained with partly chloritized biotite (20.55% vol.), slightly uralitized/chloritized augite (21.12% vol.), heavily albitized/saussuritized plagioclase (48.01% vol.) and minor orthoclase and apatite. This modal composition implies that the rocks from Tešića Majdan represent calc-alkaline lamprophyres. In more detail, they should be classified as a member of the Vaugnérite series, which represent the plutonic equivalents of minette and kersantite (Rock, 1991). Tešića Majdan lamprophyres are characterized by high Na, P, Al and low Mg, K, Ca. Their probable potassium rich nature is obscured by ubiquitous albitization resulted in the low K/Na ratio. Trace elements show typical arc signature characterized by enrichment in LILE and LREE relative to HFSE. Compared to their counterparts from the Sava Zone reported from the Klepa (Prelević et al., 2017) and Kozara (Ustaszewski et al., 2009) volcanic centers, Tešića Majdan rocks demonstrate a more enriched Sr^{87}/Sr^{86} (0.70667-0.706767) and Nd^{143}/Nd^{144} (0.512426-0.512429) isotopic signature that falls in the enriched quadrant of the Sr-Nd isotope diagram. The Pb isotope composition of the Tešića Majdan lamprophyres ($^{206}Pb/^{204}Pb$ 18.821-19.128, $^{207}Pb/^{204}$ Pb 15.669-15.681, $^{208}Pb/^{204}Pb$ 38.924-39.190) is falling within the pelagic sediment field resembling Mesozoic flysch sediments from the Vardar suture zone. This signature is also similar to post-collisional Tertiary ultrapotassic rocks (Prelević et al., 2005). Tešića Majdan lamprophyric magma is derived from a metasomatized mantle source that probably consists of metasomatic phlogopite-rich domains. These metasomatic domains are situated within a continental lithospheric mantle previously metasomatized during Mesozoic subduction events, and activated due to Cretacious transtensional tectonics.

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Calc-alkaline lamprophyres from Nízke Tatry Mts. (Western Carpathians)

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There have been reported several bodies of vein rocks (Hovorka, 1967, Krist, 1967) from a wider area between Mýto pod Ďumbierom, Jarabá and the Čertovica saddle on the southern slopes of the Nízke Tatry Mts (Western Carpathians). These bodies occur in the gneisses of the Tatride Palaeozoic crystalline complexes and they are from 2 to 25 meters thick. The examined lamprophyre rocks are similar to these rocks in composition – they are dark-green rocks with fine grained to the aphanitic matrix. The phenocrysts are formed by clinopyroxene biotite and amphibole, rarely also by quartz. Based on the IMA classification (Morimoto et al., 1988), the composition of clinopyroxene corresponds to augite. Biotite corresponds to Fe-biotite (Foster, 1960) and amphibole to magnesiohornblende (Hawthorne et al., 2012). The matrix consists of biotite, amphibole and plagioclase; there is also abundant apatite and from ore minerals mainly pyrite. The most widespread mineral is plagioclase feldspar with typical albite lamellae and basicity varying between andesite and labradorite. There is also represented alkali feldspar. The quartz is mostly allomorphous, often undulous. On the basis of modal composition (IUGS classification, Le Matre et al., 2004), we can classify the examined rocks as karsantite. Irrespective of dyke thickness, the chemical composition of these rocks from different localities is similar. They are typical for rather rich TiO_2 (2.2 weight %) and FeO (10 wt. %) and for prevailing K_2O over Na_2O. In a TAS classification diagram, the analyses of the studied lamprophyre fall within the field of basaltic andesite. In a similar lamprophyre classification diagram (SiO_2, TiO_2, CaO; Rock 1989), they lie in the field of calc-alkaline lamprophyres. The calc-alkaline character of the studied lamprophyre is documented also from various discriminant diagrams of trace elements (Hf-Th-Ta, Wood 1980; Y-La-Nb, Cabanis-Lecolle, 1989 etc.). In terms of geotectonics, they correspond to volcanic arc calc-alkaline basalts. The normalized curve of rare earth elements distribution is rather flat with a slight enrichment in LREE and a rather strong negative Eu-anomaly. The $^{87}Sr/^{86}Sr$ isotope ratio (0.717615) points to a crust material admixture during lamprophyre magma generating. The age of the lamprophyre was detected by LA-ICP-MS U-Pb dating and in both localities was identical, 259 ± Ma.

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Grain Size Distribution and Depositional Environment of Bantarujeg Area, Majalengka based on Granulometry Analysis

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Bantarujeg area is well-known research study with well-exposed outcrops and quite complex of geological setting. Many researches have been done in that area but detail observation about granulometry analysis has not been done. Granulometry analysis is the method to identify the change of grain size (mean, sortation and skewness) to determine the distribution, transport mechanism and depositional environment. The depositional environment analysis able to identify the condition, time and age of sediment deposit. The method which builds up this research is the literature review, field observation and laboratory test. The field observation shows at CJRY-1 have breccia with matrix supported, CJRY-2 have very fine – very coarse sandstone, fining upward with parallel lamination structure, CJRY-3 have shale bedding, shally and contains carbonate and CJRY-4 have sandstone bedding with cross lamination structure. The laboratory test using the statistic method shows that all of the observation areas are dominated by grain size from fine to coarse sand, the difference was found at CJRY-1 with the sortation value at 0,38, skewness value at -0,26 and kurtosis value at 0,69, CJRY-2 with the sortation value at 0,25, skewness value at -0,08 and kurtosis value at 0,73, CJRY-3 with the sortation value at 0,15, skewness value at 1,28 and kurtosis value at 0,66, CJRY-4 with the sortation value at 0,30, skewness value at 0,24 and kurtosis value at 0,57. The laboratory test using the graphical probability method has revealed that the transport mechanisms were saltation and suspension. From this granulometry analysis we can conclude that the research area is included in the marine depositional environment.

From Seismotectonics to Geodesy: What is (un)correlated in the W-Alps?

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Recent geodetic analyzes in the W-Alps brought new and accurate mapping and quantification of the vertical and horizontal deformations in the belt. Vertical motions appear about 10 times larger than horizontal ones, which support geodynamic models implying isostatic adjustments within the Alp's orogeny (intrinsic buoyancy forces). This kind of interpretations are also strengthened by the regional correlation observed between the fast uplifting core of the W-Alpine arc, and a strong 200 km deep warm anomaly imaged by the latest tomography. Indeed, still debated deep structures would play a major role in the current dynamics. However, surface processes implying GIA and erosional unloading also play the first role as they directly affect the buoyant equilibrium of the Alps. In the available modeling of such a geodynamic context, uplift should be associated with extensional tectonics. Actually, the alpine seismicity developed all along the arcuate shape of the W-Alps, is characterized by such an extensional faulting associated with a minor component of strike-slip. Thus, there is a quite good qualitative correlation in the overall alpine arc between topography, crustal thickness, extension, and uplift. Nevertheless, looking at the new quantification of the vertical motions, it appears that they partly uncorrelated from extensional seismicity: the maximum of vertical motion (2,5 mm/yr) is located to the North of the W-Alps, whereas the maximum of extensional seismicity is located more than 150 km southward. On the contrary, horizontal deformations observed by GNSS are extremely well correlated with the seismicity from a regional viewpoint, both in term of deformation mode and strain quantification. This paper points out paradoxical uncorrelations in the Alp's current tectonism, which resolution through the ongoing AlpArray-related projects should help to better understand their actual dynamics.

Lithosphere slabs beneath the Dinarides from teleseismic tomography as the result of the Adriatic lithosphere downwelling

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Recent teleseismic research of the relationships in the lower lithosphere in the marginal zone of the Adriatic microplate and southwestern Pannonian basin discovered fast velocity anomaly beneath northern part of Dinarides (Šumanovac and Dudjak, 2016). This anomaly indicates a downwelling of cold lithosphere material thus pointing to Adriatic slab descending beneath the north-western Dinarides at least to the 250 km depth. The discovery of this downgoing Adriatic slab has stimulated us to the extent the area of investigation toward east and south-east and to cover the entire Dinaridic region with the Pannonian marginal zone in order to get a complete image of the lithospheric relationships in the Dinarides and surroundings.

The study area covers the marginal zone between the Adriatic microplate (African plate) and the Pannonian tectonic segment (Eurasian plate). We created a three-dimensional seismic velocity model to 450 km depth using teleseismic tomography. Our travel-time dataset was collected by means of 40 seismic stations from the ORFEUS database and Croatian Seismological Survey database. A set of 90 teleseismic earthquakes were selected in the range 2014-2015, and relative P-wave travel-time residuals were calculated. We use the adaptive stacking technique, which was improved by Rawlinson and Kennet (2004), for calculating relative travel-time residuals. For the first time, the seismic P-wave velocity model of a relatively high resolution on the entire Dinaridic mountain belt was obtained. The resolution of the inverted tomographic images produced by the applied deployment geometry was tested with the standard checkerboard approach. Based on this model, a more reliable insight into the composition of the lithosphere under the Dinarides has been achieved.

The slow anomaly generally characterises the Pannonian basin and the boundary areas and indicates warm, soft materials. It is especially pronounced in the southwestern part of the Pannonian basin, in the Drava depression (up to 200 km). The fast anomaly extends underneath the entire Dinaridic mountain belt and indicates cold, rigid materials. In the central and southern Dinarides, the fast anomaly extends in the NW-SE direction whereas in the northern Dinarides it rotates towards the north and extends in the NNW-SSE direction. The fast anomaly generally follows the direction of the Dinarides although its intensity and width change. The anomaly is steeply sloping towards the northeast and directly indicates the sinking of the Adriatic microplate underneath the Pannonian tectonic segment. In the Northern Dinarides, the anomaly extends to the depth of 250 km, whereas in the Southern Dinarides it covers greater depths, up to 450 km.

The shallow Adriatic slab extends along the entire belt of the External Dinarides, while the deep Adriatic slab extends beneath the Internal Dinarides and ophiolite zones in the area of central and southern Dinarides, which is interpreted as remnants of the former Jurassic subduction (Pamić, 1998). The ophiolite zones represented a barrier during the occurrence of later Dinaridic subduction, which resulted in the characteristic triangular shape of the central and southern Dinarides.

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Miocene at the western margin of the Pannonian basin; record in the Slovenj Gradec Basin fill

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Between the eastern margin of Northern Karavanke and the western Pohorje Mts., an irregularly shaped and deformed belt of Miocene clastic sedimentary rocks occurs in northern Slovenia. Detailed investigations of the basin fill are still missing. Therefore, it is our aim to gradually fulfil this gap, and to complement the image of the hinterland uplift from sedimentary record of the basin. Central part of the Slovenj Gradec Basin (SGB) is treated here. Six sections were recorded, petrography and geochemical analyses were made, and modal composition of sandstones determined. Deposition in the SGB started with fossil-free fluvial sediments with remains of macroflora. Though faunal assemblage shows prevailing marine environment of deposition, it was interrupted by nonmarine periods. Sedimentary fill consists of conglomerates interlayered with sandstone, siltstones and infrequent marlstones. Main constituents of sandstones are lithic grains and quartz, frequent are micas, chlorite, and heavy minerals all derived from metamorphic rocks. Locally, fragments of carbonate rocks are abundant and less often granitoids. According to recent findings (Ivančič et al., 2016) the sandstones from the SGB belong to litharenite, subordinately also to arkose and subarkose in regard of alkalis. Recycled orogen provenance of the sediment was determined, and quartzose origin of the sedimentary rocks. The source rocks were not subjected to considerable weathering. Discrimination diagrams for clastic sedimentary rocks based on geochemical composition show collisional tectonic setting of the source rocks, but indicate that the SGB sedimentary fill had a stronger influence from passive than from active margin. Biostratigraphic division of sediments is in progress. At the present, it is based on calcareous nannoplankton assemblages found in the borehole MD-1. Upper Ottnangian, Karpatian and Badenian marine environments were determined (Ćorić et al., 2011). Based on lithological, mineral and geochemical compositions of the SGB sedimentary fill we can conclude that source rocks of the SGB sedimentary fill were broadly derived from the collisional area of the Eastern Alps and subordinately from the Karavanke igneous belt and calcareous Southern Alps. No fragments of the Pohorje granodiorite suit were found. The sediment evolved on a passive margin. The reasons for the absence of the Pohorje granodiorite fragments in the sediment can be two: either the igneous body had not emerged on the surface yet, or the eroded material was transported into another direction. If the first case is valid, than the Ribnica-Selnica half-graben sedimentary fill rich in granodiorite clasts should be younger from that in the SGB. So far, the results support the model of Trajanova (2013), proposing that the area of the wider SGB was an integral part of the western margin of Central Paratethys until late middle Miocene, and was detached from the Pannonian Basin in the course of the Pohorje Mts. south-easterly directed oblique transpressive uplift along the Labot fault during Middle to Late Miocene. The results are also accordant to the anorogenic origin of the Early Miocene Pohorje granodiorite.

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Lateral transfer of Neogene contractional deformation in the Dinarides during the Adriatic indentation

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Orogenic collisional systems are often characterized by lateral variability of contractional deformation driven by along-strike changes in the mechanics of collision or changes in the subduction dynamics. The Miocene - Quaternary indentation of the Adriatic promontory into the Southern Alps - Dinarides system is connected along the strike with the subduction of the Ionian domain and the mantle dynamics related to the evolution of the Aegean slab. The transition from the indentation in the Dinarides to the observed balance between external contraction and internal extension in the Hellenides was through to be accommodated in the Albanides segment, while the effects in external Dinarides are little known. We have performed a kinematic study in the external Dinarides of Montenegro, Croatia and Bosnia- Herzegovina to quantify the role of post-Eocene deformation that was thought to represent the last major moment of collisional deformation. This deformation has affected the Dinarides Lake System, which is a system of endemic and isolated Miocene intra-montane basins, providing critical age constraints for the kinematic evolution. The results demonstrate that these thin Miocene basins opened in response to a generalized moment of extension observed in the entire external Dinarides, fault offsets cumulating hundreds of meters of offsets in average. This was followed by a generalized latest Miocene - Quaternary inversion that transferred the contractional deformation from the internal Dinarides in the NW to the present day continental subduction recorded in the SE external Dinarides of Montenegro. The transfer still takes place along a complex system of thick-skinned thrusts that transfer their offsets gradually to a more external position via dextral strike slip faults that reach tens of kilometres of offsets. We have documented that a significant number of previously known (e.g., Split-Karlovac lineament) and newly identified dextral faults are still active at present. In essence, the entire system transfers the contractional deformation recorded in the internal Dinarides and the Southern Alps, to the active subduction recorded in the external Dinarides of Montenegro and its continuation towards the Hellenides. These observations demonstrate for the first time a kinematic connection between the active subduction and collisional processes in the Alps and Hellenides via a large-scale transfer system in the Dinarides.

Alpine thermal evolution of the Central Western Carpathian basements: constrained by zircon and apatite fission track data

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The Western Carpathians represent one of the northernmost parts of the highly curved Alpine orogen in Central Europe. The Western Carpathians, the focus of this research, were chosen to study the evolution of an orogen as a consequence of plate convergence and continental collision which are the inner part of the mountains. Zircon and apatite fission track analyses have been used in order to refer quantitative constraints on the Cretaceous to the Quaternary thermal evolution of the Central Western Carpathians immediately after the Eo-Alpine nappe stack and metamorphosis. For a case study on the thermal evolution, the Variscan consolidated crystalline basements of the Tatric, Veporic, and Gemeric tectonic units were chosen. New zircon and apatite fission track ages together with all available data enable to identify Alpine thermal phases of the Variscan crystalline basements. The Gemeric Unit, an upper most thick-skinned thrust sheet of the orogen inner part, cooled from depth levels of ~10 up to 2.5 km (temperature interval of ~250–60°C) about ~88–64 Ma ago, after the collapse of the overlying Meliata-Turňa-Silica Mesozoic accretionary prism. The middle and lower thick-skinned thrust sheets, so-called Veporic and Tatric units, cooled from the depths of ~10 up to 2.5 km about ~110–40 Ma ago. The process of exhumation was controlled by unroofing of footwall from beneath the Gemeric Unit and the Meliata-Turňa-Silica accretionary prism. The internal portion of the Tatric Unit was gradually exhumed to the depth less than ~2 km and some parts of the unit appeared at the erosional level and remained cold. However, this exhumation was replaced by the burial beneath the irregular in thickness Eocene to Lower Miocene (~45–20 Ma) strata (Kováč et al., 2016) that caused fully reheating of apatite single grain fission track ages in predominantly external part of the Tatric Unit close to the Pieniny Klippen Belt. According to apatite fission track data of ~21–8 Ma, the middle Miocene collision of Internal Western Carpathian orogen wedge with the European continental margin led to the final exhumation of the most external horsts formed by the Tatric Unit ('Tatric core mountains'). Based on geomorphological markers, the final mountain morphology of the most external part of the Tatric Unit was formed since the Pliocene (Králiková et al., 2016).

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Freshwater and marine Miocene on the Čaklovići cross section in Tuzla basin

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The Čaklovići geological cross-section is located in the Tuzla basin, about 7 km south-eastern from the Tuzla. The southern limb of Čaklovići anticline is made by sedimentary rocks. Based on paleontological research and principle of superposition, the sedimentary rocks of this area are divided on the Lower and the Middle Miocene. The Lower Miocene is dominantly composed by laminated and thinly stratified marlstones in which we can find layers of conglomerates and sandstones. Laminated marlstones contain pieces of mollusc shells. The basis of the Lower Miocene is made from the tuff layer that is about 3 meters thick. These sediments were deposited in a coastal part of a freshwater lake. The total thickness of the Lower Miocene sediments is about 33 meters. The Middle Miocene is defined based on foraminifera, which belong to zones of the Lower Badenian. The older part of the Lower Badenian is represented by *Ammonia viennensis* and *Nonion commune* zone. This zone is exclusively represented by marlstones with massive structure. Layered marlstone is only found in one centimetric interval, in the upper part of this zone. Typical macrofossil associations for this part of the Lower Badenian are *Aporrhais* and *Tellina.* These molluscs in Tuzla basin are represented in immediate upper layer of rock salt deposits, in which we can find identical foraminifera zone. Massive marlstones of the older part of the Lower Badenian were deposited in an infralittoral zone of the Central Paratethys, and their thickness is about 50 meters. The last part of researched Čaklovići cross-section is made by massive marlstones, sandstones and conglomerates. This sequence of the geological cross-section is a part of the Lower Badenian, precisely it belongs to the zone *Globigerinoides trilobus* and *Orbulina suturalis.* Typical macrofossils of the younger part of the Lower Badenian are *Vaginella* and *Corbula.* Sediments of this the Badenian section were deposited in circalittoral of the Central Paratethys. Their researched thickness is about 7 meters, and their total thickness is over 100 meters for sure. Based on previously researched cross-sections of the Lower Badenian in the Tuzla basin, it was concluded that same foraminifera zones are identical to nannoplankton zone NN5 (Martini, 1971). Čaklovići cross-section points out that in this part of the Tuzla basin, there were no salt formation deposits and in this part of the basin marine deposits are found unconformly over freshwater lake sediments. These marine deposits are regularly representing immediate roof sediments of the salt formation. The studied cross-section is an exception in the Tuzla basin, and it's unique because of the fact that the margin between foraminifera zones is visible because of the erosion, hence it's available for different geological researches.

The mineralogical composition of organic rich pelitic sediments associated with the syn- and post-rift phase of an intracratonic basin

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The investigated sediments are black shales of the north-western part of the intracratonic Dniepr-Donets Basin. The organic rich pelitic sediments are related to lithofacial characteristics of the syn- and post-rift phase from the Devonian to the Serpukhovian period. The mineral composition of the sediments reflects the depositional processes within the basin. Well core samples down to a depth of 6 km were investigated by XRD and XRF. The main clay components of the shales are mica-group minerals ($2M_1$, $1Md$, $1M$), kaolinite group minerals, chlorites, mixed-layer-minerals (especially illite-smectite) and expandable clays. Quartz, feldspar, pyrite, siderite, and calcite comprise the additional main mineral phases. Accessory phases are predominantly dolomite, apatite, and anatase. For each investigated horizon within the regarded Paleozoic period the mineralogical variability and changes are discussed taking into account findings of basin modelling (Shymanovskyy et al., 2004), sea level changes (Izart et al., 2003) and source rock potential (Sachsenhofer et al., 2010). The Late Devonian is characterized by syn-rift magmatism and salt tectonics (Kusznira et al., 1996). In the outermost north-western part of the basin, a Devonian sequence with a thickness up to 2 km reflects the proximity to the sediment source and shows varying contents of mica-group minerals, expanded clays, mixed layer clays, chlorite and kaolinite. In the lower part of the succession poorly crystallized mica-group minerals and glauconite occur. The degree of the crystallinity of the mica-group minerals increases within the succession. Regarding the nonclays the high amount of feldspars, plagioclase as well as K-feldspars is obvious. In the Devonian succession the quartz content is generally lower compared to carboniferous layers. The transition from the syn- to the post-rift phase is indicated by a high increase of the kaolinite content in the Tournaisian stage. The post-rift phase is characterized by transgressive-regressive cycles. Along the axial zone of the basin eustatic sea-level rises resulting in deep-marine conditions. Trace element ratios and C-S-Fe relationship indicate the anoxic conditions. The Tournaisian succession is marked by a sharp inserting of a predominant occurrence of detrital kaolinite. The Lower Visean is related to an overall transgressive trend with the development of carbonate platforms (Sachsenhofer et al., 2012). Shale samples of the lower Visean indicate an overall transgressive trend and the development of small carbonate platforms. Kaolinite represents the dominant clay mineral. The quartz content decreases and an increase of pyrite and siderite are apparent. An overall regressive trend is assigned to the Upper Visean succession with a distinct change in the mineralogical composition to the Lower Visean. This refers to an increase of mica-group minerals, mixed-layer minerals (primary illite-smectite), a decrease of kaolinite (except in the deepest parts of the basin) and an increase of quartz. Serpukhovian shales can be related to shallow- and lacustrine sedimentation.

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Geochemistry of the new Permo-Triassic boundary section at Sitarička Glavica, Valjevo, Serbia: no major changes except in oxygen content across the boundary

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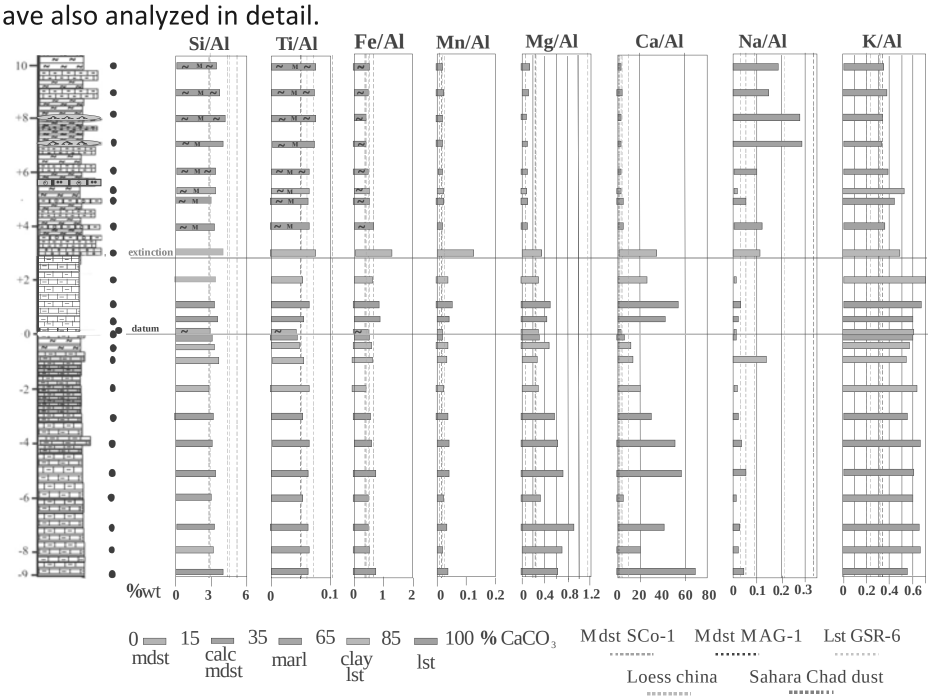
One metre spaced samples were taken for +/- 10 metres from a distinctive shale between stratigraphic units 1 and 2 of the Sitarička Glavica section, 2.2 metres below the loss of most benthos and through which there is a progressive loss of foraminifera. The elemental geochemical changes across the PTr boundary (taken at the top of unit 2) are minimal which indicating little physical environmental change, such as source type and conditions. For example, the Chemical Index of alteration (CIA) of 56-72, indicate a moderate degree of chemical weathering of the parent material with no marked changes up the section and are comparable to reference sandy and silty mudstones of Recent North American and Asian rivers. But there are some interesting variations. The K/Fe values are all higher than in modern arid regions, except for two at +2m and +3m straddling the extinction level. This is not only compatible with the extreme aridity inferred for Permo-Triassic source areas in the paleotropics, but with the wetter pluvial interval at the Permo-Triassic boundary in northern Gondwanaland from where the Sitarička Glavica sediments are thought to come from.
Some minor element and isotopic variations suggest that predominantly disoxic conditions below +4 metres changed into oxic conditions above +4 metres, about 1 metre above the palaeontologically-defined Permo-Triassic boundary. Time permitting brief comparisons will be made with the geochemistry of adjacent Permo-Triassic boundary sections in Hungary, Slovenia, Croatia and Austria which we have also analyzed in detail.



Reconciling petrological data with geophysical rock parameters in the Central Eastern Alps

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Intensely studied regions as the Alps allow interdisciplinary approaches for better understanding the complex structure of the lithosphere in orogens. For this reason, a geophysical 3D-density model of the Eastern Alps has been reworked from the petrological perspective. By modelling the metamorphic density of rocks using the Theriak-Domino software package the influence of temperature, pressure and chemical composition on the density has been analysed. Density-isopleth-plots of orthogneisses, metabasites, ultramafics and metapelites, which are typical rocks of the Tauern Window, have been calculated showing characteristic density trends for each rock type, depending on stable mineralogical phases and changes of reactions influenced by the chemical composition.

To further investigate the influence of the chemical composition on rock densities various Zentralgneiss samples were analysed. Chemical compositions of 45 Zentralgneiss samples from the literature were used in addition to five reworked and newly measured samples. By the usage of the corresponding thin sections, information on the metamorphic grade, weathering state and water content were gained. For the used temperature and pressure conditions a complex relationship between the density and composition was observed, depending mainly on an increased iron content.

Based on the petrological findings a geophysical density model has been reinvestigated using the IGMAS+ software. With respect to the results of the TRANSALP working group and information about the Moho depth, a good correlation between the measured and modelled gravity field was reached in the new petrological 3D-density model.

This model has been used to further analyse the impact of the Zentralgneiss unit on the short waves of the modelled gravity field, resulting in a shifting to a lower gravity anomaly of -15 % and +8 % for the calculated maximum and minimum density. In this study, we emphasize the importance of multidisciplinary approaches to enable well-established density models for gravity modelling and lithosphere analyses.

Modelled paleo topography of the greater Alpine region

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The interaction between convergent tectonics and surface processes is essential to understanding the formation of the Alps. During the active convergence phase, crustal shortening and thickening were the main driver for surface evolution (Handy et al., 2014). Since the Miocene, most of the Alps have entered a post-tectonic stage, in which shortening has almost ceased, and erosion and subsequent isostatic adjustment dominate vertical motions (Fox et al., 2016). Ongoing controversy about the topography or vertical motions focus on either the lithospheric structure and mantle processes or surface unloading by erosion as drivers. Observations of river basin geometry and river channel profiles in the Alps reveal ongoing geographic and geomorphologic changes, and geomorphic analysis provides interpretations of the current state of this adjustment (Robl et al., 2017). Using geomorphic tools on paleo river networks enables us not only to analyse the current state but also to interpret the past and make predictions for changes in erosion rates. We constructed a series of paleo geographic maps using sedimentology and provenance data from the literature, which was corrected for paleo location. Analysis of the modern river network geometry indicates spatial variability in erosion rates. These predictions are consistent with the modern erosion rates and exhumation rates derived from thermochronometry. Interpretation of paleo drainage maps suggests that these spatial variations in river network geometry can be extended back in time. The predicted erosion rate variability based on the river network interpretation is also consistent with past erosion rates from thermochronometric data (Fox et al., 2016). It is also apparent that disequilibrium in the river network extends to regions outside the Alpine orogeny, including the Carpathians and the Rhine Graben. A systematic change in the river network has thus continued long after tectonic shortening and is ongoing during the post-orogenic phase.

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Exhumation-related deformation of the Cycladic Blueschist Nappe (Aegean region)

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Structural mapping and kinematic data combined with amphibole mineral-chemistry microanalysis were used to constrain the nature of ductile deformation related with the exhumation of the Cycladic Blueschist Nappe in the Aegean region, Greece. The Cycladic Blueschist Nappe consists mainly of marbles, metapelites, and metavolcanic rocks, which underwent a prograde blueschist- to eclogite-facies event in the Eocene, followed by a retrograde greenschist-facies event in early Miocene. Five deformation phases (D_{1-5}) record the structural evolution of the Cycladic Blueschist Nappe. Early deformation structures ($D_{1/2}$) are locally preserved (e.g., Evia, Sifnos and Syros Islands), and are related to ESE-directed thrusting. This thrusting event resulted in the stacking of the individual units, which constitute the Cycladic Blueschist Nappe. On Evia and Syros islands, the very early exhumation stage (D_3) is expressed by E- to NE-trending upright folds. The main stage of ductile exhumation and decompression, from the stability field of glaucophane to that of actinolite was accomplished during the D_4 deformation, which is mainly associated with NE-directed shearing. Brittle to brittle-ductile NW-striking D_5 normal faults facilitated the final exhumation of the Cycladic Blueschist Nappe. The D_4 is by far the most pervasive ductile deformation phase, observed in the Cycladic Blueschist Nappe. This deformation phase is expressed by a gently dipping, transposition planar fabric, which varies in intensity from a widely spaced crenulation cleavage to a mylonitic foliation, and a well-developed (E)NE-trending stretching lineation. The foliation is axial planar in outcrop to kilometre-scale cylindrical folds with hinge lines oriented parallel or at small angles to the stretching lineation. The variable foliation intensity is the result of strain localization in D_4 ductile shear zones that range in thickness from several meters to several hundreds of meters. The kinematic analysis in D_4 shear zones revealed a dominant top-to-the-ENE shear sense in the Cycladic Blueschist Nappe. In central Aegean (Evia, Attica, north Cyclades) and Pelion areas, a major NE-directed D_4 ductile thrust emplaced the Cycladic Blueschist Nappe over a Mesozoic carbonate-rich sequence that underwent mild blueschist-facies metamorphism. This carbonate-rich sequence, named as Basal unit, displays lithological similarities with the Pelagonian Zone of the Internal Hellenides rather than the platform carbonates of the External Hellenides. In southernmost Cyclades (e.g. Ios and Sikinos Islands), the nappe is thrust over pre-Alpine basement rocks, which have also been affected by high-pressure metamorphism. This thrust contact is a mylonitic zone that operated in high-pressure metamorphic conditions and is associated with S-directed shearing. The upper plate Pelagonian rocks (i.e Uppermost unit of the Cycladic massif) are rarely exposed as klippen on top of the Cycladic Blueschist Nappe. In central Cyclades (Syros Island), the upper bounding fault represents a top-to-the-SW passive ductile detachment. These results indicate that the exhumation of the Cycladic Blueschist Nappe is associated with a dominant NE-directed shearing and restricted S-directed shearing in the southern Cyclades. We suggest that the ductile exhumation of the nappe was achieved by the synergy of the NE-directed extrusion and a penecontemporaneous indentation process of the upper plate in the south Cyclades, which caused the SW-directed shearing.

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Mafic enclaves in Pohorje granodiorite

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Pohorje (Slovenia) granodiorite contains different types of mafic enclaves, which differ in size, shape, contact, and mineral composition. To characterize and classify them, 20 samples were taken from quarries in Cezlak and Josipdol. Thin sections were analysed under the polarising microscope, for 13 samples chemical composition was determined by ICP – ES (major elements) and ICP – MS (trace elements) and for 4 samples mineralogical composition was confirmed by X-ray diffraction.

They are always holocrystalline, but in comparison to host rock finer grained and enriched in mafic minerals, i.e. biotite and/or hornblende. Their size is from few millimetres to over a meter. The contacts with granodiorite are sharp or gradual. The salic to mafic minerals ratio varies from extremely biotite rich, over the ones with an equal proportion of both minerals, to the enclaves, where salic minerals prevail over the mafic ones. More holocrystalline or more porphyry texture observed in enclaves is generally in accordance with the texture of host rock.

Feldspars, 0.1 to 4 mm large, comprise between 5 to 50%. Plagioclases are idiomorphic to hypidiomorphic, forming polysynthetic and simple twins, often normally or oscillatory zoned with epitaxial rim. They prevail over hypidiomorphic to xenomorphic orthoclase. Plagioclases are often myrmekitic intergrown with quartz. Quartz content is 5 to 30%, with grains measuring 0.1 to 1.5 mm. Grains are xenomorphic, elongate, often showing undulatory extinction and in aggregates with mosaic texture. Biotite comprises 10 to 70%, is 0.1 to 3 mm in size, mainly hypidiomorphic, with parallel oriented tabular crystals. In some cases is overgrown with hornblende, sometimes partly or totally chloritized. Hornblende share is 5 to 40%. Idiomorphic to hypidiomorphic grains measure 0.03 to 2 mm, and inside some enclaves have parallel orientation. The accessory minerals are apatite, orthite, epidote, zircon and opaque minerals, exceptionally garnets.

We distinguished at least four different types of enclaves:

- schlieren; up to several meters large, oblate shape with planar orientation and gradual transition to granodiorite, enriched in biotite, which is parallel to the biotite in granodiorite.

- xenoliths; longer axis 5 cm to 10 cm, angular, with sharp contact with country rock, enriched in biotite and hornblende; biotite orientation in xenoliths is not parallel to its orientation in granodiorite.

- surmicaceous enclaves (restites); longer axis 10 cm to 30 cm, lenticular, sharp or gradual contact to granodiorite, extremely enriched in biotite (up to 70%); their longer axis and biotite grains are parallel to the granodiorite lineation.

- mafic microgranular enclaves; longer axis few mm to 50 cm; mainly ovoid, some angular; contact with granodiorite mostly sharp, rarely gradual, in some cases rim of mafic or felsic minerals in the contact with granodiorite.

Geochemical characteristics confirm three groups, but the samples are not perfectly in agreement with mineralogical classification. Concerning all the characteristics most enclaves are mafic fine grained inclusions, followed by restites and xenoliths.

Early Cretaceous metamorphism in the Tisza and Dacia mega-units following the obduction of the South Transylvanian Ophiolites: new results from U-Th-Pb monazite and Sm-Nd garnet dating in the Apuseni Mountains (Romania)

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Petrographic data evidences two separate medium-grade metamorphic overprints in both, Tisza and Dacia mega-units of the Apuseni Mountains. New Th-U-Pb monazite data in combination with Sm-Nd garnet analyses allows the correlation of one of these two medium-grade overprints to Late Jurassic–Early Cretaceous times. Furthermore, different age clusters and monazite-allanite reactions were observed according to the structural position in the nappe stack. Permian and Late Jurassic ages in samples from the structural top of the Biharia Nappe System (i.e. the Vidolm Nappe) correlate with geochronological data from neighboring tectonic units and are interpreted as inherited detrital monazite. Together with previously published thermochronological data from the same unit and observed monazite breakdown reactions, a Late Jurassic thermal overprint of 400-450 °C is inferred. The central part of the nappe stack (i.e. the Baia de Arieș Nappe) shows allanite breakdown reactions and newly formed Th-rich monazite. Some relict Variscan and Permian ages are present, but Late Jurassic to Early Cretaceous ages are predominant. The age range shows a good agreement with the range of Sm-Nd garnet dates from the same sample. Polyphase garnet growth is observed in thin-sections and supported by medium-grade *P-T* conditions (~550° C/0.5-0.8 GPa). Thus, the formation of new monazite in the Baia de Arieș Nappe occurred due to prograde allanite breakdown at peak metamorphic conditions. Together with previously published geochronological data and structural observations, we correlate the Late Jurassic to Early Cretaceous prograde overprint of the Dacia Mega-Unit with E-directed Alpine nappe stacking following Late Jurassic obduction of the South Apuseni Ophiolites on top of the Biharia Nappe System. Two samples from the structurally lowest position in the nappe stack (i.e. the Bihor Unit, Tisza Mega-Unit) yielded Variscan (Carboniferous to Permian) and Triassic ages, together with a significant peak of mid-Cretaceous ages from low-Y monazites. The mid-Cretaceous age cluster shows a good agreement with a Sm-Nd garnet age (104±2 Ma) from one of the samples and correlates with other geochronological data from the eastern periphery of the Bihor Unit. We consider NW-directed thrusting, followed by E-directed exhumation of the Bihor Unit to be responsible for the observed distribution of mineral isograds and geochronological data. Together with petrographic evidence of polyphase garnet growth, this implies that also the Tisza Mega-Unit experienced a strong regional metamorphic overprint and synkinematic garnet-growth during late Early Cretaceous times. Our new findings contrast earlier views that attributed medium-grade metamorphism in the Apuseni Mountains exclusively to the Variscan orogeny and low-grade metamorphism to the Alpine orogeny.

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