19 th meeting of the Central European Tectonic Studeis Group (CETeG)

12-15th April, 2023

Kazincbarcika, NE Hungary

Abstract Book

Temporal evolution of the Paskhand salt diapir during folding in the Zagros Fold and Thrust Belt (Cenozoic time), Southern Iran

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The Zagros Fold and Thrust Belt in southern Iran is a well-known area for its impressive salt diapirs outcrops which are sourced from the Pre-Cambrian to Early Cambrian Hormuz Formation. The positive and negative accommodation spaces adjacent to the salt diapir result from the salt movement-sedimentation interaction that creates unconformity-bound packages of thinned and folded strata (halokinetic sequences). The Paskhand salt diapir, located in the Fars region, provides an excellent case study area analyzing the evolution of salt diapirs through halokinetic sequences that have been considerably affected by shortening. Due to complexity and asymmetrical changes in the halokinetic sequences around the Paskhand salt diapir, there are divided into 5 sectors which is separated from each other by extensional fault, and in which each sector, the geometric features and sedimentary structures such as unconformity, drape folding, thickness and facies changes were documented and then structural profile and stratigraphic column from each sector were performed. Based on that, we speculate about the timing and structural evolution of the Paskhand salt diapir and suggest that the Paskahnd salt diapir was episodically reactivated eight times during the Oligocene-Miocene time. The asymmetric salt rise rate in each episode was caused by the shortening rate intensity of the Zagros orogeny. Perpendicular to the shortening, this stratigraphic unit is interrupted by an allochthonous salt sheet as a result of lateral extrusion of the Hormuz salt, which is perpendicular to the Zagros shortening. In addition, this withdrawal and uplifting of the salt diapir caused strong lateral changes in accommodation spaces and sedimentation rates during this time interval. This is reflected in the asymmetric thickness changes in unconformity-bound packages around the diapir. Based on the thickness of halokinetic sequences (HS0 to HS8), the episodic reactivated movement of salt diapir became shorter in duration.

The scenario of the evolution of the Paskhand salt diapir can be imagined as follows: 1) The collision pressurized the diapir that pushed the surrounding halo kinetic sequence sideways, along the axis of the large anticline. 2) Initial movement of the diapir relative to the regional datum is indicated by alternating gypsum and sandstone layers associated with dolomite clasts sourced from the diapir (lower Gachsaran), 3) evidence of alluvial fans and debris cones shedding dolomite blocks from the diapir into the reefal carbonates, (Upper Gachsaran Fm) and 4) development of halokinetic sequence of the upturned beds (Guri Mb).

Keywords: Hormuz Formation, Salt diapir, Zagros Fold and Thrust Belt, Halokinetic sequences

Crustal-scale thrusting and subsequent collapse at the Palaeoproterozoic suture between Sarmatia and Fennoscandia (East European Craton) as interpreted from the TTZ-South deep seismic profile (SE Poland to Ukraine)

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The TTZ-South regional seismic profile runs NW-SE, roughly along the Teisseyre-Tornquist zone (TTZ) at the SW margin of the East-European craton (EEC), near its junction with the Paleozoic platform of northwestern Europe. The results obtained from this profile reveal a complex geometry of the upper crust, interpreted here as representing the NW-vergent and NE-SW striking overthrust-type, Paleoproterozoic (~1.84-1.8 Ga) Fennoscandia-Sarmatia suture (FSS) at the contact between the two major segments of the EEC. The overthrust continues down-dip into the middle and lower crust and to the MOHO, showing a crustal-scale staircase trajectory. A composite internal structure of the southeastern, Sarmatian, craton segment is interpreted as comprising two tectonically juxtaposed major crystalline basement units of dissimilar crustal structure, overthrust to the NW, namely the southern, Moldavo-Podolian, devoid of a lower crustal layer, and the northern, Lublino-Volhynian, units. On the leading, NW, edge of the latter unit, two smaller-scale thrust slices, representing marginal Sarmatian terranes are distinguished. The results of the TTZ-South project, combined with those of other nearby deep seismic profiles, are consistent with continuation of the East European crystalline cratonic basement across the TTZ from the NE to SW and its plunging into the deep basement of the Paleozoic platform. Effects of a late-stage, extensional deformation responsible for the origin of the mid to late Proterozoic (~1.4-0.6 Ga), SW-NE trending Orsha-Volhynia rift basin (aulacogen) are also probably recorded in the uppermost crustal layer. A thick Ediacaran succession, deposited in this basin, must have been later tectonically thickened due to Variscan orogenic deformation. The Moho depth varies between 37 and 49 km, resulting in the thinnest crust in the SE, quick changes across the TTZ, and slow shallowing from 49 to 43 km in the NW. The abrupt Moho depth increase to the NW from 43 to 49 km at around the middle of the transect is considered to reflect the overlying Sarmatian lower crust as being overthrust upon that of Fennoscandia and, thus, resulting in the lower crust tectonic duplication. Subhorizontal and wavy seismic boundaries below the Moho, at depths from 53 to 80 km, can be indicative of large-scale thrusting and folding in the uppermost mantle.

U-Pb zircon age of Cretaceous magmatism at Vršatec in the Pieniny Klippen Belt, Slovakia

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In addition to the presence of Miocene volcanism, which is quite common in the Pieniny Klippen Belt, infrequent occurrences of Cretaceous volcanism are also present. Several magmatic bodies of this age have already been described in the Pieniny area (e.g. Spišiak & Sýkora 2009 Geoch, Spišiak et al. 2011 GeolQuart, Oszczypko et al. 2012 GeolQuart, Krobicki et al. 2019 GeolCarp). The Pieniny Klippen Belt forms a narrow, but lengthy (up to 600km), highly deformed tectonic structure. It separates the Outer and Inner Carpathians and comprises of sedimentary succesions of Lower Jurassic up to Paleogene age.

A new outcrop of Cretaceous magmatism was described at Vršatec in the Pieniny Klippen Belt in Western Slovakia by Spišiak et al. (2011 GeolQuart). The magmatic body occurs within the Upper Cretaceous deep-marine pelagic variegated marlstones of the Lalinok Fm. The age of hosting sedimentary rocks was previously determined by lithostratigraphy and biostratigraphy and estimated to Upper Cretaceous, however younger than 100 Ma revealed by globotruncanas found in peperites (Spišiak et al. 2011).

Heavy mineral separation as well as U-Pb zircon dating were performed using an ion microprobe SHRIMP IIe/MC at the Micro-Analysis Laboratory at the Polish Geological Institute – National Research Institute in Warszawa.

New, detailed data confirmed the Upper Cretaceous age of analyzed magmatic rock suggested by litostratigraphical observations. The age of the magmatic event was estimated to approximately 81 Ma based on an U-Pb zircon concordia. The obtained date may shed new light on the evolution and development of the Carpathian igneous rock complexes and the Pieniny Basin itself.

Acknowledgement: The research is supported by the National Fund for Environmental Protection and Water Management project No. 22.2301.2001.00.1 and by the Slovak Grant Agency for Science, project 1/0435/21.

Deformation history in a pre-rift sediment (Oligocene Hárshegy Sandstone) during basin evolution (based on deformation band and vein analyses)

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Slip events along pre-existing faults in the crust occurs whenever the shear stress can be resolved on an existing fault plane. Reactivation of existing faults is very common, especially when the fault or shear zones are close to ideal orientations for a slip in a given stress field. However, in a strongly deformed area, that was affected by multiphase deformation it is hard to recognize the early structures, fault history can be followed by various deformation-related structures and associated diagenetic alterations, which can help with the relative timing of faulting episodes.

In this study, Palaeogene successions are investigated, focusing on the Oligocene Hárshegy Sandstone in the Buda and Pilis Hills in order to reveal new evidence for the immediate pre-rift evolution of an area, which belonged formerly to the North Hungarian-South Slovakian Paleogene Basin. Locally, this rock contains a dense network of deformation structures such as deformation bands (DB), DB-related faults, and chalcedony veins. Although the possible origin of siliceous cementation and vein formation were related to volcanic hydrothermal activity, the role and relative timing are not clear in connection with the development of the DBs, possible greater faults and their reactivations.

Separating measured data, types of deformation elements and reactivated planes indicate that at least three phases of deformation can generally be presented in this rock. One is related to abundant DBs, few veins or striated deformation band faults, which can relate to (N)NE–(S)SW trending extension.

Deformation bands show moderate and intense cataclasis including quartz comminution, which mechanism has a supposed formation depth of at least several hundreds of meters. The siliceous cement precipitation is strongly related to DBs and obviously to veins. These bands could have formed before or contemporaneous with the siliceous cement precipitation. In a few samples, a fault-like slip surface was also evolved, presumably during the late step of progressive deformation. Based on orientations and supposed depth range of DB formation, this deformation could have occurred from immediate pre-rift to the early syn-rift phases: from Late Oligocene to Early Miocene.

The second one is represented by subordinately DBs, but mainly veins and faults formed by N(NW)–S(SE) compression and perpendicular extension related to a transtensional deformation (or E–W extension). In this phase, (W)NW–(E)SE trending normal planes were reactivated as strike-slip faults, which indicates their younger formation in relative chronology. The oblique reactivation on silica cemented (or 'crusted') DB or vein planes refer to another phase of deformation, but new veins also formed. This deformation can mostly be tied to the Middle Miocene part of the syn-rift phase.

Reactivation of N–S trending normal planes as oblique strike-slips and joints may represent the subsequent deformation phase, which can be related to the post-rift phase of deformation.

Siliceous cementation might be a continuous process, which could start in the pre-rift, but is mainly related to the syn-rift phase. Deformation (fault activity) can induce the fluid migration from downward, which resulted in chalcedonic cementation of DBs and extensive veining.

Hydrothermal alteration within a fault zone, especially extensive silicification could result in an increase of the cohesive strength of the zone together with a significant change in internal friction compared to the host rock.

The case of silica-cemented DBs having sharp contact with the host rock, where reactivation could occur, is further investigated in order to reveal the main compositions and spatial element distributions across the deformation zone.

SEM-BSE and micro XRF analysis showed that Fe, Ti, (Mn), and S are enriched compared to Si in a very fine, dark zone between DBs and host rock.

The observed deformation mechanisms were tied to burial history compiled by borehole data and cross-sections. The formation thickness data also confirm several hundred meters of burial during late Oligocene and Early Miocene, similar to values expected from the deformation mechanism of DBs.

However, DBs can be clearly related to (N)NE–(S)SW to E-W trending extension, greater faults with a similar strike, which are dominant in the fault pattern of this area, are supposedly reactivated during post-rift phase(s).

Acknowledgements:

The research was supported by Hungarian Scientific Research Fund (NKFIH OTKA) 139275 and OTKA 134873.

Illite K/Ar dating of fault zones, sedimentary sequences and low-grade metamorphic rocks

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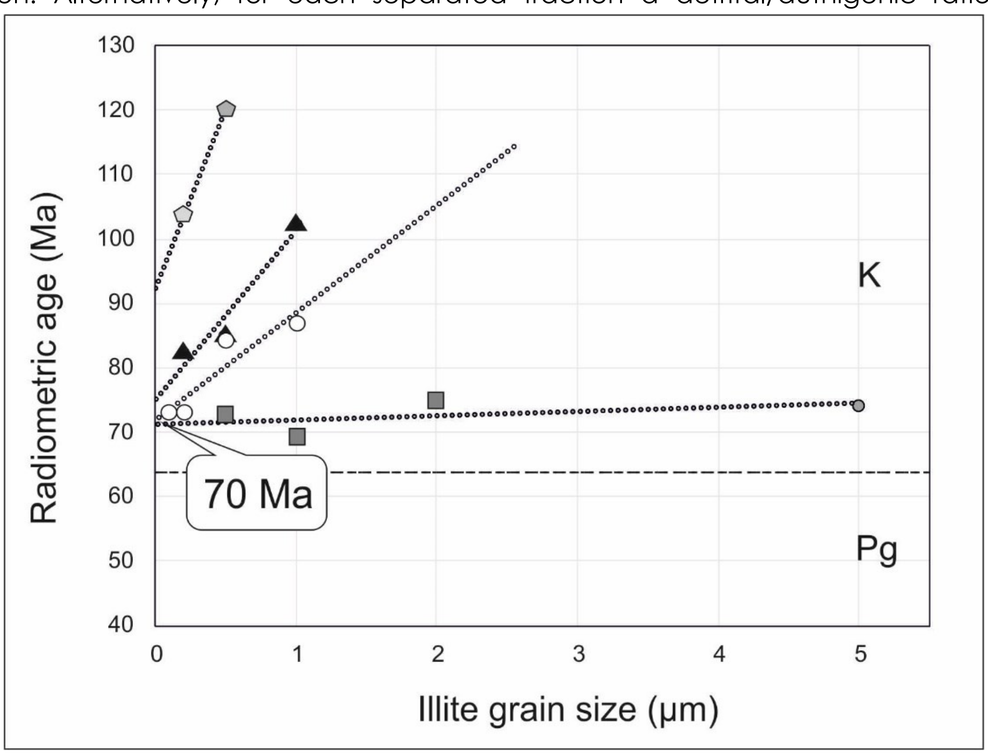
Dioctahedral mica illite is a unique mineral that forms in various low-temperature (≤350 °C) environments including shear zones, sedimentary basins as well as low-grade metamorphic rocks. As illite is often the only K-bearing authigenic mineral in these environments, it provides a unique opportunity to determine the age of faults, subsidence of basins or metamorphic processes. Illite, has however a complex mineralogy: detrital illite and muscovite have ordered crystal lattice ($2M_1$ polytype), the particles are usually hexagonal and form relatively big crystals in the sediments. On the other hand, authigenic illite is fine grained (<1 μm), platy or needle-like and its crystal lattice is less ordered ($1M_d$ polytype). In pelitic rocks, according to the "instantaneous formation and growth model" the finest grain size fraction containing only authigenic illite will represent the end of the thermal event (diagenesis, metamorphism). Separated grain size fractions with decreasing grain sizes have progressively more authigenic illite and the interception of the regression line with the radiometric age axis (Figure 1) fitted on the grain size-K/Ar age spectrum provides the age of the crystallization. Alternatively, for each separated fraction a detrital/authigenic ratio can be



calculated from the ratio of the $1M_d/2M_1$ polytypes determined from X-ray powder diffraction spectra.

The method has been applied on three study areas in the Pannonian Basin including the Nekézseny fault to the north of the Bükk Mts., the Boda Claystone Formation in the Mecsek Mts. and the low-grade metamorphic nappes in the southwestern part of the Bükk Mts.

The Nekézseny Fault forms the structural boundary between the south-vergent Bükk Mountains (Dinaric affinity) and north-vergent Uppony Mountains (Alpine affinity). The samples were collected from three shallow boreholes that drilled through the Nekézseny Fault Zone, as well as from nearby surface outcrops. The samples contain illite, chlorite and minor smectite, but no kaolinite. The K/Ar age vs. grain size spectra are variable: in one sample the radiometric ages vary around 70 Ma irrespectively of the grain size. In the other samples, the K/Ar ages increase with increasing grain size, indicating decreasing authigenic/detrital ratios with increasing grain size. The theoretical intercept of all regression lines with the K/Ar axis, however, points to 70±2 Ma (Figure 1), suggesting Late Cretaceous age for the main thrust event.

The Boda Claystone Formation in the Mecsek Mts. (Tisa Megaunit) is a Permian playa lake sediment sequence. It is a lithologically heterogeneous, including claystone, siltstone, dolomite and evaporitete beds. Samples were taken from unaffected units and from shear zones. Both sample sets provided ages around 200 Ma, suggesting that the tectonics did not affect the radiometric clock of the illite in the dated samples. Hydrothermal veins from the neighboring Mecsek Granite Formation provided similar ages, supporting a regional heat effect presumably associated with the Triassic rifting of the Tethys ocean.

An attempt has been made to prove thermal and age differences between the nappes (Paraautochtonous, Mónosbél-, and Szarvaskő nappes) of the western part of the Bükk Mts. Our preliminary age data ranging from 90 to 130 Ma do not show any systematic correlation between the tectonic units, structures and metamorphic ages, yet.

Fluid and melt inclusions trapped at different geodynamic settings – how can small droplets contribute to the tectonic models?

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Fluid, a non-solid flowing phase under subsurface conditions, coexist with rocks that form the tectonic units, and thus make profound impact on plate tectonic processes via melting relations and solid-fluid interactions. Physico-chemical properties of fluids can be characteristic for the geodynamic setting in which they have equilibrated with the rocks. Fluids (including melts) can be entrapped in growing or recrystallizing minerals, manifested as primary fluid and melt inclusions, observable under the microscope. These inclusions are micrometer, or even submicrometer sized within rock-forming minerals providing the opportunity to understand geochemical and geological processes in a holistic solid-fluid approach. In this presentation, we show inclusions studies from different geodynamic settings, mainly representing entrapment at the deeper part of the lithosphere: 1) multiphase fluid inclusions from the Cabo Ortegal Complex metamorphic terrane and 2) melt inclusions from early magmatic cumulates from the East African rift system.

1) The Cabo Ortegal Complex of the Iberian Massif exposes a Variscan subduction-exhumation zone, comprising of an assemblage of high-pressure and high-temperature metamorphic units, which are thought to represent fragments of both continental and oceanic lithosphere. Eclogites and granulites, now being exposed on the surface, are rich in garnet that contain abundant multiphase fluid inclusions (MFI). The metamorphic rocks shared a common high-grade tectonometamorphic evolution in a subduction zone during the formation of the Variscan belt of Europe.

The studied MFI trapped in garnet of eclogite and granulite are primary (trapped during garnet growth) and represent a homogeneously entrapped COHN-dominated fluid. During the retrograde path of the enclosing rock, MFI went through post-entrapment re-equilibration, resulting in 1) partial H_2O loss and 2) formation of multiple step-daughter minerals via fluid-host interactions. Thermodynamic models revealed that step-daughter assemblage is stable at relatively low pressure and low temperature (between 2–9 kbar and 300–400 °C) conditions. Our model and the microstructural data of the MFI suggest that the formation of the step-daughter minerals is expected at the same time due to metastable behavior at elevated pressure and temperature. Accordingly, we suggest a scenario of N_2-enrichment of fluids during their exhumation path at a temperature horizon of 300–400 °C. The release of these fluids may contribute to the understanding of N_2-rich fluid composition during devolatilization in the forearc regions of convergent margins.

2) Melt inclusions were studied within samples from the Kerimasi volcano in the East African Rift System, latter being an active rift zone considered as the classical example of a continental rift system. Alkaline and silica-undersaturated magmas, such as melilitites and nephelinites are common in the Earth's continents, related to the early rifting process, and are frequently associated with carbonatites. They occur typically 1) at the propagating tip and 2) on the flanks of the rift. Along the rift zone, the within-rift sequences show a decrease in silicate undersaturation with time and the melt composition upon the further progress of the rifting becomes silica-saturated at the rift axes.

Perovskite crystals contain high amount of primary melt inclusion from magnetite-perovskite cumulates. This study suggests that oxide cumulates, mainly built up by magnetite and perovskite can thus be a significant container of such early-stage silicate – carbonate melt (+fluid) immiscibility. The temperature of complete dissolution of daughter minerals in the melt inclusions and the high CO_2 – content of the silicate melt (5.4–9.8 wt%) support early formation of the rock and entrapment of melts at high temperatures (~1100 °C) and pressures (≥1 GPa).

We compared the studied silicate melts in the inclusions with a global dataset of 146 continental melilitite and 640 nephelinite compositions (GEOROC database). We argue that the studied Ca and alkali-rich melilitite (silicate) melts formed in an early stage of continental rifting and were able to exsolve carbonatite melts that crystallized voluminous calcite carbonatite rocks during their evolution. In contrast, magnesian melilitite and nephelinite volcanic rocks from intracontinental settings lie compositionally far away from any immiscibility field at feasible pressures and were only able to unmix carbonatite melts during their late-stage evolution, leaving little opportunity for calcite crystallization. In other words, we conclude that chemical composition and volatile-content of the melt can be even more sensitive for the stages of the refiting process than previously thought.

These above works have been supported by the NKFIH_FK132418 and K_142855 projects, as well as the MTA FI Lendület Grant (LP2022-2/2022).

Alpine granite duplex formed from two Variscan granite blocks in the Tribeč-Zobor crystalline basement: determination by age, mineral stabilities and structural data

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White mica Ar/Ar and zircon U-Pb SHRIMP geochronology, different mineral stabilities, particularly monazite and allanite, and structural data were used for deciphering of two juxtaposed granite blocks in the Tribeč-Zobor basement (Western Carpathians). Granites from the crest part in the Tribeč-Zobor crystalline basement represents metamorphosed / mylonitised monzogranite c. 355 Ma in age. Subhedral S-type granodiorite/tonalite with almost unaltered monazite are exposed below these aforementioned mylonitised granites which contain intensively broken down monazite Monazite in the subhedral S-type granitic magma remained unaltered due to rapid cooling after emplacement into shallow crustal position. In contrast, the intensive monazite alteration observed in the recent upper positioned metamorphosed/mylonitized granites is interpreted as a result of slower cooling in a deeper crustal level. The absence of monazite recording Alpine tectonism suggests that the secondary coronas around monazite originated during the Variscan post-magmatic cooling and not during the Alpine overprint as previously was generally meant in the Western Carpathians. The underlaying subhedral granites are lithologically heterogenous S-and I- type granitic rocks formed in wider time span of origin ca 358-348 Ma what indicate their affiliation to different Variscan block against to upper positioned metamorphosed ones.

An age of c. 78 Ma, yielded by $^{40}Ar/^{39}Ar$ single grain fusion geochronology of muscovite, records the timing of the Alpine overprinting of monzogranite in the crest zone of the Tribeč-Zobor basement. The Alpine tectonism recorded at age of ca. 78 Ma was followed by thrusting of the most probably Fatric/(Veporic) Unit over the Tatric Unit. The Alpine monzogranite from crest part of the Tribeč-Zobor basement was metamorphosed under P-T conditions of 450-500 °C, 7.5-8 kbar. This data is similar to those calculated for other units in the Western Carpathians that were pervasively reworked during the Alpine orogenesis.

The observed deformational structures in the crest monzogranites are related to the evolution of sinistral shear zones with NE–SW strike and subvertical inclination. The granites are influenced by plane strain, which is characterised by sub-horizontal to gently dipping spaced, to pervasive tectonic foliation to an NW or SE direction. The granitoids with well-developed tectonic foliation can be characterised as protomylonite with evolved S fabric, however, in many places S-C fabric is visible and the mineral lineation shows a general top-to-the NW tectonic transport. Late Cretaceous to Paleocene shearing observed in these mylonitised granite shows final different NW – SE shortening.

Overall, the Alpine stacking of the two Variscan magmatic blocks was subhorizontal. Structurally, the Tribeč-Zobor Variscan basement underwent different Variscan and Alpine evolution and can be interpreted as the Alpine Tribeč granite duplex.

This work was supported by the VEGA project no. 0075/20 to Broska, the National Science Centre, Poland, project no. 2021/43/B/ST10/02312 to Majka, and by the Slovak Research and Development Agency under contracts Nos. APVV-21-0281.

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This work was supported by the National Science Centre, Poland, project no. 2021/43/B/ST10/02312 to Majka, and the VEGA project no. 0075/20 to Broska and

Revising Tatra Mountains crystalline basement: microstructural and geochronological insights into the Variscan assembly

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The crystalline basement of the Tatra Mountains is composed of pre-Mesozoic crystalline rocks belonging to the Tatric Superunit, overlain by Mesozoic and Cenozoic sedimentary cover and nappes of the Fatric Superunit. Metamorphic rocks are the most abundant in the western exposures of the basement (the Western Tatra Mts.) and display an inverted metamorphic sequence. Traditionally, the basement was divided into two units: the Upper Unit (UU) composed of high-grade, often migmatized rocks representing the hanging wall, and the Lower Unit (LU) made of medium-grade rocks in the footwall. Juxtaposition of the metamorphic rocks is related to the Variscan thrusting with a top to the S–SE sense of shear under ductile conditions, whereas the Alpine deformation is believed to be limited to brittle normal faults with NW-ward hanging walls. However, relatively poor exposure creates ambiguity in differentiating between UU and LU in Polish Tatra Mts. Thus, the presence and location of the boundary overthrust remain an open question impeding further work on (1) conditions and timing of Variscan deformation, (2) a number of deformation events, and (3) role of Variscan structures during Alpine deformation event.

Here, we present the results of fieldwork, as well as microstructural and geochronological investigations, that were conducted along two profiles targeting the presumed thrust fault on the northern slopes of Smreczyński and Trzydniowiański peaks in Poland. The field studies confirm the presence of a 10's to 100's of meters wide high-strain zone. A gradual increase in the degree of migmatization is observed ascending the profile, but no significant difference in lithology is observed. At the outcrop scale, rocks display a penetrative S2 foliation and F2 isoclinal folds with foliation-parallel, subhorizontal axial planes and NNE-SSW trending fold axis. Structural analysis revealed a bimodal distribution of poles to the S2 foliation, defining a km-scale F3 fold across the study area with a NE-SW trending horizontal axis and vertical axial plane. At the micro-scale, the penetrative S2 foliation is defined by alternations of quartzo-feldspathic and mica-rich layers. Quartz and plagioclase grains show elongation parallel to alignment of white mica, biotite, and sillimanite. Within mica-rich domains, the F2 isoclinal folds are readily observed. Locally, low- or strain-free white mica overgrows the fabric, with grains oriented (sub)perpendicular to the S2 foliation. One sample displays the F3 open folds reworking the S2 foliations, F2 folds and white mica overgrowths. Quartz, plagioclase, white mica, and biotite show brittle fracturing along the F3 axial planes, and biotite is also frequently transformed into chlorite along fractures.

Zircon ion microprobe U-Pb geochronology was conducted on three metasedimentary rocks and a metaigneous rock, with two samples obtained from each of the alleged LU and UU. Metamorphic zircon grains and rims overgrowing older cores in two samples provide ages of c. 360-340 Ma. Detrital cores in the three metasedimentary rocks show well-defined peaks at c. 570-530 Ma with minor Paleozoic, Proterozoic, and Archean peaks. One metasedimentary sample provides an additional peak at c. 520-500 Ma. The metaigneous rock, sampled within presumed LU, displays a peak of ~490-480 Ma with a few inherited Precambrian cores and entire grains. There are no significant differences with U-Pb dates and provenance between the two alleged units.

Altogether, our results confirm the existence of a high-strain zone within the studied profiles that is associated with the S2 and F2 structures. High pressure-temperature formation conditions of these structures are attested by the presence of sillimanite and may be attributed to Variscan tectonics. However, (1) lithological differences across the high-strain zone are not observed, and (2) the uniform detrital zircon records infer similar provenance for the alleged units. These similarities suggest that all samples likely represent only one crystalline unit, questioning the presence of the LU in the Polish Tatra Mountains. The F3 folds possibly represent a late Alpine deformation event, which previously was recognized solely by normal faults. This contribution shows that a revision of the Tatra Mts. tectonostratigraphy is critically needed.

Acknowledgement: Research funded by the National Science Centre, Poland, project no. 2021/43/B/ST10/02312. It was supported by the Foundation for Polish Science stipend, and "Juan de la Cierva" Fellowship (JFJC2021-047505-I) funded by MCIN/AEI/10.13039/501100011033, ESF (European Social Fund) and CSIC (M.Bukała). We also acknowledge the Tatra National Park for help and permission to conduct fieldwork.

U-Pb detrital zircon and $^{40}Ar/^{39}Ar$ muscovite geochronology of Cambrian – Ordovician rocks from the Holy Cross Mountains, Southern-central Poland

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The Holy Cross Mountains of south-central Poland are adjacent to the Trans-European Suture Zone (TESZ), a critical boundary that separates the East European Platform (EEP) from the Variscan orogen in central Europe. Neoproterozoic to early Paleozoic rocks in this region are critical to understanding the amalgamation of peri-Gondwanan vs. Baltican terranes, yet remain understudied. Nine Cambrian-Ordovician sedimentary rocks from the Holy Cross Mountains were sampled for zircon U-Pb and muscovite $^{40}Ar/^{39}Ar$ geochronology from nine Cambrian-Ordovician samples to better understand the geodynamics of southwestern Baltica during this time.

Sample RC20-01 is a fine-grained shale from the locality of Pierzchnica. This sample contains 13% Cambrian, 37% Neoproterozoic, 23% Mesoproterozoic, 17% Paleoproterozoic, and 10% Archean zircon (n=182). Major Paleozoic-Neoproterozoic detrital age peaks are at c. 536 Ma, 571 Ma, 616 Ma, 686 Ma, and 744 Ma. The Mesoproterozoic to Archean main detrital populations are 1144–1325 Ma, 1499–1822 Ma, 1969–2158 Ma, 2484–2788 Ma, and 2889–3049 Ma. The maximum depositional age (MDA) of 536 Ma is obtained for the sample using the youngest age peak.

Sample RC20-04 is phyllite from the locality of Podmąchocice. The detrital zircon are 3% Cambrian, 6% Mesoproterozoic, 37% Mesoproterozoic, 48% Paleoproterozoic, and 6% Archean (n=240). The Cambrian-Neoproterozoic signature is characterized by peaks at c. 498 Ma, 525 Ma, 539 Ma, 619 Ma, 630 Ma, 715 Ma, and 734 Ma The main population of the detritus is in the Mesoproterozoic-Archean, ranging between 927–2241 Ma and 2481–2748 Ma. The MDA is 498 Ma.

Quartz sandstones were collected from the localities of Wiśniówka (RC20-06) and Antoniów (RC21-06). These samples collectively contain 6% Cambrian, 28% Neoproterozoic, 28% Mesoproterozoic, 28% Paleoproterozoic and 10% Archean detrital zircon (n=444). The Cambrian-Neoproterozoic detrital signature is defined by peaks at c. 556 Ma, 582 Ma, 609 Ma, and 734 Ma. The Mesoproterozoic-Archean detritus ranges between 943–2219 Ma, and 2498–2961 Ma. The MDA of the two samples ranges between 525–532 Ma.

Four Cambrian sandstones were collected in the locality of Stara Zbelutka. Collectively, detrital signatures of the Cambrian rocks (RC21-01, RC21-03, RC21-04, RC21-07) yielded 2% Cambrian, 24% Neoproterozoic, 32% Mesoproterozoic, 34% Paleoproterozoic, and 7% Archean grains (n=903). Cambrian-Neoproterozoic peaks are at c. 534 Ma, 554 Ma, 585 Ma, 621 Ma, 672 Ma, 708 Ma, 745 Ma, and 810 Ma. The Mesoproterozoic-Archean detritus ranges between 952–2182 Ma, and 2489–3093 Ma, with main peaks at c. 1181 Ma, 1515 Ma, 1797 Ma, and 2074 Ma. MDAs for the Cambrian samples range between 528–550 Ma. Several grains in sample RC21-03 have well developed low-U rims that yield dates of c. 510 Ma that are distinctly younger than the youngest peak at 528 Ma . An additional sample of Ordovician sandstone was collected from Stara Zbelutka (RC21-05) is unconformably deposited on the Cambrian sequence. The sample contained 5% Cambrian, 20% Neoproterozoic, 38% Mesoproterozoic, 29% Paleoproterozoic and 8% Archean grains (n=239). The main Cambrian-Neoproterozoic peaks are at c. 498 Ma, 537 Ma, 555 Ma, 608 Ma, 654 Ma, 688 Ma, 717 Ma, and 738 Ma. The Mesoproterozoic-Archean detritus range between 1000–2284 Ma, and 2567–3076 Ma. The Archean peaks are at c. 2563 Ma, 2711 Ma, 1819 Ma, and 3374 Ma. The MDA of sample RC21-05 is 498 Ma.

Single–grain fusion muscovite $^{40}Ar/^{39}Ar$ geochronology was performed for sample RC21-03. It is one of the aforementioned Cambrian sandstones that is unconformably overlain by the basically undeformed Ordovician sequence. Muscovite are observed as both prismatic, randomly oriented grains (200–270 μm), and as deformed grains within the grain boundary network of the framework minerals (130–190 μm). Coarse-grained muscovite provides a weighted average of 538±2 Ma (MSWD=1.8; n=7) and is interpreted as detrital muscovite. Fine-grained muscovite yields 511±3 Ma (MSWD=1.5; n=7), which is interpreted as the timing of a deformation event that recrystallized detrital grains and reduced grain size.

Altogether, the results represent the first comprehensive detrital zircon study (n=2008) in the region of the Holy Cross Mountains. Major Mesoproterozoic to Archean peaks suggest correlation with events or igneous suites documented in the Baltican paleocontinent, including the Svecofennian event at c. 2000–1800 Ma, the Transscandinavian Igneous Belt at c. 1850–1650 Ma, the Rapakivi granite at c. 1650–1500 Ma, the Blekinge-Pomerania granitoids at c. 1500–1450 Ma, and the Sweconorwegian Orogeny at c. 1150–900 Ma. Younger age distributions in the Neoproterozoic and Cambrian suggest a signature derived from a peri-Baltican active margin, but further investigation is necessary to confirm this hypothesis. This new data also reveals a late Cambrian deformation event, recorded by both muscovite recrystallization and perhaps low temperature growth of U-poor metamorphic rims on detrital zircons.

This research is funded by National Science Centre (Poland) project no. 2019/33/B/ST10/01728.

Pre-Alpine diapirs and allochthonous salt sheets. Southern Subalpine chains, Haute-Provence, France : the effects of precursor salt structures in the evolution of a fold and thrust belt.

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Many of the Alpine folded belts (e.g. Pyrenees and the Northern Calcareous Alps) contain evaporitic successions, exposed diapiric structures and minibasin (Soto et al., 2017, Granado et al., 2019). The structural style and evolution of these mountain belts has been fundamentally affected by salt tectonics.

In the fold and thrust belt of the Southern Subalpine chains, Upper Triassic evaporites are associated with many Alpine structures. The Subalpine chains have been recently revisited and detailed geological mapping was carried out near Castellane and around the Tertiary Barrême basin. Reinterpretation of structures revealed a complex structural evolution. Stratal and structural geometries as well as stratigraphic relationships display evidence of continuous salt tectonic activity from the Liassic onwards, which culminated in salt extrusion and the development of allochthonous salt sheets during Albian-Cenomanian. East of the Barrême basin, the reduced, subvertical and incomplete Rhaetian-Barremian section of the Clavoune mountain is interpreted as the roof of an early developed salt swell, which steepened as the swell developed into a diapir.

During the early stages of its evolution, the Gévaudan diapir (Emre, 1977, Lickorish and Ford, 1998) was the source of an Albian-Cenomanian allochthonous salt sheet. The vertical and reduced section which is exposed now on the Clavoune mountain represents the Jurassic-Lower Cretaceous roof of the diapir overridden by extrusive salt. The diapir was later cut and displaced by a thrust fault during the development of the thin-skinned fold and thrust belt.

Thin and incomplete Jurassic-Lower Cretaceous sections and allochthonous salt also exposed south of the Barrême basin, in the vicinity of the city of Castellane. The Castellane diapir also fed an extrusive salt sheet during the deposition of the Albian-Cenomanian black shales.

The pre-erosional extent of these salt sheets is unknown. However, dismembered carapace blocks of the diapir exposed together with Keuper gypsum in Albian-Cenomanian sediments suggest a significant lateral extent of the sheets. Sedimentation was highly influenced by the presence of the extrusive salt sheets in the Vocontian basin during the middle of the Cretaceous and later, during the Late Cretaceous. Thickness and facies changes of Albian-Cenomanian and Upper Cretaceous sediments within synclinal depocenters bounded by Upper Triassic gypsum or equivalent welds, the presence of local unconformities and pinch-outs against the bounding gypsum bodies and welds suggest that the Albian-Cenomanian black shales and Upper Cretaceous pelagic sediments may have been deposited in salt-withdrawal basins on top of the salt sheets- i.e. secondary minibasins. Alpine contractional deformation from Late Cretaceous to recent times also affected the salt sheets and they became thinned and welded. The syn-kinematic deposition of the Alpine foreland basin was also influenced by the presence of allochthonous sheets. Paleocene conglomerates, the so-called Poudingues d'Argens were deposited locally in secondary minibasins. The poorly sorted conglomerates may have been formed by the reworking of the underlying Upper Cretaceous minibasin fill. Local unconformities along unusual contacts (probably welds), as well as rapid thickness and facies changes are also present in the Eocene-Oligocene succession. We suggest that the Barrême basin, classically a thrust-sheet-top basin developed on top of the allochthonous Albian-Cenomanian salt sheet. The basin depocenter migrated westwards during Eocene-Oligocene times possibly associated with progressive salt withdrawal in advance of thrust sheet loading.

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Detrital rutile U-Pb geochronology of the Magura Superunit, Western Carpathians

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The External Carpathian Flysch Belt (ECFB) is a Paleogene accretionary wedge located in front of the Pieniny Klippen Belt and the Cretaceous nappe stack (Central Western Carpathians). The Magura and Silesian-Krosno Superunits are part of the ECFB. The focus of this investigation is the Magura Superunit, which consists of the Rača, Bystrica and Krynica units. As there are no outcrops of paleo-oceanic crust sensu stricto, the sedimentary rocks of the ECFB are the only available source of information about the subducted or eroded material. We applied U-Pb geochronology to detrital rutile from the Magura Superunit, to better understand the evolution of the Alpine-Tethys suture zone in the Western Carpathians.

Ten medium-sized sandstone samples were collected along a transect across the Magura Superunit (Bystrica and Krynica units) in the Nowy Targ region (Poland). The samples represent synorogenic sedimentary rocks with deposition ages between the Upper Cretaceous and the Oligocene. Approximately 200 grains of rutile were separated from each sample and c. 100 grains were selected for further analysis. U-Pb dating of rutile was conducted at the Swedish Museum of Natural History in Stockholm using Laser Ablation Inductively-Coupled Plasma Mass Spectrometry.

The ages and appearance (shape, inclusions, exsolution features, etc.) of the dated rutile grains show significant variation, suggesting that rutile originates from different sources. Prominent peaks representing the Variscan (ca. 400-280 Ma) and Alpine (ca. 160-90 Ma) tectonic events are well-defined in each of the dated samples. Interestingly, four separate Alpine signals are identified. The two peaks represented by most of the rutile grains with ages of 137-126 Ma and 115-105 Ma are found in all samples. In two sandstone samples deposited between the Eocene – Oligocene and Upper Cretaceous – Paleocene, a younger peak occurs at 94-90 Ma. A peak at 193-184 Ma is also present in those two samples as well as in a third sandstone deposited between the Palaeocene and Eocene. In addition, smaller Proterozoic peaks (c. 1770 Ma, 1200 Ma, 680 Ma, and 600 Ma) are present in the majority of the samples.

Because rutile requires relatively high pressure to crystallize, its formation is only possible at very specific events during the orogeny. The new age data suggest correlation with a number of tectonic events, including the Jurassic subduction of the Meliata Ocean (~180-155 Ma), the Early Cretaceous thrust stacking of the Veporic and Gemeric domains (145-100 Ma) and the Late Cretaceous subduction of the Váh Ocean (90-70 Ma).

This research is funded by the National Science Centre, Poland, project no. 2021/43/B/ST10/02312.

Using petrochronology to re-investigate the age of the HP metamorphism in the French Massif Central

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The P–T–t evolution of eclogite samples from a locality of the French Massif Central where a Silurian age for the high-pressure metamorphism is commonly accepted is reinvestigated. Petrology combined with LA-ICP-MS U-Pb dating and trace-element analysis in zircon and apatite discard the Silurian age and rather reveal an Ordovician (c. 490 Ma) rifting, a Devonian (c. 370 to 360 Ma) subduction and a Carboniferous (c. 350 Ma) exhumation in this part of the French Massif Central.

The petrological study using pseudosection document a prograde evolution in the eclogite facies marked by an increase of pressure above 20 kbar associated with a strong temperature increase from 650 to 850 °C. Peak-temperature and incipient decompression to the high-pressure granulite facies (19-20 kbar and 875°C) were accompanied by partial melting of the eclogite. Further decompression resulted in partial equilibration in the high-temperature amphibolite facies (<9 kbar, 750-850°C). Local fractures filled by analcite and thomsonite testify to late interaction with alkaline fluids. Metamorphic zircon with eclogitic REE patterns (no Eu anomaly, flat HREE) and inclusions (garnet, rutile and probably omphacite) shows concordant apparent ages that spread from c. 370 down to c. 310 Ma. A c. 350 Ma age of apatite attributed to cooling following decompression from the eclogite facies indicates that zircons younger than 350 Ma, were rejuvenated but preserved an apparent eclogitic signature. It is suggested that interaction with alkaline fluids at low temperatures would lead to the recrystallisation of zircon while leaving apatite unaffected.

Comparison with available P–T–t data from eclogites in Western Europe shows that Devono-Carboniferous high-temperature eclogites are also recognized in the Saxo-Thuringian and Moldanubian zones of the Bohemian Massif suggesting they belonged to the same subducting bloc. Devono-Carboniferous trench/arc and arc/back-arc relationships recognized in the Bohemian Massif and the French Massif Central respectively point to a southward subduction in both areas. This comparison challenges the historical interpretation of a northward subduction in France and brings an overall more coherent picture of the Variscan belt.

The P–T–t evolution of a migmatite dome and its metamorphic envelope: a case study from the Southern Altai Belt in Mongolia.

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The Southern Altai Metamorphic Belt (SAMB) is a strip of Palaeozoic high-grade polymetamorphic terranes extending from Eastern Kazakhstan to Mongolia. In its Mongolian segment, the age of the metamorphism is inferred from isotopic data in magmatic rocks and their relationship with polyphase structures, the direct dating of metamorphism is mostly missing. A section in Mongolia exposes from north to south: migmatites associated with Devonian and Permian magmatic rocks, Grt–St and Grt–St–Ky micaschists and low-grade to unmetamorphosed sediments. A detachment zone encompasses the micaschists and the roof of the migmatites dome. To infer P–T–t history of this dome-like structure, we selected two micaschists samples and a migmatite for pseudosection modelling coupled with LASS in-situ U(-Th)-Pb and trace element analyses of monazite.

The Grt–St and Grt–St–Ky micaschists samples contain two generations of garnet, assigned to metamorphic events M1 and M2. Staurolite and kyanite occur in the matrix, staurolite encloses garnet 2 suggesting crystallization during M2. Staurolite and kyanite are locally replaced by sillimanite assigned to a third M3 phase of metamorphism. The lack of inclusions in garnet 1 preclude the determination of a stable assemblage during M1 but the zoning is compatible in both samples with compositional isopleths indicating prograde P–T path from 525-550 °C and 4-5 kbar to 550-575 °C 5-6 kbar. The garnet 2 composition is compatible with the staurolite and kyanite-bearing assemblages indicating important heating and limited pressure increase from 550-575 °C and 6-7 kbar to 600-650 °C and 6-8 kbar, and in the second sample to 650-676 °C and 7-8 kbar during M2. The growth of sillimanite indicates a subsequent decompression below 6 kbar during the M3. Isotopic data of the monazite included in garnet 1 yield Carboniferous dates of c. 350 Ma, interpreted as the age of M1. The monazite dates in garnet 2, staurolite, sillimanite and the matrix of both samples spread from c. 305 Ma to c. 285 Ma. Despite the absence of a clear systematic difference of monazite dates with the textural position, the high MSWD (= 2) of the WMA date calculated with the whole monazite population suggests that all the spots do not belong to a single homogeneous population. Hence, the spread is interpreted in terms of crystallization of monazite during heating and slight pressure increase related to M2 at the Carboniferous-Permian boundary, followed by (re)crystallization related to M3 during the activity of the detachment, in the Permian. Overall, the isotopic results in the micaschists show that the M1 is significantly older than M2 and M3.

The migmatite sample contains only one generation of garnet, kyanite inclusions in plagioclase, and matrix with alternating sillimanite-biotite-rich and felsic layers. Garnet displays a zoning with decreasing spessartine from the core to the inner rim, typical of prograde zoning. The outer rim marked by an increase of spessartine is interpreted as a result of diffusion during the decompression. The sample is devoid of muscovite suggesting that most of the melt has been lost preventing rehydration on the retrograde P–T path. In the H_2O-undersaturated pseudosection, kyanite and melt are present in a field where the compositional isopleths for the garnet inner-rim intersect, indicating conditions of 8-10 kbar and 750-775 °C. The presence of sillimanite indicates a decompression and cooling to 3-5 kbar and 550-700 °C. To trace the prograde part of the P–T path, melt was re-incorporated to attain H_2O-saturated solidus. The isopleths for the garnet core composition intersect in the chlorite stability field at 550-575 °C and 5-7 kbar pointing to an apparent important heating with moderate pressure increase to peak P–T conditions. All the monazite from this sample yields a well-defined date of c. 285 Ma, identical to the younger monazite dates in the micaschist samples, and therefore interpreted as dating the (re)crystallization of monazite during the migmatite exhumation, contemporaneous with the activity of the detachment zone during M3. Consequently, the prograde garnet growth and kyanite may be interpreted to be contemporaneous with the M2 metamorphism in the micaschist samples, as they share similar prograde P–T paths, however, a late Carboniferous age and relation to M1 metamorphism cannot be excluded. The presence of Devonian magmatic rocks in the migmatitic zone of this section together with the absence of the monazite older than Permian suggests that the metamorphic evolution may have been more complex.

The Grt–St and Grt–St–Ky micaschists resembling the typical result of Barrovian metamorphism formed through the superposition of two metamorphic events with significantly contrasting ages and dT/dP gradients. Geochronological data indicate that M2 & M3 in the micaschists are closely related with the exhumation of the migmatites and with the activity of the detachment zone. Near isobaric heating before decompression in the micaschists suggests that the shear zone migrated from the migmatites to the metasediments. We suggest that the Barrovian assemblage formed during the advection of heat from the migmatites undergoing exhumation and that the narrow spacing of the isograds is a result of extensional tectonics.

Unique under-dip toppling predisposed by geological structures, Javorníky Mts., Outer Western Carpathians

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Outer Western Carpathians form a series of flysch nappes that are progressively thrusted and folded. The area of interest is located in the Rača Unit, which belongs to the Magura group of nappes. The Zlín Formation, which crops out here, is strongly folded into kilometer-sized tight and steeply inclined folds, which have fold axes plunging in the WSW direction and the axial plane steeply dipping to the NNW. Because the formation consists of massive sandstone benches interspersed with clay layers, the folds have the character of kinked (angular) folds. As this is an area with large height differences, rapid erosion processes, and extensive gravitational movements of rock masses, many landslides occur here, among which are the sites of topplings. Toppling is a process that usually occurs when the incline of the bedding is opposite to the slope ('anti-incline toppling'). However, in this area, under-dip toppling was observed, e.g. toppled beds dipping in the same direction as a slope but under a higher dip angle.

High-resolution LiDAR data were used to investigate the location, geometry, and tectonic settings of the topplings. The data revealed, that topplings in Javorníky Mts. are situated in the SSE-dipping fold limb, where under-dip toppling only can take place. The topplings are usually accompanied by transversal faults, which allow more easily breaking out of sandstone benches. Shortly after the bed was rotated and pulled out, a small depression occurred behind the toppled beds. The depression is filled with an accumulation of sediments and organic material, which were sampled and analyzed using the C14 radiocarbon method. The results show that the sediment within the newly created accumulation zone is of Holocene age.

Since under-dip toppling requires lifting the center of gravity of the toppled layers, its origin is somewhat difficult to explain. Perhaps the overturning of layers occurred as a result of activation by movement during a nearby earthquake, as some faults bear indications of recent movements.

The research was funded by the Grant Agency of the Czech Republic (GC22-24206J).

Geology and tectonics of the Main Ethiopian Rift (East African Rift System)

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The Main Ethiopian Rift (MER) provides a unique insight into the process of active continental rifting between the Arabian, Nubian and Somalian plates where all phases of continental rifting have been recorded (Corti, 2009; Ebinger, 2005). The MER progressively propagates in NE–SW to N–S direction with length about 1000 km through the Ethiopian and Somalian Plateaus (e.g., Corti, 2009; Woldegabriel et al., 1990). The extension rate ranges from ca. 1 mm/year in the south up to 5.5 mm/year in the north (Stamps et al., 2021). The MER is commonly divided into three segments – Northern, Central and Southern, each representing different phases of continental extension, with varying fault and morphological architecture, strain pattern, timing and character of the volcanic activity (e.g., Agostini et al., 2011; Hayward and Ebinger, 1996).

Based on multidisciplinary research of the northern part of the Southern Main Ethiopian Rift resulting from a field geological and structural mapping, paleostress analysis, morphotectonic and remote sensing data, petrological and geochemical assessment of volcanic rocks, K-Ar dating and gravity survey including Linsser indices calculation, following conclusions can be drawn.

The studied area in the northern part of the Southern Main Ethiopian Rift (SMER) recorded a typical continental rift-related tectonic and magmatic (volcanic) evolution including (a) pre-rift (Eocene to Oligocene) volcanic activity initiated by extensive flood (plateau) alkaline basalt to trachybasalt eruptions due to crustal thinning and mantle plume(s) ascent, followed by (b) fault-dominated early-rift (Miocene) bimodal volcanism associated with incipient rift valley formation and (c) late-rift (Pliocene to Holocene) bi-modal volcanic activity comprising alternation of alkaline basalts and alkaline to subalkaline rhyolite to trachyte lava domes, formation of numerous lava domes accompanied with deposition of volcaniclastic material.

The principal rift-related normal faults are mostly vertical, ~NNE(N)–SSW(S) trending, parallel with prominent morphological escarpments and axis of the rift. The subordinate faults dip steeply to moderately to ~NNE or SSW, associated with well-developed steeply to moderately plunging slickensides and normal to oblique-slip kinematics. The regional paleostress field calculated from the mapped faults reflects the continuing rifting between the Nubian and Somalian plate, in the succession of earlier E-W extension (N90°) direction, changing to E(ENE)–W(WSW) extension (N80°), gently oblique to the rift-axis.

Acknowledgments

This research is financed by the Czech Development Agency, in frame of the Development Aid Cooperation project between the Czech Republic and Federal Democratic Republic of Ethiopia.

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Salt tectonics in the Northern Calcareous Alps (Austria): from Triassic minibasins to Jurassic inversion

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The Northern Calcareous Alps (NCA) in the Eastern Alps (Austria) have emerged in the last decade as a province relevant for understanding salt tectonics in passive margins. This area developed during the Triassic as a Meliata Tethys-facing passive margin, with thick carbonate platforms developing above a mobile Permian evaporite substrate. In the central part of the NCA (the Salzkammergut region), fault block geometry of the pre-salt basement is interpreted to be the result of oblique rifting, with a rhomboidal map pattern of NE-SW trending extensional faults and NW-SE trending relay ramps and transfer faults. This basement fault arrangement in turn controlled the development of salt structures, with salt walls nucleating above basement faults. This pattern rhomboidal map pattern can still be recognized today and has at least in part been recycled during Alpine orogenesis. This layout of salt structures also exerted a strong control on the distribution of carbonate facies during the Triassic, with the presence of intra-platform "channels" in which deeper water, condensed carbonate sequences (the renowned Hallstatt facies) deposited above subsiding diapirs. Salt structures that grew under extension during the Triassic were later strongly shortened by Late Jurassic tectonism, leading to varying and sometimes perplexing structural configurations. The result is that the Triassic of the central NCA consists of thick platform carbonates (over 2000 m thick) that aggraded in subsiding minibasins, separated by narrow or welded salt structures, some of which are capped by a somewhat chaotic imbrication of relatively thin (under 300 m thick) deep water carbonates.

Although many aspects remain still uncertain, emerging observations indicate that salt tectonics in the NCA started in the Anisian (Middle Triassic) and likely even as early as the Early Triassic. Although salt tectonism mostly masks possible contributions by basement faulting to basin configuration, it appears that basement extensional faulting had ceased by the Early Triassic. Thereafter, basin development was controlled by thermal subsidence, by subsidence of carbonate minibasins into evacuating evaporites, and by basinward gliding of the supra-salt sediments. In a first stage from Early to Middle Triassic, the initial configuration of minibasins and salt walls was established, with dominantly vertical subsidence of supra-salt sediments. In a second, Upper Triassic stage, gliding of supra-salt minibasins towards the rift axis (southwards) accelerated, leading to some of the most spectacular preserved evidence for salt tectonism including growth wedges in Upper Triassic carbonates (the Norian Dachstein Limestone) and a strong differentiation of the platform and basin domains (i.e. development of the Hallstatt facies).

The implications of the interpretation of Triassic salt tectonism extends beyond the passive margin stage and provides a framework to understand the evolution of the NCA during Eo-Alpine and Alpine contraction, from the Cretaceous to the Miocene.

Extension during the Miocene syn-rift phase in the central Pannonian Basin (Pilis-Buda hills region); fault geometry and interpretation

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In order to reconstruct plate tectonic movements during the syn-rift phase within the Pannonian Basin it is required to understand the thinning and the extension of the curst within the region. A few studies have been published on estimating extension. Yet neither of these works were done by accurate geometrical balance of cross sections. A small number of further studies have been done that were however mainly concentrating one local quarries or a trench. Thus neither of these studies were concentrating on lager regions.

The aim of this study is to understand extension of the crust along a NE-SW cross section. Along the research it was found that earlier geological maps of this area need an update as well. Hence field observations have been actively done, so far mainly in the Pilis-Buda hills in order to get all the data needed for further balancing.

Some of the outcrops differ from the ones listed on the map, also understanding of the faulting in the area changed greatly through the past decades. Based on recently gathered field data, observed faults were classified into different deformational phases.

The main dips of the observed beddings have a NE direction, Triassic formations have a steeper, 20-30° dip, whereas Cenozoic formations dip with a milder, 10-20° dip. However close to larger faults these angles may be altered greatly. Most observed faults are dipping mainly in SSW direction, however minor modifications can be observed that makes dipping direction vary from WSW to S directions. Stepovers, relay ramps, curved fault traces, merge and debranching further complicate the fault pattern.

Based on former classification deformation was categorized as D9a that formed during the Ottnangian-Early Badenian (18.5-16 Ma). It is to note, however, that borehole data and the stratigraphy of individual fault blocks, and cross sections indicate pre-Miocene (Eocene and Oligocene) fault slip events. The amount of this Paleogene extension should be distracted from the total value in order to obtain syn-rift extension.

Steep faults were also observed that have a NE-SW-NNE-SSW strike. These may have formed as strike-slip faults together with the SSW dipping normal faults. Also they may have originally formed within the Cretaceous and reactivated during the Miocene extensional phases. If they formed as an individual phase they may be classified as D10 phase that formed during the late Badenian-Sarmatian (14-11 Ma).

As observed faults were plotted on stereograms, some were clearly showing a steep NE-SW strike. The other group of measured structures however showing strikes varying between NW-SE to ENE-WSW were difficult to group into clearly separated phases. These have an almost constant transition between directions of fractures. Based on the observed fault pattern on stereograms two different interpretations were made for these more complex fault patterns. The simpler explanation is the classic Mohr fault pairs solution whereas the other interpretation would be a three-dimensional strain field. It was published before that deformation can not only be followed in a plain strain manner, instead it may exist in three dimension strain which results in two conjugate sets of normal faults in case of extension. This interpretation would be unique within the Pannonian Basin.

Acknowledgements:
The research was supported by Hungarian Scientific Research Fund OTKA 134873.

Conodont Colour Alteration (CAI) data from the eastern Internal Western Carpathians with emphasis on the Silica Superunit

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The Silica Superunit (Silicicum) is the uppermost rootless nappe system in the eastern Internal Western Carpathians (IWC). According to the Late Palaeozoic–Mesozoic tectonostratigraphic scheme of the IWC units and the Gemer zone, the present structural position of the Silica nappes is palinspastically incorrect (Plašienka 2018 - Tectonics). Plašienka (2018) stated that "the original paleogeographic position and emplacement time of the Silica nappes are the most ambiguous issues of the entire geodynamic history of the IWC".

Most authors see the palaeogeographic position of the Silica nappes as part of the northern passive margin of Neo-Tethys (Meliata) Ocean (ALCAPA margin), which relies generally on the Triassic – Jurassic tectonostratigraphy with 2 phases of platform evolution: Steinalm Carbonate Ramp with its drowning in the late Pelsonian and subsequent deposition of deep-water sedimentary rocks (late Pelsonian–Ladinian), followed by the complex Wetterstein Carbonate Platform evolution (late Ladinian to early Carnian with older forerunners), the "Mid-Carnian" siliciclastics, and the Dachstein Carbonate Platform (Norian–Rhaetian), with its classical facies belts: Hauptdolomit facies (restricted lagoon), Dachstein Limestone facies (open lagoon), Dachstein Reef Belt, reef-near deep-water shelf (Gosausee Limestone facies), distal shelf (Hallstatt Limestone facies), and continental slope (Meliata/Pötschen facies). Above the shallow-water Dachstein Platform follows the deposition of the condensed Lower Jurassic Adnet group and Middle Jurassic radiolarites with incorporated reworked allochthonous blocks (Meliata, Telekesoldal and Drnava mélange, equivalent to the different Hallstatt mélanges in the NCA).

These facies belts with its overlying Jurassic sedimentary rocks, best preserved in the Northern Calcareous Alps, can be also in details visited in the Silica Superunit of the IWC. On the other hand, from the point of their uppermost structural position, the Silica Superunit with a distinct structural and metamorphic gap (and often evaporites) at their base may have a "southern" upper plate provenance. However, several parts of the Silica Superunit show during Triassic–Jurassic times a slightly different tectonostratigraphy, i.e. deposition of deep-water limestones above the Wetterstein Carbonate Platform without a "Mid-Carnian" siliciclastic event.

Testing all different tectonic units in the IWC, the CAI values confirm the nappe stack: the lowermost Bôrka/Meliata s.l. unit yielded conodonts with CAI values up to CAI 8.0 (6.5–8.0), the Turňa/Torna unit yielded CAI values 5.5–6.0. The Silica Superunit, or better, what is believed to be part of the Silica nappes, shows a highly diverse CAI pattern. Whereas the Silicic units (Muráň unit and equivalents) west of Gemeric unit show CAI values of CAI 5.0, and CAI 5.5–6.0 from Middle and Upper Triassic sedimentary rocks (including Upper Triassic fore-reefal limestones; but some exceptions with CAI values of 1.0–1.5 in enigmatic outliers could be traced), the situation south of the Gemeric unit is rather complex. There are sections with high CAI values (CAI 5.5–6.0), intermediate CAI values (CAI 2.0, 2.5–3.0), and low CAI values of CAI 1.0–1.5. Units with high CAI values of CAI 5.0, and 5.5–6.0 (including the Middle Jurassic Telekesoldal mélange, or outer shelf sedimentary rocks like the Bódvalenke section) and the intermediate units with CAI values up to 3.0 (including the Meliata mélange s. str.) have an ALCAPA tectonostratigraphy. In contrast, all units with low CAI values of CAI 1.0–1.5 show a different tectonostratigraphy, especially in the Late Triassic. These units rest often on remnants of evaporites or an evaporitic mélange.

The thermal overprint of the units with very high, high, and intermediate CAI values is connected with the Middle–Late Jurassic orogenesis forming the Neotethyan Belt in the Western Tethys Realm, whereas the emplacement of the units with low CAI values of CAI 1.0-1.5 seems to be related to the second orogenesis, the Mid-Cretaceous one (“eoalpine”, as preserved in the Veporic unit).

On base of these results, the classical nappe stack concept of the IWC has to be improved, and shed new light also on existing palaeogeographic reconstructions, which have to be changed significantly.

Timescale of pervasive melt migration in the continental crust

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Movement of a large volume of granitic melt is an important factor in the compositional differentiation of the continental crust and the presence of melt in rocks profoundly influences their rheology. Different mechanisms controlling melt migration through crust were proposed. We suggest that pervasive melt flow, analogous to reactive porous melt flow in mantle, could be possibly one of them. It is generally accepted that migration of felsic melts in continental crust starts with short distance pervasive microscopic flow into segregation veins which extract melt. However, we show that pervasive melt flow may be a regional mode of melt migration in continental crust. In such scenario, melt driven by deformation passes pervasively along grain boundaries through the whole rock volume. And the term pervasive melt flow is used for grain-scale, diffuse, porous and reactive flow of felsic silicate melt through rocks. This is effectively an open-system process that thoroughly reworks the resident rock mass. Through-flow of melt destroys pre-existing fabrics and the original chemical and isotopic nature of the protolith. Melt segregation is inefficient and protolith become isotropic granite-like, with partly preserved relics of the original, without ever containing more than a few melt percent at any time. The fabric and geochemical nature of these granites encapsulates the complex history of hybridization.

In order to decipher duration of pervasive melt migration we used precise U-Pb monazite ID-TIMS (isotope dilution thermal ionization mass spectrometry) and U-Pb monazite Laser Ablation Split Stream (LASS) geochronology in combination with monazite chemistry as well as U-Pb zircon SHRIMP geochronology. Monazite reveal continuous chemical equilibration with passing melt. They are getting progressively enriched in HREE and depleted in Eu. Monazites in the least affected rock preserve original magmatic zoning in Th and U, in contrast to more with melt equilibrated rock types, where this zoning is lost. Data for each migmatite type reveal similar date spread for both cores and the Y-rich well defined rims of single monazite grains, indicating a disconnect between U-Pb dates and chemical zoning. There is also no correlation between U-Pb ages and Yb/Gd ratio. This suggest perturbance of the isotopic system. We interpret these random distribution within-grain date variations as a result of dissolution-reprecipitation reactions between monazite grains and melt. During the coupled dissolution-reprecipitation radiogenic Pb was redistributed within the grain. This is supported by dissolution of apatite into silicate melts that stabilizes monazite during migmatitization, preventing their dissolution but not reaction with passing melt. Redistribution of radiogenic Pb resulted in meaningless individual ages from different migmatite types, but gave overall duration of the thermal event – pervasive melt flow. Duration of pervasive melt flow was dated 8-10myr. This suggest that porous flow of silicate melts in continental crust is a process which can operate over a long time and impacts on the rheology of the crust during orogeny.

Basin inversion in the Mecsek Hills (Mecsek nappe, Tisza unit, SW Hungary)

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Inherited normal faults receive more and more attention in the structural interpretation of fold and thrust belts worldwide. Several studies show that the inversion of rift -related grabens and halfgrabens has an essential role in the development of an orogen. Basin inversion resulted in the formation of specific structures such as inverted normal faults, and associated inversion anticlines, footwall short-cut thrusts and backthrusts. The basin-filling sediments frequently show increasing strain gradients in the vicinity of the basin bounding normal fault (buttressing).

Our study area is in the Mecsek Hills where Variscan metamorphic rocks and the overlying Permian to Early Cretaceous sedimentary cover of the Mecsek nappe are exposed. The Permian-Mesozoic sedimentation was governed by two major rifting phases during the Permian and the Early to Middle Jurassic. The study area suffered intense folding and thrusting during the Late Cretaceous, during which the Mecsek nappe formed, which represents the lowermost alpine thick-skinned nappe of the fold and thrust belt of the Tisza unit. This fold and thrust belt is unconformably overlain by the Miocene succession that is related to the opening of Pannonnian back-arc basin. The presence of Mesozoic rift-related normal faults has been postulated for a long time in the Tisza unit, based on lateral facies changes, however, their role in the Cretaceous nappe emplacement has not been investigated yet.

We created several cross-sections based on field, well and seismic data. Based on these cross-sections, we interpreted the structure of the Mecsek Hills as an inverted halfgraben, where the major basin bounding normal fault was the Mecsekalja Fault (MF). The relatively competent Permian-Triassic succession of the Western Mecsek is folded into an open inversion anticline that is dissected by several backthrusts which are antitethic to the MF. In the eastern part of the Mecsek, the relatively incompetent Jurassic succession is buttressed against the rigid footwall block of the MF, which is built up by Variscan metamorphic rocks. In this area the inversion related thrusts are syntethic to the MF. This eastern segment of the MF is a young-on-older Late Cretaceous thrust, which possibly came into being due to the reactivation of a Jurassic normal fault. The inversion related folds and thrusts are unconformably overlain by Miocene strata, nevertheless, the geometry of Miocene deposits indicates the Neogene transpressional, strike-slip reactivation of the Cretaceous compressional structures.

Syntectonic hydrocarbon migration in a Triassic fractured marlstone body

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The Middle to Upper Triassic formations of the Kantavár quarry, located in the Western Mecsek Mts., Hungary, provide an excellent location to study the area's structural development and subsidence history. A tectonized section of the succession is revealed in the quarry, where a mineral vein system with varying texture and microstructure can be observed. A member of this vein system, like many Triassic to Jurassic formations in the Mecsek Mts., is associated with hydrocarbon (HC)-bearing fluid migration.

In the argillaceous limestone, calcareous and argillaceous marlstone bodies, strike-slip faults, normal faults, mineral veins, bituminous stylolites, and joints were observed. Two dominant vein types were distinguished in the quarry, whose relative age is revealed by their crosscutting relationship (Fig. 1). The older veins ($Vein_{GREY}$) are made up of grey calcite, which contains numerous parallel wall rock inclusion bands indicating crack-seal vein formation mechanism. The crystal morphology is typically stretched; the grains have serrated boundaries and extend across several crack-seal zones. In wider (>3 cm) members of the $Vein_{GREY}$ generation or in wider (>2 mm) crack-seal zones (asterisk in Fig. 1), the inclusion bands are less typical, and the dominant crystal shape is blocky or elongate blocky. The younger veins ($Vein_{WHITE}$) are composed of white calcite as well as minor amounts of dolomite, quartz, and dickite. The calcite, dolomite, and quartz crystals usually have blocky, elongate blocky, or irregular shapes, while dickite appears as flakes or amorphous clusters.

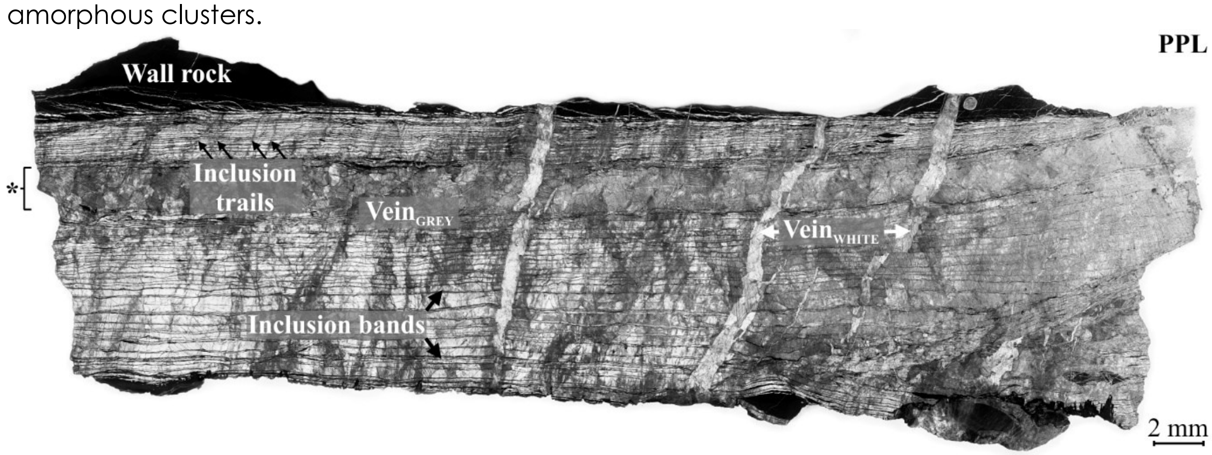

Fig. 1. The grey calcite veins ($Vein_{GREY}$) are crosscut by white calcite veins ($Vein_{WHITE}$). Within the $Vein_{GREY}$, inclusion bands of wall rock fragments can be observed. The asterisk indicates a wide crack-seal zone, with elongate blocky and blocky as dominant crystal morphologies. PPL – plane-polarized light.

Hydrocarbon-bearing fluid inclusions were observed in the older, grey calcite-cemented veins ($Vein_{GREY}$). The fluid inclusion assemblages form evenly distributed clouds in the crystal cores or planes almost at right angles to the wall rock inclusion bands. The homogenization temperature of the HC-bearing inclusions is below <65 °C, while co-genetic aqueous inclusions homogenize between 105 and 125 °C into the liquid phase. Based on the UV fluorescent properties of the HC-bearing inclusions, the fluid consists of condensate to volatile oil.

Based on crystal morphology, both types of veins formed from advective fluids, which migrated through open fractures. The serrated boundaries of the stretched crystals in the $\text{Vein}_{\text{GREY}}$ suggest ataxial or stretching vein growth, whereby crack-sealing was the dominant vein-forming mechanism. Based on their textural position, the fluid inclusions in the core of the crystals are of primary origin, i.e., formed contemporaneously with the crystal growth of the $\text{Vein}_{\text{GREY}}$. On the other hand, the fluid inclusion assemblages perpendicular to the wall rock inclusion bands are probably pseudosecondary and were formed as inclusion trails during the sequential opening of the veins; thus, they are syntectonic as well. Therefore, it can be concluded that during the formation of the $\text{Vein}_{\text{GREY}}$, hydrocarbon-bearing fluid migrated in the fracture system. The generation of hydrocarbons during catagenesis is a plausible explanation for the development of elevated fluid pressure, which is essential for the growth of the crack-seal veins. On the other hand, the younger, white veins ($\text{Vein}_{\text{WHITE}}$) can be interpreted as syntaxial veins. Further investigation of these minerals and their fluid inclusions can significantly contribute to the understanding of the structural evolution and fluid migration history of the area.

Acknowledgements

The research was supported by the ÚNKP-22-4 New National Excellence Program of the Ministry for Culture and Innovation from the Source of the National Research, Development and Innovation Fund and by the National Research, Development and Innovation Office, Hungary (K-138919).

Zircon isotopic and geochemical record of early Palaeozoic volcanism and sedimentation of the Kaczawa Complex, the Sudetes (SW Poland)

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The Kaczawa Complex (SW Poland), contains early Palaeozoic felsic, intermediate to basic volcanic rocks and Cambrian to early Carboniferous sediments, which are all involved in complex processes of the Variscan collision(s). Protoliths of these rocks represent different stages of the development of the Saxothuringian ocean, which started to develop in the early Palaeozoic and ultimately closed in the latest Devonian to early Carboniferous. New LA–ICP–MS U–Pb geochronological and trace element compositional analyses of zircons from some rocks occupying the early Palaeozoic part of the stratigraphic column of the Kaczawa Complex (Osełka metarhyodacytes, Lubrza metatrachytes, Radzimowice slates and Gackowa metasandstones) were performed to provide more insight into the early stages of the development of the Saxothuringian ocean.

The U–Pb dating of zircons from the Osełka metarhyodacites yields a crystallization age of 500±5 Ma, while the zircon dating of the Lubrza metatrachytes yields a Concordia age of 495±3 Ma. These data confirm the early Palaeozoic age of volcanism in the Kaczawa Complex, but they strongly suggest not two events but rather a single event of bimodal volcanic activity. Zircon geochemistry (Nb=2.05-24.53 ppm, U=285-2150 ppm, Y=685-18394 ppm, U/Yb=0.40-1.79, and Nb/Yb=0.002-0.021) suggests that the magmas of the Osełka rhyodacites originated by melting of the Cadomian continental crust. The contents of Nb, U, and Yb in zircons (Nb=1.6-168 ppm, U=68-845 ppm, U/Yb=0/26-1/64, and Nb/Yb=0/003-0.248) suggest that trachytic magmas developed partly in a plume-influenced setting.

The accompanying metasedimentary rocks, i.e., Radzimowice slates and Gackowa metasandstones, have comparable detrital age spectra showing Neoproterozoic to early Cambrian maximum depositional ages. The predominance of Neoproterozoic zircons clustering at approximately 580-605 Ma, 630-640 Ma, and 730-770 Ma indicates that the sedimentary basins were mainly supplied by erosion of crystalline rocks of Ediacaran to Tonian ages. Palaeoproterozoic and Archean components (1.7 Ga, 2.0-2.1 Ga, and 2.9-3.0 Ga) are less common, which jointly suggests that the source areas for the Kaczawa Complex metapelites during the formation of the Saxohuringian basin may have been located in the West African Craton of Gondwana.

Acknowledgment: The research was financed by a grant from the National Science Center, Poland No. 2018/29/B/ST10/01120.

The Zábřeh Crystalline Unit - geochronological data and their geotectonic implication

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The Zábřeh Crystalline Unit (ZCU) is situated on the eastern margin of the Bohemian Massif and is rimming the Orlice-Sněžník Unit from the south. As such, the area of ZCU was rather neglected in the studies concerning the tectonic evolution of the Bohemian Massif.

The newly discovered narrow zone of gabbros, garnet amphibolites and high-grade gneisses (Zejfy-Hynčina belt) exposed in the middle of ZCU inspired us to perform a detailed geochronological and geochemical study to constrain the geodynamic evolution of the ZCU.

The study was conducted on eight samples, four samples of metasediments and four samples from the Zejfy-Hynčina belt.

The metasediments from the northern part of ZCU are represented by fine- to medium-grained quarzitic phyllites with the upper Cambrian to lower Ordovician protolith age constrained by detrital zircon geochronology. On the other hand, the fine-grained metagreywacke from the southern part of ZCU yielded the upper Neoproterozoic age, and the metaconglomerate from the southernmost part was deposited during the early Cambrian. The KDE of the ages can be correlated with other units of the Bohemian Massif and they show a typical distribution of the Cambro-Ordovician sequence of Peri-Gondwana with significant affinity to the West African Craton.

The Zejfy-Hynčina belt consists of gabbroic rocks, amphibolites and felsic high-grade gneisses surrounded by metabasites, likely originated by strong retrogression under greenschist facies conditions. Gabbros to metagabbros are solid, dark rocks made of amphiboles with plagioclase-epidote matrix and were intruded during the upper Cambrian (493 Ma). Tonalitic gneisses are made of quartz, plagioclase, amphibole, garnet, biotite and chlorite and are spatially juxtaposed with gabbros. The obtained data show similar age to gabbroic rocks (493 Ma).

The metasediments associated with the metabasites are migmatized greywackes - the light strips of leucosome alternate with dark strips of melted rock. The original greywacke consisted of plagioclase, quartz, muscovite, biotite, K-feldspar and epidote. In the melanosome, the muscovite is not present and some of the biotite decomposes into secondary chlorite. The zircons from the melanosome yielded the maximal age of sedimentation of the lower Cambrian. Interestingly, the distinct population of zircons giving middle Devonian ages (around 390 Ma) with significantly higher values of U/Th have been identified in leucosome-bearing layers. This is interpreted as the early Variscan metamorphism and partial anatexis related to the back-arc extension identified in the Jeseníky Mountains by Schulmann & Gayer (2000) and Janoušek et al. (2014).

Similar mafic rocks were earlier described in the Staré Město Belt and the Nové Město Crystalline Unit surrounding the ZCU. The results of our study indicates that the ZCU represents a segment of abandoned Cambro-Ordovician rift zone developed along the northern margin of Gondwana. The area was probably affected by early Variscan metamorphism likely related to Devonian back-arc opening.

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Introduction of the new 1:500 000 scale map of young geological deformations formed during the neotectonic phase in Hungary

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The presentation introduces the new 1:500 000 scale map of young geological deformations in Hungary, including all important deformation structures (faults and folds) related to the neotectonic evolutionary phase (<6–8 Ma) of the Pannonian basin.

The new map is based on the interpretation of nearly 2900 2D seismic profiles and 70 3D seismic volumes, as well as on the critical evaluation of the results of published neotectonic studies, furthermore unpublished, but relevant research/exploration maps/reports. An important novelty of the map is that not only the near-surface manifestations of the neotectonic faulting, but also their roots in the underlying pre-Pannonian substratum are displayed, allowing correlation between various reactivated fault segments of longer fault zones and aiding the better understanding of the regional structural context.

The new map provides a significantly more accurate definition (actual position, extension and geometry) of the neotectonic structures and provide more details compared to previous regional studies. The prevailing (E)NE–(W)SW striking neotectonic fault pattern clearly reflects the control of identically oriented pre-Pannonian fault systems during the neotectonic deformations. These (E)NE–(W)SW striking, major pre-Pannonian fault systems (Mid-Hungarian fault zone, Kapos fault zone, etc.) are related to the Early to Middle Miocene formation of the Pannonian basin.

The new map allowed the identification of several neotectonic domains with markedly different deformation patterns. In all domains the neotectonic fault pattern clearly reflects the control of identically oriented pre-Pannonian (mostly synrift) fault systems during the neotectonic phase. Markedly different orientations in the neotectonic structures indicate important differences in the overall orientation of the underlying fault systems. These observations demonstrate that neotectonic activity is predominantly due to the reactivation of pre-existing (predominantly synrift) structures all over the Pannonian basin, as also indicated by previous studies.

Despite experiencing the largest Middle- to Late Miocene extension and the formation of the deepest depocenters in the whole Pannonian basin, SE Hungary practically lacks any observable neotectonic activity, which is a striking, but still poorly understood feature. Unfavorable fault orientations, furthermore the combination of thick sedimentary cover and insufficient displacements along the major root zones in the pre-Pannonian basement are speculated behind this phenomena.

Detailed 3D seismic analysis of fault segment geometries indicates a consistent regional pattern: sinistral shear along (E)NE–(W)SW oriented, and dextral shear along (W)NW–(E)SE oriented fault zones, respectively. These observations — together with the E–W trending contractional/transpressional structures (folds, reverse faults, imbricates) occurring in western and southern Hungary — indicate a dominantly strike-slip stress regime with a laterally slightly rotating (from N–S to NNE–SSW) maximum horizontal stress axis ($\sigma 1$) during the neotectonic phase. This is basically in agreement with observed characterictics of the currently active stress regime.

Lateral displacement along major root zones amounts to a maximum of 2–3 km during the neotectonic phase considering estimations based on published modelling results. Hence, the magnitude of the neotectonic phase within the Pannonian Basin with an intra-plate setting can be considered as a weak tectonic event compared to active tectonic movements related to plate boundaries.

Introduction of the new seismotectonic map of Hungary (scale - 1:500 000)

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The new seismotectonic map of Hungary in a scale of 1:500 000 has been constructed in the frame of a national excellence program (2018-2.2.1-NKP-2018-00007, supported by the National Research, Development and Innovation Office). The constructed map represents the first seismotectonic map of Hungary.

The construction and interpretation of the new map have been preceded by extensive research activities including the construction of the new seismicity, neotectonic, stress and strain regime maps of Hungary and its surroundings. These activities have all contributed to the better understanding of the structure and geodynamics of the Pannonian basin and its Carpathian frame. The new map integrates the latest available seismological, tectonic and geodynamic knowledge in Hungary, furthermore provides important input for the new seismotectonic hazard map of Hungary.

Seismicity data of the region include the combination of the instrumentally detected earthquakes (occurred since 1996) and documented historical seismological events (occurred before 1996). The iLoc and other multi-event algorithms were used to precisely locate the instrumentally detected earthquakes. The final dataset, filtered from various anthropogenic events, contains altogether 82 642 events up to the end of 2020. Except for the very active Vrancea-zone, the region is generally characterized by shallow earthquakes mostly occurring in the upper crust. Hungary is characterized by moderate seismicity in comparison to the surrounding Alp–Carpathian–Dinaridic frame. Events exceeding M=5 are explicitly rare (altogether less than 20). This suggests a moderate and rather slow stress accumulation in the rigid upper crust.

Calculated focal mechanism solutions of selected earthquakes in Hungary indicate mostly strike-slip, or — less frequently — reverse sense movements. Based on calculated/published focal mechanism solutions, the stress regime of the region was calculated. In Hungary, strike-slip to transpressional regimes occur associated with a predominantly (N)NE–(S)SW oriented maximum horizontal stress direction (S_{Hmax}), that — regarding the calculated stress regimes — corresponds to the maximum principal stress (σ_1) direction. Extension/transtension occurs only locally in the studied region (mainly in the Southern Carpathians). Calculated stress regimes displayed with a continuous color scale forms the background of the new seismotectonic map.

Using GNSS data, the recent crustal deformation was also studied in Hungary and in its surroundings. It is characterized by shortening and transpression within Hungary. However, strain rate data show relatively small absolute values (1–10 nanostrain/year). Largest crustal strain rate (6–10 nanostrain/year) was detected in southwest Hungary that decreases rapidly toward the North/Northeast (1–2 nanostrain/year). Moving to the North and the East, the type of deformation gradually changes to transtension/extension in the Slovakian and Romanian Carpathians. The type and magnitude of the strain rate are also shown on the new seismotectonic map.

The fault model of the new seismotectonic map derives from the new neotectonic map of Hungary that has also been developed in the frame of the project based on the interpretation of previous 2D and 3D seismic datasets. The displayed faults represent the pre-Pannonian root zones of important faults (independently from their neotectonic reactivation) that ensure a comprehensive overview of the local and regional structural context. Considering various direct and indirect data (seismicity, direct structural and/or paleoseismological observations, young geomorphological indicators, structural relationship to other known active faults, etc.), the inferred Quaternary structural activity of the displayed pre-Pannonian root zones are also indicated on the map. Altogether, active faults/fault zones are mostly (E)NE–(W)SW oriented and largely coincide with root zones that display a prominent neotectonic reactivation. Regarding the calculated stress regime and the orientation of the maximum principal stress, these faults generally have a sinistral strike-slip kinematics.

The results introduced briefly above clearly support the ongoing inversion of the Pannonian basin and its surroundings. The geodynamics of the region is basically influenced by the "Adria-push" (i.e. the continuous north/northeastward movement of the Adriatic microplate) and the "locked" position of the Pannonian basin within the Carpathian frame, not allowing for further eastward escape.

Middle-Late Triassic Hallstatt Limestone blocks in the Avdella ophiolitic mélange as indicators for the provenance of the Pindos ophiolites.

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Most of the geodynamic models about the ophiolites of the Albanide/Hellenide orogenic belt contradict to whether the Mirdita/Pindos ophiolites originated A) from a parautochthonous oceanic basin (Mirdita/Pindos Ocean) or B) represent remnants of a far-traveled ophiolite nappe stack derived from a Neo-Tethys Ocean located east of the Pelagonian/Korabi units. In order to contribute to the questions about their origin we investigated the Avdella mélange, a tectono-sedimentary succession of Middle to Late Jurassic age exposed below the Pindos ophiolites at the western edge of the Pelagonian unit, in northern Greece. By definition, ophiolitic mélanges are formed during ophiolite obduction, appear at the base of the obducted ophiolites and may scrap off blocks from the lower plate, and can therefore provide detailed insights regarding their route. In addition, in front of the obducting ophiolites a nappe stack can be formed in lower plate position. In front of the nappes deep-water trench-like basins were formed containing sedimentary mélanges. These mélanges can be later incorporated in the nappe stack and get sheared.

The Avdella mélange is characterized by a block-in-matrix structure and is intensively folded associated with a W- to SW-ward sense of movement. Its thickness extent up to several hundred meters and is composed of blocks and slides that reaches from meter to hundreds of meters. Specifically, the mélange contains a variety of rocks, including Triassic ophiolites with their sedimentary radiolarite cover, siliciclastic volcano-sedimentary rocks and Triassic carbonates, incorporated in an argillaceous-radiolaritic (Jurassic) matrix.

Conodont dating and microfacies analysis were conducted to carbonate blocks which were found in different outcrops of the Avdella mélange in order to obtain a better understanding about their palaeogeographic provenance. These blocks include: red nodular limestone with chert concretions dated with the conodonts Gladigondolella-ME and Neocavitella sp. as Early Carnian, red and gray radiolarian-filament wackestones dated with the conodont Norigondolella cf. navicula as Early Norian (Lacian 1-2), gray siliceous limestone with red chert nodules containing the conodonts Norigondolella cf. navicula and Epigondolella rigoi (Lacian 2) and reddish limestones with Epigondolella sp. assigning a Middle Norian (Alaunian-?Sevatian) age.

Ages and microfacies of these blocks dated as Early Carnian, Early and Middle(-Late) Norian indicate an open marine depositional environment that correspond to a Late Triassic Hallstatt Limestone succession, well-known from the Northern Calcareous Alps, the Inner Western Carpathians, the Dinarides, the Albanides and the Hellenides. Furthermore, similar successions are preserved in the Pindos Mts. to the west of the Pelagonian units. Hallstatt Limestones originally had been deposited in a distal shelf area during Middle Anisian to Rhaetian with subsequent Early Jurassic sediments. These facies oriented along the continental slope facies (Meliata facies) and both represented the outer passive continental margin to continental slope of the northwestern and western Neo-Tethys realm. Therefore, the occurrence of the Triassic Hallstatt Limestone blocks within the Avdella mélange demonstrate that the west-directed obducting ophiolites overrode a sequence formed along the outer western passive margin of the Neo-Tethys Ocean to the east. In Middle to early Late Jurassic times the obducted Pindos ophiolites took place on top of the Pelagonian unit, and the newly formed deep-water basins received material from the advancing Pindos (=Hallstatt Triassic(-Middle Jurassic) sedimentary rocks) and ophiolite nappes. Subsequently the Pindos ophiolite nappe stack overthrusts its foreland basin forming a typical ophiolitic mélange, in case of the Avdella mélange mixed ophiolitic material with blocks from the outer shelf (Hallstatt facies zone).

The detection of a reworked Hallstatt Limestone sequence below the obducted ophiolites shows that the ophiolites represent far-traveled nappes from the east (Neo-Tethys Ocean). The reworked Late Triassic Hallstatt Limestone succession corresponds to Late Triassic sedimentary successions preserved in the western Pindos (sedimentary rocks) nappe. On base of these results the Pindos nappe represents a far-traveled Middle Jurassic nappe bulldozed by the obducting ophiolites to the west. An independent Pindos Ocean or a deep-water Triassic-Jurassic Pindos Basin west of the Pelagonian unit is in contradiction to our results which confirm a single ocean model, i.e. the Neo-Tethys Ocean to the east with the Pelagonian unit as part of the wider Adria.

Acknowledgment: In the frame of the IGCP 710 "Western Tethys meets Eastern Tethys".

Introduction of the new seismotectonic hazard map of Hungary

(scale - 1:500 000)

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The new seismotectonic hazard map of Hungary in a scale of 1:500 000 has been constructed in the frame of a national excellence program (2018-2.2.1-NKP-2018-00007, supported by the National Research, Development and Innovation Office). The constructed map represents the first seismotectonic hazard map of Hungary.

The construction and interpretation of the new map have been preceded by extensive research activities including the construction of the new seismicity, neotectonics, active tectonics maps of Hungary and the evaluation of local site responses to earthquakes and its correspondence to? geomorphology and shallow layer's lithology. These activities have all contributed to the better understanding the seismological and tectonic hazard of Hungary and provide initial information on the potential location of future fault displacements and their predictable local effects for the society and experts.

Detailed description about the collection and representation of displayed seismicity data and the fault model can be found here in the abstract titled Introduction of the new seismotectonic map of Hungary (scale - 1:500 000).

In order to derive local site response more than 100 measurements of the shear (S-)wave velocity of the uppermost 30 m rock (V_{S30}) have been measured and collected. This parameter is important to determine the typical increase in amplitude of the upward propagating seismic waves causing bigger shaking effect at the given location due to the local soil properties. V_{S30} data were compared to geomorphological and lithological parameters of the measurement sites in order to characterize the investigated area. Our results revealed that most of the territory of Hungary belongs to the Eurocode 8 soil class C characterized by 180-360 m/s due to its general basin character. Tertiary hills and foothills show higher velocities (~300-800 m/s), that corresponds to the top of C or B soil classes depending on the thickness and properties of the covering younger sediments. Hard rock outcrops belong to the Eurocode 8 soil class A (V_{S30} > 800 m/s). Most hazardous soil class (D; V_{S30} < 180 m/s) have not been directly identified by our measurements (minimum measured V_{S30} are 197-200 m/s). However, it became also clear that depending on the thickness and quality of the young sediment in alluvial and lacustrine lowlands occurrence of soil class D cannot be eliminated.

Based on these initial data set, correlation between topographic gradient between V_{S30} have been established. Our results revealed that the characteristic topographic gradient of soil classes slightly differ from globally determined values (C: 0.3–3%, B: 3–11%). Estimated soil classes based on the topographic gradient are presented as the background color of the map.

High risk geomorphological features (alluvial and lacustrine lowlands; called potentially D on the map) and close surroundings of basement outcrops (5–20 m thick loose sediment covering hard rocks; here called potentially E) have been manually identified based on geomorphology, surface geology and our borehole database.

The new map integrates the latest available seismological, tectonic and geophysical geomorphological knowledge in Hungary and provides initial information for interested people and architects. Topographic gradient of soil classes available in widely referred literature (based on global datasets) are locally reviewed and fine-tuned. For example, soil classes D and C appear on steeper topography increasing the overall hazard. Area that are exposed to seismotectonic hazard can be defined by the occurrence of densely located earthquake epicenters and/or locations with active faults, furthermore by local soil classes belonging to category D or E. These areas are Csurgó–Nagykanizsa, Zalaszentgrót, Répcelak (Bük–Mihályi–Sárvár triangle), Komárom, Várpalota–Mór, Pincehely, Csepel, Szabadszállás, Heves, Hatvan–Jászberény, the neighbourhood of Miskolc, eastern side of Bakony Mts., Vértes Mts., southern side of Dunazug Mts., Diósjenő fault, southern foothills of Bükk Mts., and the southwestern side of Zemplén Mts. Our mapping campaign revealed some irregularities in alluvial sediment thickness variations that can be referred to the neotectonic activity of a given fault or fold. These are the following areas: Rába River, southwestern part of Danube Basin, Danube valley between Budapest and Paks, valleys of Hernád, Kapos, Sió, Kerka and the Dráva Basin.

The new seismotectonic hazard map of Hungary can be downloaded among others and vector data can be requested at Geomega website (www.geomega.hu).

The role of the asthenosphere in the recent geodynamics of the Carpathian Pannonian region

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There are several recent joint geophysical and geochemical studies demonstrated that there is usually a global partially molten layer in the upper mantle between ~100 – 150 km depth, which can be broadly equated to the low velocity zone (LVZ). The low velocity zone is a well know shell of the upper mantle where the velocity of seismic waves is considerably reduced. There are several different explanations for this velocity reduction nowadays but the most commonly accepted one is the presence of small (<1-2 %) incipient partial melt. This partially molten layer is the somewhat deeper less viscous part of the upper mantle also referred to as the asthenosphere. The outermost rigid layer is the lithosphere which includes the uppermost thin part of the mantle and the crust. The lithospheric plates float on the underlying asthenosphere.

The asthenosphere typically considered only as a passive actor when it comes about the Neogene geodynamics of the Carpathian-Pannonian region including both the extensional and the subsequent tectonic inversion stage. Dynamic of the asthenosphere, which is commonly referred to as asthenospheric flow is thought to be generated by slab rollback when the slab exerts suction on the asthenosphere on its front and simultaneously expels the asthenosphere from its back generating toroidal asthenospheric flows. In addition asthenospheric flow can also be generated by collision of continental lithospheric plates which squeezes the asthenosphere out parallel to the strike of the orogenic belt. In addition asthenospheric flow can be also produced by smaller scale regional or larger scale global upper mantle convections and can exert a drag on the bottom of the overlying plates. A special case of broader upper mantle flows are plumes which raise either from the mantle transition zone (440 – 660 km) or the upper mantle – core boundary and can be of both thermal and chemical nature.

In the first part of the presentation a brief review is provided on what could be the cause for the lower seismic velocities in the asthenosphere globally. In the second part it will be summarised what kinds of asthenospheric flows have been proposed so far to explain the formation of the Carpathian-Pannonian region, and how such flows can be better imaged by geophysical deep surveys and how can it help us to refine our geodynamic models on the formation and evolution of the region.

Structural analysis and deformation record of the Nízke Tatry Mts. along the Čertovica Fault between the Tatric and Veporic Units (Western Carpathians)

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The Nízke Tatry Mts. is a mountain range that extends into the central part of the Western Carpathians. The Nízke Tatry Mts. is divided into two important sub-units both from a geomorphological and geological point of view. Their western part is called Ďumbierske Tatry and it contains the Tatric crystalline basement. Their eastern part called Kráľovohoľské Tatry is composed of the Veporic crystalline basement (Mazúr & Lukniš, 1986). The geographical boundary, as well as the geological boundary of both tectonic units roughly, coincides with the Čertovica Fault. Along this important shear zone, the Tatric Unit is tectonically overlain by the Veporic Unit during the Alpine tectogenesis (Maheľ, 1986). The studied territory was influenced by at least two orogenetic cycles – older Variscan and younger Alpine. Based on the structural analyses, it was possible to determine several deformation events. The older group of deformations $\mathrm{D^V}$, which were accompanied by the Variscan higher-grade metamorphism and the younger deformations group $\mathrm{D^A}$ is featured by deformation structures of low-grade (retrograde) metamorphism, phyllitic foliations, S-C fabric, cataclasis and minor recrystallization. In the study area, the Variscan deformation $\mathrm{D_2^V}$ is the earliest pervasive deformation with pronounced evolution of $\mathrm{S_2^V}$ metamorphic foliation, locally with preserved isoclinal and root-less folds of planar fabric $\mathrm{S_1^V}$. Stretching and mineral lineation ($\mathrm{L_2^V}$) are usually oriented in the ENE–WSW direction. The fabric of $\mathrm{D_2^V}$ is intensively folded by folds ($\mathrm{F_2^V}$) and evolution of $\mathrm{S_3^V}$ axial planes in many places. The Alpine $\mathrm{D_1^A}$ deformation was accompanied by low-grade metamorphism and was depicted by space to zonal and in some places pervasive foliation ($\mathrm{S_1^A}$). This deformation is characterised by a typical S-C fabric, where S planes are $\mathrm{S_2^V}$ and C planes represent $\mathrm{S_1^A}$ foliation. The crenulation and intersection lineations ($\mathrm{L_{1c}^A}$) have the NE–SW to E–W trends. The $\mathrm{D_1^A}$ deformation is also accompanied by pronounced evolution of NNW–SSE stretching and mineral lineation ($\mathrm{L_{1t}^A}$). Shortening in the NNW–SSE direction is also evidenced by asymmetric folds with an ENE-WSW orientation od fold axes ($\mathrm{F_1^A}$) and line intersections ($\mathrm{L_{1c}^A}$). The youngest observed Alpine deformation $\mathrm{D_2^A}$ is related to extension and exhumation of the Tatric crystalline basement with top-to-the east transport defined by Alpine lineations $\mathrm{L_2^A}$ on spaced planar structures ($\mathrm{S_2^A}$).

Acknowledgement: This work was supported by the Slovak Research and Development Agency under contracts Nos. APVV-21-0281 „Alpine geodynamical evolution of the Western Carpathian inner zones", APVV-17-0170 „Early Alpidic tectonic evolution and paleogeography of the Western Carpathian" and the VEGA Grant No. 1/0346/20.

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Stratigraphic and tectonic results of geological mapping of the Muran plateau, Central Western Carpathians, Slovakia

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Detailed geological mapping of the Muráň plateau, Central Western Carpathians, Slovakia was performed in the years 2010 - 2019. The plateau is situated as a thin-skinned nappe structure on the SE side limited by the sharp Muráň Fault. The Muráň nappe is considered part of the Silicic nappe system emplaced on the Veporic basement during Upper Jurassic - Early Cretaceous, subsequently the unroofing of the Veporic basement SE of the Muráň Fault removed more southern parts of the nappe, thus making the Muráň plateau a relic Silicic outlayer. However the geological mapping proved, that the stratigraphy as well as the inner structure and tectonic history of the Muráň nappe are more complicated. The main results of our mapping can be summarized as follows:

The existence of two nappe units, supposed earlier by some authors (Havrila, 1997) have been proven, where often the detailed micropaleontological study was a key for deciphering these units. The both nappes show Silicic as well as Hronic elements.

There is a very heterogenous plastic complex built by mostly Lower Triassic shales and sandstones, rauhwackes with incorporated bodies of Permian rhyolites and Carboniferous phyllites between the relatively rigid footwall of Veporic unit and the Middle Triassic to Jurassic carbonatic part of the Muráň Nappe.. The thickness of this plastic complex varies between 0 to 120-150 m and shows many structural irregularities, duplexes.

Formerly the Middle Triassic formations of the Muráň Nappe were considered as a “deep water” type in the lower and a “carbonate platform” type in the upper nappe. However, the detailed stratigraphical study shows, that in both products of deep as well as shallow water sedimentation are present. The main difference is how the overthrust plane is cutting them. The Anisian “deep water anomaly” can be correlated with the “reifling event” known from the Alps and also the Aggtelek Karst in northern Hungary.

Overall 10 tectonic events since the Cretaceous were distinguished based on paleostress study and map-level structures. In addition, it should be noted that the most recent neotectonic events, manifested mainly by uplifting and/or subsidence of parts of the area, probably had a much greater influence on the evolution of the area than previously thought.

Acknowledgements

This contribution was supported by the projects of the Ministry of the Environment of the Slovak Republic no. 16 06 and 17 13 - Updating the geological structure of problematic areas of the Slovak Republic at the scale 1:50000 maps.

Modes and geometry of detachment doming in large hot orogens - insights from physical modelling: examples from the Central Asian Orogenic Belt

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The classical concept of the detachment folding describes displacement and buckling deformation of a competent layer above a weak, usually low viscosity layer, horizon during tectonic shortening. From this definition, and based on the Biot-Ramberg theory, the geometrical parameters of detachment folds depend on contrasting rheology of both layers or on a rheological gradient in a complex multilayer. These systems were originally studied in the relationship to the thin-skinned deformation and salt tectonics, and recently in association with large-scale lithosphere deformation. Here the heated lower crust is partially molten and a thin melt layer at the MOHO depth serves as a detachment horizon during collision and shortening.

The Central Asian Orogenic Belt (CAOB) in Mongolia and NW China represents one example of such behaviour where the hot and partially molten lower crust developed arrays of magmatic-metamorphic domes during complex and polyphase regional deformation. The major Permo-Triassic event that formed such structures in the Mongol-Hingan oroclinal system is also associated with increased thermal fluxes and with the high-grade metamorphism.

We employ physical modeling to understand 1) the geometrical, kinematic and dynamic internal behaviour of such types of the detachment folds, as their formation is controlled by thermally dependent rheological gradient and nonlinear shortening rates, and 2) large-scale behavior of such systems when deformation is associated with parallel or oblique indentation or the progressive closure between the confining limbs of large oroclinal structures. The natural prototype for our analogue models are for example Chandmann or Bugat metamorphic domes situated in the Mongol-Altai Zone or Roc de Frausa Massif in the Eastern Pyrenees.

Results of the physical modelling are investigated by advanced applications of image analysis methods (PIV and photogrammetry) to quantify geometry and dynamics in the large-scale and local areas. We found correlation between the line curvature of the rheological interfaces, amount of melt and initial conditions of such collisional systems. Moreover, migration of the melt and deformation of the lower crust are coupled in a complex manner varying towards backstop regions which affects kinematics and geometry of developed fold belts or domes.

Centrifuge analogue modelling of transcrustal granite-migmatite fault-parallel extrusions: examples on the Moldanubian unit of the Variscan Bohemian Massif

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The Variscan orogenic collapse was accompanied by voluminous post-orogenic S-type granite-dominated magmatic activity in the Bohemian Massif (Žák et al. 2014). Verner et al. (2014) and Žák et al. (2020) interpreted the ~NE–SW branch of the Moldanubian batholith and its migmatitic host (the Pelhřimov complex) as an exhumed core complex with a pseudo-diapiric upwelling along an opening fault driven by extensional gravitational collapse. Detailed petrology and geochronology constrained the migmatitization at ~329 Ma and exhumation from ~21 km to ~9 km depth at a rate of 6–7 mm/year (Žák et al. 2011). Based on the 3D gravity modelling, seismic refractions and reflections, the emplacement was influenced by the existence of the underthrusted Brunovistulian (Brunia) microplate (indentor) beneath the lower to mid-crustal Moldanubian unit (Guy et al. 2010, Verner et al. 2014). The surface expression of this deep boundary is marked at the present-day erosional surface by the NNE-SSW striking Přibyslav mylonite zone. Due to limited exposure, field studies provide only a near-2D view on the internal architecture of otherwise 3D vertically-extensive transcrustal magmatic systems. The extrapolation of the surface data may leave us with sometimes unclear and contentious emplacement models. Careful field studies along with analogue modelling may help to fill the missing gap.

Centrifuge analogue modelling

Generally, analogue modelling is limited by the scaling of the gravitational potentials of small-scale experiments in the laboratory to large-scale geological systems. Thus the vertical inversion of lighter and heavier rock analogues has to be supported by artificial gravity (centrifugal force) to allow realistic scaling together with reasonable time for the model run. To investigate the vertical extrusion of partially molten granitic and migmatitic masses which formed the Moldanubian batholith, we employed centrifuge modelling at the Hans Ramberg Tectonic Laboratory, Uppsala University, Sweden (Ramberg 1981). Our modelling strategy was to activate a predefined normal fault and initiate simultaneous material extrusion along the weakened fault zone. To investigate the general behaviour of such extrusions, we tested several scenarios were we modified the rheology of middle and lower upper crust and the horizontal anisotropy of molten (silicone), partially molten (silly putty) and solid-state (plasticine) segments. Furthermore, various orientations of the predefined fault with respect to a defined geometry of the crust were captured in our modelling.

The deformation pattern in the upwelling silicone marked by differently coloured layers revealed a gradient of vertical displacement and progressive folding, both in the extruded part and beneath the diapiric channel in the source region. Another important result is the presence of descending backflow streams in the feeding channel between the source layer and surface dome. The main four experiments included step-by-step improvement of the modelled domain to progressively reach a more complex and specific geometrical setup, which corresponds to assumed space relationships between the Brunia microplate and Moldanubian unit. The fault dip direction and dip were set as 110°/60° (i.e., a normal fault striking obliquely to the extension direction) to better simulate the mylonite zone. Three of these experiments resulted in a simple material inversion with lateral asymmetry of fault opening. We observed first-order (molten-partially molten crust) and second-order (partially molten-solid crust) divergent diapirism along the opened fault. The map view revealed two independent conduits with effusion of the lower upper crust to two opposite directions which correspond well to structural and map patterns of the Pelhřimov complex. The last model incorporated also the asymmetry to the lowermost layer. Here, we simulated higher density Brunia (the competent plasticine indentor) at one side of the magma reservoir, while the opposite side represented the Moldanubian unit (less competent silly putty) which is characterized by the presence of lower-density rocks. We observed multiple localized melt effusions which were elongate in extension direction and rimmed by "anatectic" material from the middle layer of the model. Some secondary and small-scale diapirs were developed in the middle-lower level of the main conduit.

We claim that these models successfully simulate the geometric-kinematic pattern of the material inversion which might have occurred during the formative stage of the Pelhřimov Complex and which is in good correspondence with the field data. Moreover, tested scenarios have implications to other systems where large and hot orogens undergone post-orogenic collapse and extrusions of partially molten materials along weakened or detached zones.

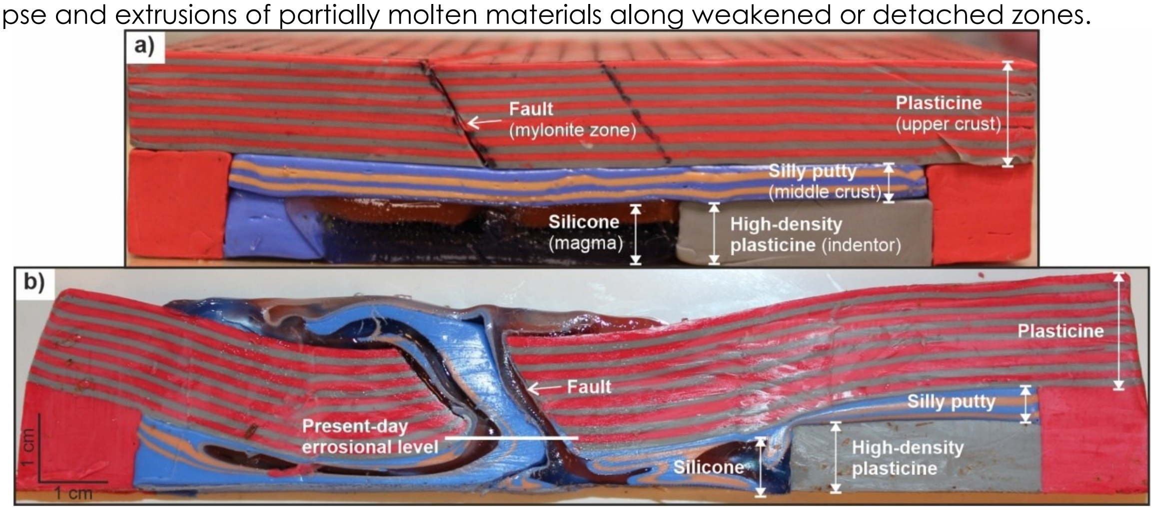

Figure 1 Representative section through model number No. 6 highlighting the diapiric upwelling of silicone and silly putty along the pre-defined fault a) before and b) after centrifuging.

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Insights from trace element zoning in high-pressure metamorphic garnet

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The compositional zoning of major divalent elements in garnet is useful in reconstructing the pressure-temperature (PT) history of metamorphic rocks. However, the zoning patterns of trace elements can provide a more well-preserved record of petrogenetic evolution because of their strong affinity for garnet and slow diffusion rates. Large porphyroblast of garnet in micaschist from the Variscan high-pressure (HP) metamorphic terrain of the Krušné hory Mountains (Saxothuringian zone, Bohemian Massif) was selected for a detailed compositional study.

Using electron probe micro-analyser and laser ablation-inductively coupled plasma mass spectrometry (LA-ICP-MS), three distinct types of compositional zoning in garnet were identified by compositional mapping. These zoning types were classified as continuous core-to-rim change, concentric annular changes, and overprinting of a pre-existing distribution, which provide information on the original mineral composition and texture before garnet overgrowth. The study focuses on the formation mechanisms of each type of zoning, their dependence on pressure-temperature change, and fluid availability.

The high abundances of Sc, Y, and heavy rare earth elements (Lu, Yb, Tm, and Er – HREE) in the very core of the garnet grain (Fig. 1) might indicate a rapid diffusion of these elements from the matrix into the garnet after nucleation, and the creation of a diffusional halo around early grown garnet. The assumed prograde PT path growing up to HP and medium-T (MT) conditions is supported by observations of the distribution of some trace elements, including (1) gradually increasing Co and Zn contents toward the rim, which behave similarly to Mg and inversely to Mn, indicating in particular a continuous increase in temperature; (2) overprint zoning of Ti and partly of Ca, Sm, Eu, Gd, and Tb in the central part of the grain, which changes to purely concentric annular zoning in the rim part that requires an increase in temperature; (3) well-developed overprint zoning of Cr throughout the garnet grain suggesting temperatures only up to MT; and (4) depletion of Y, and most of rare earth elements (HREE, Ho, Dy, Tb, Gd, Eu, and Sm – REE) in the rim part and enrichment of coupled $^{VIII}(Na, Li)^{+}$ + $^{IV}P^{5+}$ substitution elements, which has been experimentally documented from HP to UHP conditions.

Furthermore, the observed inverse annular oscillatory distribution of Sc and V may reflect fluctuating oxygen fugacity during garnet growth, caused by changes in the availability of the fluid matrix medium carrying the trace elements. In such a case, higher fluid availability would result in more Sc entering the garnet structure along with Y and REE, with which it correlates well positionally, and vice versa for V. The formation of annular zoning in trace elements can be linked to the breakdown of main and accessory phases during garnet growth, which subsequently releases and incorporates elements into the growing garnet. Moreover, the presence of fluid medium in the matrix originating from dehydration reactions can control the extent and frequency of the observed annular variations. Therefore, annular zoning in garnet can be attributed to both the decomposition of the trace element-bearing phases and the availability of a fluid medium.

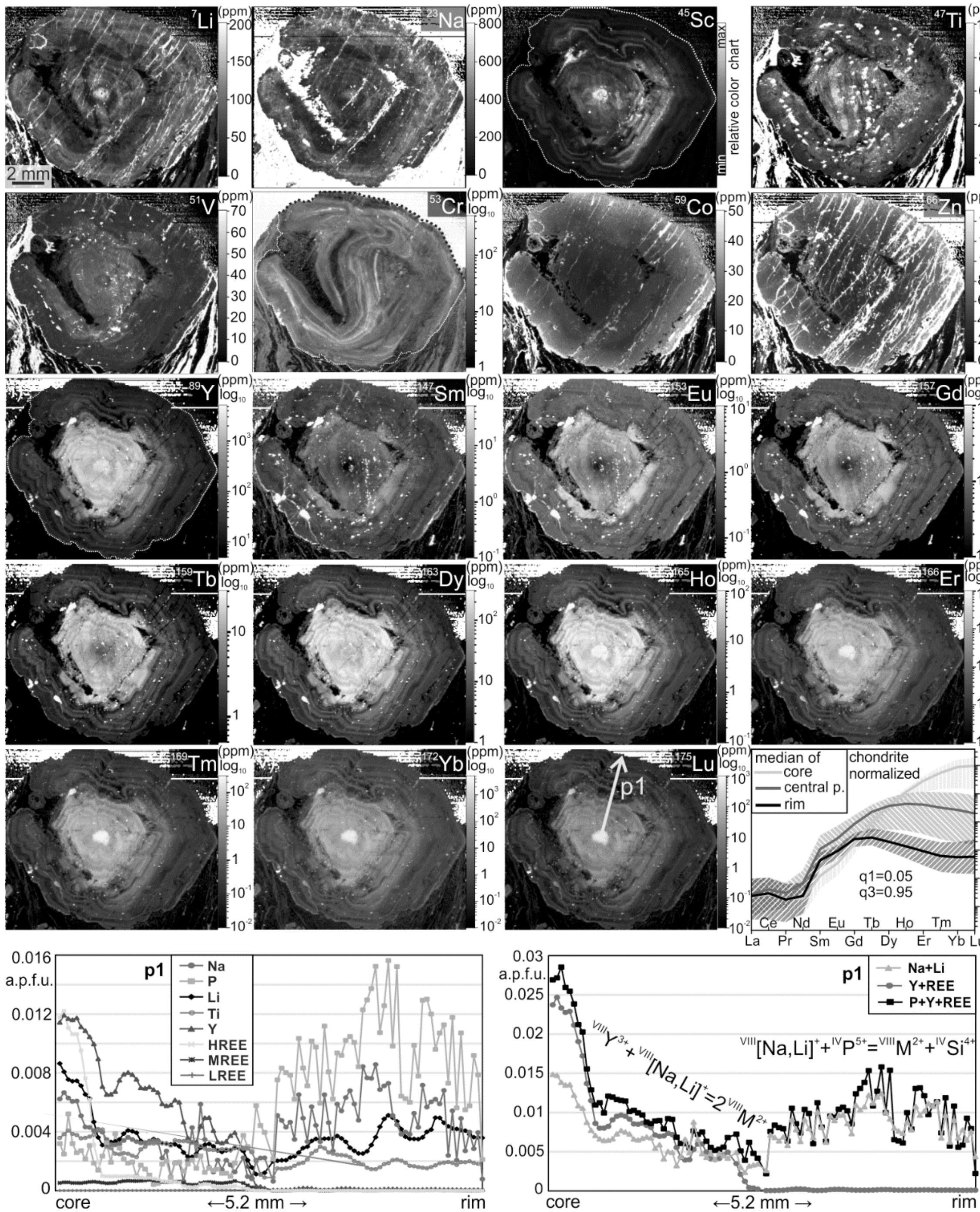

Figure 1: LA-ICP-MS maps of trace elements featuring a large garnet grain and surrounding matrix minerals sorted by increasing nucleon number of analysed isotopes. The maps are quantified, except Sc, because of the peak overlay with Si analysed values. Areal REE data of the core (highest values of HREE in centre), central, and rim parts are plotted and normalized to the chondrite values, while the medians are plotted as lines, and the range of values from q1=0.05 to q3=0.95 are shown as hatched transparent fields. Compositional profile (p1) with Li, Na, P, Y, and REE (HREE, mid-heavy (M)REE and light (L)REE) contents displays the coupled Y-alkali and P-alkali substitutions (recounted to atoms per formula unit – a.p.f.u.). The "M" in substitution refers to the divalent main elements.

Acknowledgement: This work was supported by institutional funding from the Center for Geosphere Dynamics (UNCE/SCI/006).

Investigating the Deformation History of Serpentinized Orogenite Peridotite Using AMS

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The Mohelno orogenic peridotite body located in the eastern margin of the Bohemian Massif, Czech Republic, is considered a deep part of the thickened orogenic root that developed during Variscan continental convergence. The peridotite body is a large-scale fold structure that has undergone a complex tectonic and metamorphic history, recording deformation in the mantle, emplacement into lower orogenic crust, and exhumation within the granulite complex to middle crustal levels. The crystallographic preferred orientation of olivine and orthopyroxene preserved in coarse-grained relics of the Mohelno peridotite partially records the oldest part of the evolution, but this original structure is reworked by pervasive deformation resulting in an ultramylonitic fabric. Later, in the middle crustal conditions, the peridotite is affected by serpentinization to varying degrees, disturbing the original anisotropy of magnetic susceptibility (AMS) record and making it difficult to interpret. Temperature limit of serpentinization with respect to the development of the mylonitic microstructure in the Mohelno peridotite indicate, that serpentinization occurs as static process after folding. The presence of antigorite and iron oxides are the primary products of serpentinization in the studied peridotite. Moreover, by recalculation of density measurements and projecting against bulk magnetic susceptibility, it has been observed that serpentinization has a widespread effect, altering between 50% to 100% of the rock volume. In the course of our investigation, based on identification of peridotite microstructures and their comparison with different magnetic structure parameters, we distinguished several subtypes of samples corresponding to different degrees of pervasive serpentinization. Then, modeling of AMS using the topotactic relationships between olivine, orthopyroxene, and newly growing serpentine minerals + magnetite has allowed us to understand the AMS evolution during the serpentinization process. To understand the arrangement of ferromagnetic grains in the most serpentinized cases, we analyzed their geometry in 3D from micro-CT data. This has enabled us to relate distinct AMS fabrics to the original mantle structure of olivine and pyroxenes and to the late deformation evolution of already serpentinized peridotite.

Modeling of a joint system using 3D photogrammetry based on air born images, on the example of a sandstone quarry in Szczytno—Zamek (Polanica Zdrój, Sudety Mts., Poland)

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A photogrammetric model of the Upper Cretaceous jointed sandstone in Szczytno Zamek at Polanica-Zdrój (Sudety Mountains - Stołowe Mountains, Poland) was made. The characteristic structural feature of the area is fault system with dominant direction N—S and fractures with almost vertical dip (80-90°). Air born photos (from four-rotor unmanned aircraft vehicle – UAV, drone) The UAV that was used is a DJI mini 3 pro, equipped with a high-resolution camera with 48 Mpx. This equipment allowed high-precision 3D models of the walls of the inactive quarry to be made. Additionally, from-the-ground imagery was used for modelling. The quarry has three, well-exposed walls, from which digital 3-D models were created. Two of them were used for the work presented. A single model needed an average number of 300 photos. The photogrammetric model of the quarry was made with Agisoft Metashape Professional software.

Photogrammetric models were carefully analyzed to initially determine the most characteristic fractures. For extracting the structural data, the models were imported into Blender 2.8 software. Tangential planes to the observed fractures surfaces were superimposed on the models. Arranging the planes so that they fit the fractures required proper rotation of the object. Then, the parameters of the planes orientation in a 3-D space were obtained (strike azimuth, dip azimuth, dip). After that, data was presented on diagrams in stereographic equal-area projection, rose diagrams, and histograms of the dip azimuth and dip distribution.

The results were analyzed and interpreted. Mean azimuth of the planes were determined. The obtained results were compared with the measurements made using a geological compass and the literature data of the studied area. The measurements show that in the study area there are two joints systems. The first system is directed towards SE, with vertical dip about 80° on average. The second system is directed towards NW, and vertical dip about 69° on average. The research shows that the results obtained from the digital models of the exposure are similar to the general measurements described in the literature, as well as measurements made in the field. Compared to classical measurement methods, the measurements were conducted with high accuracy (up to 2 - 3 °). The accuracy of the results is much higher than the ones using a classical measurement method.

In conclusion, that research proves that the digital photogrammetry method can be a valuable tool of modern geological cartography. The method has the potential to improve the efficiency and quality of gathering of structural data, as well as encourage other scientists to use modern tools on a daily basis.

The link between deep fluids and surface gas emanation in the Southeastern Carpathians

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A multidisciplinary geological-geochemical-geophysical approach within the framework of the of the Topo Transylvania project has been initiated in the town of Covasna (Kovászna) to understand the source of the local non-magmatic, deep-origin gas emanations at the internal part of Carpathian Bend area.

We investigated the origin of three fluid components (H_2O, CO_2 and He) of gas-rich mineral water springs of Covasna town and surrounding area. We measured the δ^2H, $\delta^{18}O$ stable isotopic ratio of all the sampled spring waters and, where possible, the $^3He/^4He$ and $\delta^{13}C$ stable isotopic ratio of helium and CO_2, respectively, dissolved in the spring waters. Based on the stable isotopic ratio results, the spring waters and the majority of the gasses originate from a metamorphic source. However, local groundwater flow can overwrite the metamorphic stable isotopic signal of the upwelling H_2O and, thus, the preservation of the deep stable isotopic signal is topographically controlled. In addition, the elevated helium stable isotopic ratios (R/Ra) suggest the contribution of an upper mantle source component.

We propose that lithosphere-scale weakening zones support fluid flow from the upper mantle towards the surface in the Carpathian Bend area. The elevated gas emanations of the region are linked to the recent geodynamic evolution of the Carpathian Bend area. Mantle fluids most likely originate from dehydration of the sinking Vrancea slab and/or from the associated local asthenospheric upwelling. Mantle fluids penetrate the lower crust via lower crustal-upper mantle shear zones and may shift the composition of crustal pore fluids consequently inducing crustal decarbonization and devolatilization metamorphic reactions in the lower and middle crust. Based on the low local geotherm and the p-T-X(CO_2) conditions of calc-silicates, we infer that deep fluids may play a more important role than temperature in the generation of crustal fluids in deep-seated deformation zones. In the upper crust, deep-origin fluids are channelized toward the surface along faults resulting in the emergence of gas-rich springs, many of them located along the basin boundaries as observed at the eastern margin of the Târgu Secuiesc Basin where Covasna is located. Our findings at the Southeastern Carpathian bend area show a strong similarity to other deep-seated deformation zones worldwide (e.g., Himalayas, Alps, San Andreas Fault) making it a good natural example to understand the connection between the deep sources of gas emanations, deep-seated deformation zones, and surface-emerging gas-rich springs. In addition, these results suggest that Covasna is a suitable location for deep-origin gas monitoring, more precisely for the installation of an Integrated Geodynamic Station here.

Paleomagnetic record of Central Carpathian Paleogene rocks in the NW part of the Spišská Magura region

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Central Carpathian Paleogene Basin (CCPB) lies within the Inner Carpathians. It extends from the Pieniny Klippen Belt in the north to the massifs of Central Western Carpathians (CWC) in the south. The CCPB developed upon the upper plate in the collision zone between the ALCAPA and the European Plate. From Eocene until early Miocene the CCPB was shaped into a broad, fore-arc basin, filled with siliciclastic material. The remains of this basin are several structural sub-basins such as Levoča, Podhale, Orava, and Liptov Basin.

We are presenting the preliminary results of a paleomagnetic study that was carried out in the eastern part of the Podhale Synclinorium, in the Spišská Magura region (Slovakia). The main goals of this study were: identification of the ferromagnetic minerals, assessment of detailed paleomagnetic record with a focus on its magnetic carriers and time of origin, as well as interpretation of the obtained paleomagnetic directions in terms of the postulated lateral rotation of the Carpathian arc.

To identify magnetic minerals in the Central Carpathian Paleogene strata, we opted for commonly used magnetic procedures, such as isothermal remanence acquisition and thermal demagnetization of the samples, including the Lowrie test. It was found that the dominant ferromagnetic mineral in the studied material was soft and demagnetized mostly at a temperature of around 580 °C. This analysis indicated the predominantly fine-grained magnetite as a main paleomagnetic carrier with probable subordinate content of maghemite and titanomagnetite. To investigate a potential paleomagnetic record in the rocks, a thermal demagnetization procedure was used. The natural remanent magnetization of the samples was weak (up to $8*10^{-4}$ A/m) and revealed rather poor-quality paleomagnetic components during thermal treatment up to 350-450 °C. Above these temperatures, magnetic mineral alternations were observed, hindering further analysis. Paleomagnetic directions obtained in the study were scattered, yet with north-trending declinations. The directions were more likely to be of post-folding age, since the paleomagnetic inclinations after tilt-correction were too steep for the location's latitude.

Relatively low blocking temperatures of measured paleomagnetic components, the domination of normal-polarity vectors, and their resemblance to the present-day magnetic field pointed to the likely removal of primary magnetization. Significant burial temperatures and magnetic mineral recrystallization might have been responsible for the pronounced remagnetization in the Spišská Magura region compared to adjacent areas where paleomagnetic reconstructions were carried out successfully by other authors.

Inherited age signature in zircon from andesites of the Pieniny Klippen Belt, Poland

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Neogene andesitic rocks form small-volume hypabyssal dykes and sills in the Polish part of Western Carpathians (Birkenmajer 2003, BulPAS; Birkenmajer & Pécskay 2000, SGeolPol; Nejbert et al. 2012, Lithos). They represent the calc-alkaline magmatic event that intrude both the the Pieniny Klippen Belt and Magura nappe. The Pieniny Klippen Belt forms a narrow, tectonic structure that separates the Outer and Inner Carpathians. It comprises deformed Mesozoic to Neogene sedimentary rocks. The Magura napp is the southernmost unit of Outer Carpathian flysch sediments and comprises mainly sandstones and mudstones. The age of andesitic magmatism in the Polish part of the Pieniny Klippen Belt and surrounding rock sequences seems generally well known. The ages of magmatic rocks spread from 12,8 Ma to 10,8 Ma (e.g. Pécskay et al. 2015, ASGP; Anczkiewicz & Anczkiewicz, 2016 ChemGeol). However, most of the data were obtained using the K-Ar method (e.g. Pécskay et al. 2015, ASGP).

The magmatic samples for U-Pb zircon dating were investigated with use of SHRIMP IIe/MC ion microprobe at the Polish Geological Institute – National Research Institute in Warszawa. Beside the previously mentioned Neogene ages which reflected the time of magmatism, the older ages have been also received in the analyzed rock suit from the Pieninic andesites. Such old ages observed in the analyzed samples may be remnants of the magma assimilation of the surrounding rocks or inherited due to the melting of older rocks in the magma chamber. The zircon grains show the maximum peaks age of ca. 270-260 Ma and 290-280 Ma as well as large, broad and well-defined ranges of Neproterozic (2200–1900 Ma) and Archean (3000-2600 Ma) peaks. The broad spectrum of small peaks between 750 Ma and 420 Ma has also been detected.

The large number of inherited ages that have been observed during the study of igneous rocks allows us to look at the obtained results almost as in the context of the provenance of sedimentary rocks. In this case, however, we are dealing with information that we can analyze in the context of bedrock and/or host rocks.

Acknowledgement: The research is supported by the National Fund for Environmental Protection and Water Management project No. 22.2301.2001.00.1.

The complexities of the Variscan Saxothuringian wedge demystified

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The geodynamic evolution of the western Bohemian Massif is commonly interpreted in the context of an Andean-type subduction followed by a continental collision from the late Devonian to early Carboniferous (Schulmann et al., 2014). A major tectonic boundary, identified as the Teplá suture, is located between the Saxothuringian domain lower plate and the Teplá-Barrandian and Moldanubian domains representing the upper plate. Despite general agreement on the architecture of this contact, mainly from its upper plate perspective, many contrasting ideas have been proposed for the geodynamic evolution of the Saxothuringian domain. From our study, it became evident that major complexity arose from the significant discrepancy between today's architecture of the Saxothuringian domain and the metamorphic record of its individual units or even lithologies.

In this contribution, we aim to summarize the results of our detailed field structural investigation combined with thermodynamic modeling, geochronology, and microstructural observations in order to constrain the geodynamic evolution of the Saxothuringian domain. We demonstrate that this domain represents a large orogenic wedge (called Saxothuringian wedge), which could be divided into an older outer part, composed of low-grade, locally HP phyllites, and a younger inner part, formed by HP micaschists, orthogneisses, and UHP rocks. Microstructural study of various orthogneiss bodies in the innermost part of the wedge revealed a complex spatial arrangement of UHP and HP units/rocks juxtaposed during their exhumation. The tectono-metamorphic record in the intercalated micaschists allowed us to identify two main processes leading to today's architecture of the inner wedge. The first process corresponds to the exhumation and mid-crustal stacking of buoyant continental rocks emerging from various depths of the subduction channel. The second process reflects the vertical thinning of these units induced by the continuous underplating of continental units emerging from the subduction channel. This phase was associated with the substantial reworking of the previous fabrics developed during stacking and led to vertical condensation of metamorphic isogrades and consequently apparent LP-HT conditions developed during the termination of this exhumation process.

To conclude, the evolution of the Saxothuringian wedge between ~360–340 Ma results from the subduction of thinned continental margin below the Teplá-Barrandian and Moldanubian accompanied by the scrapping of the sedimentary cover and formation of the early accretionary wedge by stacking of the LP-HP rocks currently preserved in its outer part. This phase was followed by the exhumation of a significant portion of buoyant and deeply subducted HP-UHP continental material leading to massive ductile thinning at around ~335 Ma forming the inner part of the Saxothuringian wedge. Finally, a late Variscan N-S shortening was responsible for the significant deformation of the Saxothuringian wedge at ~330 Ma.

Restoration of the earlier fabrics and metamorphic isogrades indicate that this late deformation occurred at high-angle to the original convergence responsible for the assembly of the Saxothuringian wedge.

A novel high temperature experimental approach: deciphering the evolution of cumulate texture

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Circumstances of formation of mafic cumulate rocks remain as one of major open questions of igneous petrology. Due to inaccessibility of the studied environment and doubts regarding credibility of preserved natural textures, experimental research offers an opportunity to closely emulate the desired conditions and observe the cumulate formation in a controlled environment. In order to study the mechanisms of crystal settling and subsequent textural evolution of cumulate rocks, we devised a novel experimental methodology and conducted two series of experiments with olivine crystals suspended in haplobasaltic melt.

The new setup has been designed to withstand the conditions up to 1400 °C in oxygen-containing atmosphere, while also preserving the sample in one piece for subsequent textural analysis. In order to avoid the consumption of noble metal containers, the setup is constructed using two low-cost, commercially available materials: a graphite capsule, which acts as a sample container, and an outer fireclay shell providing heat resistant protective shield and preventing graphite oxidation. The main advantages of our new methodology lie in combination of easily accessible materials, which allow customization of the setup for any sample or furnace size with little limitations, with durability and easy production in larger quantities. The method has been designed especially for experimental studies of igneous textures and kinetics, but also has the potential for effective preparation of synthetic materials.

Experimental work itself comprised twenty-five experimental runs in two separate series, which differ in amount of crystals contained within the starting material. First suspension contained 10 wt. % of natural olivine crystals and represented a liquid rich environment, while the second emulated a high crystallinity mush with 60 wt. % of crystal content. Both suspensions were prepared using natural olivine crystals (~Fo_{90}) mixed with haplobasaltic glass, in order to simplify the system yet faithfully imitate the parental environment of mafic cumulate rocks. Run durations of the experiments ranged from 20 minutes to 21 hours.

Following the run completion, each sample was subjected to detailed textural analysis. Its primary goal has been to observe the development of crystallinity, median grain size and spatial distribution of grains (clustering index, R) with time, in attempt to decode the processes which acted upon the forming cumulate and liquid within. In a liquid-rich environment, crystallinity sharply grows up to 50 wt. % in under 4 hours as a record of mechanical accumulation, along with sharp linear increase in median grains size and change in spatial distribution of crystals from clustered (R = 0.85) to ordered (R = 1.1). Crystal-rich samples also show increase in crystallinity and grain size, however, the values of both variables begin to stagnate immediately following the first hour of experiments. As a result, we observed contrasting behaviour of the two suspensions in each variable of interest, and also successfully tested the new methodology of high temperature experiments.

Combined seismological and petrological study on the seismic anisotropy of the Carpathian-Pannonian upper mantle

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Seismic anisotropy in the Earth's mantle can be studied using both seismological and petrological approaches. Shear-wave splitting analyses allow to distinguish single or multi-layered anisotropy while delay time of the fast and slow polarized wave can indicate its thickness. Seismic properties can also be inferred from lattice preferred orientation of deformed minerals within mantle peridotites. In this study we present a shear-wave splitting map for the western part of the Carpathian-Pannonian region (CPR), an extensional basin recently experiencing tectonic inversion. We compare the results with seismic properties reported from mantle xenoliths to characterize the depth, thickness, and regional differences of the anisotropic layer in the mantle.

Mantle anisotropy has different characteristics in the northern and the central/southern part of the studied area. In the northern part, i.e., the Western Carpathians, the lack of azimuthal dependence of the fast split S-wave indicates a single anisotropic layer, which agrees with xenolith data from the Nógrád-Gömör volcanic field in the vicinity. However, systematic azimuthal variations in several stations in the central part of the Pannonian Basin point to multiple anisotropic layers, which may be explained by two distinct xenolith subgroups described in the Bakony-Balaton Highland. The shallower layer has been interpreted to have a 'fossilized' lithospheric structure, representing former asthenospheric flow, whereas the deeper layer is assumed to reflect structures attributed to present-day convergent tectonics, which is supported by the regional NW-SE fast S-wave orientations. Spatial coherency analysis of the splitting parameters suggests that the center of the anisotropic layer lies at ~140-150 km depth under the Western Carpathians, which adds up to a total thickness of ~220-240 km. Thicknesses estimated from seismic properties of xenoliths yield lower values, suggesting heterogeneously distributed anisotropy or different orientation of the mineral deformation structures.

Continental margin and arc subduction – numerical models and comparison with the Variscan Bohemian Massif

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In the Variscan Bohemian Massif, (ultra)high-pressure granulite massifs witness subduction of felsic crust-like material to depths of more than 100 km and temperatures of 800–1000 °C. Based on their metaigneous composition, these granulites have been usually interpreted as former continental crust that was dragged into the large depth by a subducting continental lithosphere, then exhumed back to the crustal level and added - "relaminated" – to the upper plate. This concept has been tested by numerical-modeling studies that confirmed the viability of such a process. Numerical models further indicated that during exhumation (at least some of) the granulites traversed the upper-plate asthenospheric and lithospheric mantle. Despite these advances, the pre-subduction location of the protolith of these granulites is unclear and several hypotheses have been put forward: they either formed a part of an extended continental margin, a small continental terrane or a magmatic arc.

In order to identify the most probable source of the protolith, we examine the dynamics of subduction and subsequent exhumation, accretion, or collision of different kinds of buoyant blocks. We use two-dimensional numerical models that simulate deformation, thermal evolution and (in a simplified manner) also melting, melt removal/emplacement, (de)hydration reactions and fluid percolation. All our models use the same numerical-modeling framework, but their initial setups differ as they mimic different types of the buoyant blocks entering the subduction zone. We examine the role of various properties of these blocks (crustal thickness, thermal structure, compositional stratification, inherited weak zones) as well as of properties of the subducting and overriding plates. We compare our results with the tectonic scenarios proposed for the formation of the Bohemian Massif. Based on this comparison, our models can provide a basis for discrimination between possible styles of collision that lead to the formation of the Bohemian Massif.

Deformation and metamorphism of newly discovered iron oxide-apatite ores from Svalbard

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The newly discovered iron oxide-apatite ore bodies on Prins Karls Forland, Svalbard, record different styles and grades of deformation, metamorphism and metasomatism. Notably, the ore bodies were recognized within a major crustal shear zone developed under amphibolite to upper greenschist facies conditions. Two principal varieties of ores were distinguished based on their textures and apatite-monazite composition. One variety contains fluorapatite and mostly low-Th monazite, typical for iron oxide-apatite ores worldwide. This ore type is found in the structurally upper part of the aforementioned shear zone and exhibits lower degree of deformation. The other variety, besides fluorapatite, contains fluor-chlorapatite and predominantly high-Th monazite. The latter is likely a product of secondary Th-enrichment. The degree of deformation in this variety is much higher. Texturally, the lesser deformed ore consist of angular, recrystallized magnetite and minor hematite grains cemented by silicate-apatite aggregates. The ore type in question underwent deformation in rather brittle regime, which resulted in the cataclasis of formerly massive magnetite ore. The more deformed ore is represented by a foliated type with alternating magnetite-hematite and apatite-silicate layers. In the foliated ore, modal abundance of hematite increases, and its textural position as elongated, flat-parallel oriented aggregates suggests syn-deformational oxidation of magnetite, which is otherwise preserved as porphyrocrysts and minor interstitial grains. The most spectacular textural variety resembles typical augen gneiss with the augen composed of magnetite embedded in the matrix dominated by elongated specular hematite, apatite and silicates. Based on these observations, it becomes apparent that the different varieties of ores underwent distinct, protracted metamorphic and metasomatic history. The grade of deformation recorded by particular ore bodies can be correlated with apatite and monazite distribution and their composition, suggesting strain-induced metasomatic overprint. Collectively, an interplay between deformation, metamorphism and fluids resulted in contrasting mineralogy of the ores. Tentatively, we propose that the ores were formed in connection with emplacement of the nearby occurring small scale gabbroic intrusions into a Neoproterozoic sedimentary succession hosting both the ores and the gabbros. Subsequently, they were subjected to the Ellesmerian (c. 360 Ma) amphibolite facies metamorphism and deformation, followed by the Eurekan (c. 55-45 Ma) lower amphibolite/greenschist facies tectonothermal event. Preliminary monazite geochronology points to nearly total Pb-loss and age resetting during the Eurekan stage in highly deformed ores, whereas less deformed ores yield inconclusive monazite dates, implying partial disturbance of Th-U-Pb system. To our knowledge, such ore bodies were recognized in the High Arctic for the first time. Their textural appearance, including augen gneiss fabric, is also unique and has not been recognized elsewhere.

The Transdanubian Range unit, a far travelled fragment of Adria: quality controlled Mesozoic paleomagnetic results and their tectonic interpretation in the Adria – Africa geodynamic system

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The Transdanubian Range Unit (TRU) belongs to the ALCAPA megaunit, together with Austroalpine and Western Carpathian units. It is generally agreed on that the TRU had been moving in close co-ordination with Adria, the largest crustal block of the Central Mediterranean, throughout the best part of the Mesozoic. Adria, in its turn, is conceived as an African promontory after the opening of the Alpine Tethys. Since the beginning of the application of the plate tectonic concept to the Mediterranean, the models made use, explicitly or implicitly, of the kinematic constraints provided by the paleomagnetic method, namely quantitative values about past orientations and latitudinal positions of the different tectonic units.

The African / Adriatic affinity of the TRU had been already demonstrated on paleomagnetic grounds in the 1980s. Since that time, a large number of paleomagnetic data have accumulated for this unit as well as for Northern Adria, calling for a new synthesis which would contribute to the better understanding of the TRU - Adria and the TRU+Adria - Africa relationships in the past.

The above task requires quality controlled paleomagnetic data, which are available for the TRU from the Early Triassic through the Pliocene (1992 independently oriented samples from geographically distributed 112 sedimentary localities and igneous sites). Data sets of similar size and quality are ready for comparison from northern stable Adria (642 samples from 90 localities) as well as from the NE imbricated margin of it (799 samples from 90 localities), representing the time interval of 170-45 Ma.

The above data sets exhibit similar trends in time variation of the paleo-latitudes as well as in paleo-declination for at least till the Aptian, but possibly till the end of the Cretaceous. Thus, we computed integrated paleo-latitude and paleo-declination curves, which reflect the major displacements of Northern Adria and the TRU, using spline as well as the running mean methods. Eventually, the variations shown by the integrated paleo-latitude and paleo-declination curves together with available ones for stable Europe and Africa are interpreted in the light of geologically indicated tectonic events in the following way.

1. From the Late Permian till the Early Jurassic, the TRU, which was located close to the NW termination of the Neotethys, travelled to the north, as all continents did.
2. From the Early Jurassic on the TRU shifted to the S, while rotating in the CW sense. Up to the late Early Jurassic (or till the mid-Jurassic) this movement could have been generated by intensive rifting, afterwards by the spreading of the oceanic lithosphere in the Alpine Tethys. With this displacement, Adria (together with the TRU) occupied a latitude close to Africa, yet rotated more in the CW sense than Africa. We tentatively interpret this as the sign of independent displacement with respect to both Africa and stable Europe.
3. Around 150 Ma, there is a turning point in the sense of rotation, and a northward movement is witnessed. The fast northward shift continues till the Aptian, which was the time of the first intensive Mesozoic deformation in the TRU. Some authors connect this to the scraping off the TRU from its original basement and incorporation to the Upper Austroalpine nappe system.

4. By the late Albian, the pre-Aptian position is recovered in latitude. It is from here that a new event of northward shift is observed. This shift seems to be faster till about 80 Ma for the TRU than for stable Adria, which gives us an alternative timing for the detachment of the former to the latter. This period corresponds to the main phase of Austroapline nappe stacking carrying the TRU on its top.

Acknowledgement: This work was financially supported by the National Research, Development and Innovation Fund of Hungary, project K 128625 and 134873. For this study several sites from the natural protected areas were sampled, and we would like to thank the Governmental Office of Veszprém County and the Balaton-felvidék National Park.

Electrical resistivity structure of the of the European Lithosphere in Poland derived from 3-D inversion of magnetotelluric data

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We present a large and complex three-dimensional (3-D) model of the resistivity distribution in the lithosphere at the transition from the East European Craton to the younger Palaeozoic Platform of Western Europe. The model was created by inverting magnetotelluric (MT) and magnetovariational (MV) data from 593 points collected over the last 50 years. ModEM code was used to invert the data and obtain the conductivity distribution model. The full size of the mesh with edges was 3000 by 3000 kilometres and 600 kilometres in the vertical direction, and the modelling field was digitized with 104 x 104 x 52 (+10 air) cells in geographic orientations. A trial-and-error approach was applied to select the best model parameters, such as the starting model and the covariance matrix. As a result, a 3-D model of resistivity distribution in the crust and upper mantle was obtained. The results show a variable thickness of the sedimentary layer, increasing westward, and the presence of deep and extensive conductive anomalies in the crystalline crust. Early Permian continental rifting that caused SW-ward lithospheric thinning, localised crustal stretching and subsidence of a broad sedimentary basin had a primary impact on the distribution of resistivity anomalies. While the pre-Permian resistivity structure was mostly obliterated during the rifting event, the effects of Late Cretaceous-Paleogene accretion of the Western Carpathians and inversion of the Permian-Mesozoic Polish Basin are clearly detectable in the resistivity pattern. A major resistivity anomaly, reaching down to the Moho, coincides with the Pieniny Klippen Belt. The source of the anomaly is probably sediments rich in a conductive phase (most likely carbon) that were subducted deep into the crust. The anomaly presumably represents a tectonic suture associated with accretion of the Western Carpathians. It reaffirms the idea of the Pieniny Klippen Belt being a shallow representation of a crustal-scale suture between the European plate and smaller terranes arriving from the south. In general, our study highlights a role of relatively young tectonic processes in the evolution of the transition zone linking old and stable Eastern Europe with younger and mobile Western Europe.

Authors acknowledge financial support from the Polish National Science Centre grant no. UMO-2017/25/B/ST10/01348

Rock mass strength influenced by deformation in the Bükk Mts, Hungary

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The strength of natural rock masses has been assessed by the authors based on Rock Mass Rating of selected outcrops in a study area in the Bükk Mountains, Hungary. The results reveal highly variable RMR values for outcrops exposing similar rocks even in the same formation. This is the result of a great diversity of discontinuity surfaces occurring in the exposed rock masses as a result of different grades of structural deformation.

RMR evaluation of the studied outcrops has been based on the measurement and estimation of six parameters in the study area. The six parameters have included the followings:

on-site estimation of the unconfined compressive strength (UCS) of the rocks exposed by the outcrops based on Schmidt hammer measurements (Proceq Rockschmidt);
Rock Quality Designation measurements both horizontally and vertically;
measurements of the distance of discontinuity surfaces, randomly scattered across the outcrops;
field observation of the state of the discontinuity surfaces (rough or smooth appearance, weatheredness of the surfaces, presence of open fractures, faults or slickensides);
assessment of the presence of water along the discontinuity surfaces;
and finally, the measurement of the orientation of discontinuity surfaces.

Although the original method of RMR evaluation has been modified by the authors the highest values are still moderate which can be explained primarily by the relatively high density of discontinuity surfaces, such as joints, faults and fold limbs and foliation.

Outcrops with the highest RMR values expose more compact, continuous rock masses that are deformed as a continuous unit. Such rock masses compose major peaks and ridges. Low RMR values occur frequently as strongly deformed rock masses with strong foliation or dense fractures and folded structures are frequent throughout the study area. Lowest RMR values represent very low strength and extremely poor quality rock masses in the outcrops. Such strongly deformed rock masses generally occur at the junction of primary Mohr joints or along major faults.

Both high and low strength rock masses can be detected in specific morphological features, they are reflected in the topography. Low strength rock masses are usually found along major valleys or at the meeting of significant valleys. However, not only surface landforms reflect the strength of rock masses and their grade of deformation but subsurface karst features also reveal rock mass strength. Caves especially likely to occur in zones of high structural deformation and thus low rock mass strength. Cave passages seem to follow primary joint systems or major faults based on the comparative analysis of the orientation of several dozen cave passages and the strike directions of primary joints measured on the surface near the caves.

Validation of two methods for studying the geometry of fault deformation and fault kinematics on the Chelungpu active fault, Taiwan

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Taiwan is located on the complex convergent boundary of the Philippine and Eurasian plates. Subduction progresses roughly 8 cm per year, which indicates strong tectonic activity in this area. Due to this phenomenon, the island is cut by a network of active faults accompanied by numerous earthquakes. One of these faults, the Chelungpu fault, was reactivated during the Jiji earthquake (known as the '921 earthquake'), which occurred in 1999. This thrust fault is a 105 km long surface rupture generally trending in a north-south direction and dipping to the east. The fault is located in the western foothills of the Central Mountains. The structure of this fault was revealed, excavated, and conserved in Zhushan City, within a unique museum of great scientific value called Chelungpu Fault Preservation Park, which presented brittle tectonic processes to the professional and general public. It is evident, that this active fault is well-studied, so the sense and direction of movement are known. Therefore, the fault provides a suitable environment for testing two newly developed modern methods, i.e. the study of anisotropy of magnetic susceptibility (AMS) of fault gouge and the 3D-contactless magnetoresistive positioning system. Both the hanging and foot walls of the fault were subjected to sampling, and special samples were taken from the fault gouge. The preliminary results of the AMS showed that the fault has strike-slip kinematics with a very small thrust component. It is in good agreement with the overall kinematic if we consider that the fault here has an anomalous NNW-SSE direction. The magnetoresistive positioning method revealed that the movements along the fault are periodic in the same direction when the thrust and normal movements of micrometer dimensions alternate. The directional alignment of the movements is again in good agreement with the overall kinematics; however, the pulsation demonstrates an unrecognized and unexplored behavior of the fault.

The research was funded by the Grant Agency of the Czech Republic (GC22-24206J).

Structural interpretations of clustering results applied to 3D orientation data

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In this presentation, two distinct structural models of clustering results applied to 3D orientations are presented (Fig. 1). The study motivation was to detect geometric anomalies in geological terrains. To accomplish this, we decided to use clustering algorithms capable of grouping geometrically similar observations into one cluster. The dissimilarity metric used in our study was the squared Euclidean distance which, under the condition of unit normal vectors, is equivalent to cosine distance (1-cos(x), where x is the angle between vectors). The orientation data used for this study were normal and dip vectors of triangles that were faces of the Delaunay triangulations serving as models for the investigated terrains. We found out that the clustering results were sensitive to the selection of the triangles' representation. This means that given one dissimilarity metric the resulting partitions can be different for normal and dip vectors. Indeed, using relevant computational geometry theorems, we fitted a cylinder and a cone as models for the normal and dip vectors clustering versions, respectively. The study testifies to limitations of using unsupervised learning to detect geometric anomalies and points to further possibilities of using computational geometry theorems to interpret partitions on stereonets.

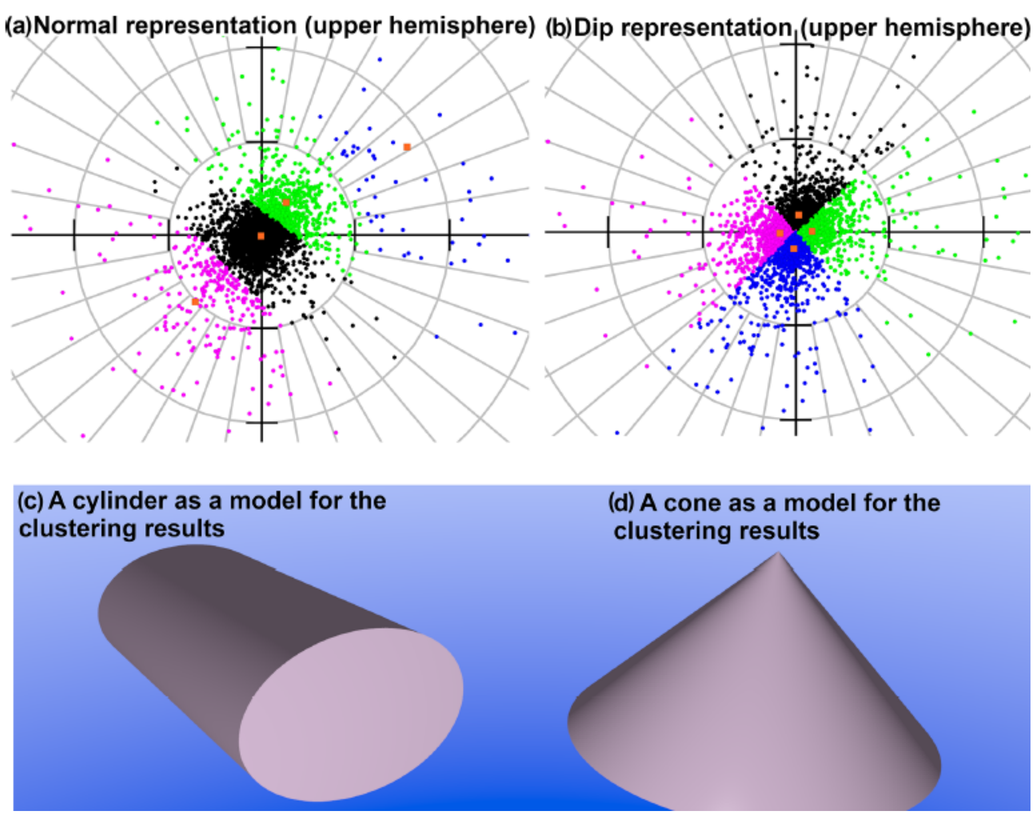

Fig 1 An observed clustering pattern: (a) when normal vectors are clustered, the cluster centers are almost collinear. We now that collinear cluster centers imply parallel boundaries between clusters; this result suggests that the boundaries between clusters may point to an axis of a potential megacylinder. (b) When dip vectors are clustered, there is a common vertex for all clusters near the origin. This effect suggests (using a relevant theorem) that the centers are co-circular, which implies a common value of dip angle (confirmed numerically), thus pointing to a potential megacone. To improve the visibility of boundaries between clusters, we applied the stereonet, which presents the projection of points from the upper hemisphere (tips of unit

normal vectors obtained from dip vectors) onto the horizontal plane. (c) A cylinder as a model for the partitioning results of normal vector representation. (d) A cone as a model for the partitioning results of dip vector representation.

Acknowledgements: The study was supported by the National Science Centre, Poland, grant number 2020/37/N/ST10/02504.

Geophysical study of the Paleoproterozoic structure of the East European Craton in Poland: Fennoscandia-Sarmatia suture zone

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A prominent geological domain in Europe – the East European Craton (EEC) consist of three large tectonic units merged during the Paleoproterozoic (about 1.8 Ga) i.e., Volgo-Uralia in the east, Sarmatia in the south, and Fennoscandia in the northwest. The latter two, Fennoscandia and Sarmatia, continues into Poland with their boundary deeply concealed beneath Ediacaran to Phanerozoic sediments. Therefore, the position of the Fennoscandia-Sarmatia suture can be only constrained by borehole and geophysical data. The later became important in Poland, where a sedimentary cover on the SW slope of the EEC often attains a thickness exceeding the penetration depth of boreholes. Despite a general agreement on the NE-SW trend of the suture between Fennoscandia and Sarmatia, its precise location remains uncertain and has been a subject of conflicting interpretations over the past decades.

The seismic profile EUROBRIDGE'97 pointed to the Minsk Fault as a possible suture between Fennoscandia and Sarmatia. Its continuation in the territory of Poland would be represented by the Hanna Fault. However, recent publications advocate the position of the suture farther north within the Grodno-Bialystok deformation zone between Fennoscandia and the Belarussian-Podlasie Granulite Belt. The latter, obliquely cutting and bending a range of Fennoscandian domains, is considered a great shear zone associated with the collision of Fennoscandia and Sarmatia. Finally, it was recently postulated that the Fennoscandia-Sarmatia boundary is a diffuse cryptic suture zone, c. 150 km wide, where materials from two colliding plates are mixed over large distances to form a unified continental crust.

This work aims to detail the geometry and position of the collisional suture between Fennoscandia and Sarmatia using potential field data and high-resolution seismic reflection profiles. We make use of PolandSPAN™ data located in eastern Poland and running perpendicular to the potential location of the Fennoscandia-Sarmatia suture, profiles PL1-1000 and PL1-1100 with a total length of ~900 km. Seismic interpretation is supplemented with 2-D gravity and magnetic modelling along both the seismic lines and analysis of regional 3-D geophysical horizons including the Moho, top of crystalline basement and top of pre-Permian sediments. Qualitative analysis of gravimetric and magnetic data allowed to determine the location of the main crustal discontinuities and lithological changes consistent with the commonly known NE-SW metamorphic belts. Quantitative analysis of the potential field data supported by seismic reflection profiles enabled the construction of two two-dimensional geological models perpendicular to the course of the studied suture. The models identified a fragment of the lower crust with increased density and bodies of rocks with increased both density and magnetic susceptibility in the middle and upper crust, potentially representing mafic and ultramafic rocks. Our results reaffirms recent views on the location of the Fennoscandia-Sarmatia suture and provides insight in its deep structure, including possible relics of a fossil oceanic domain.

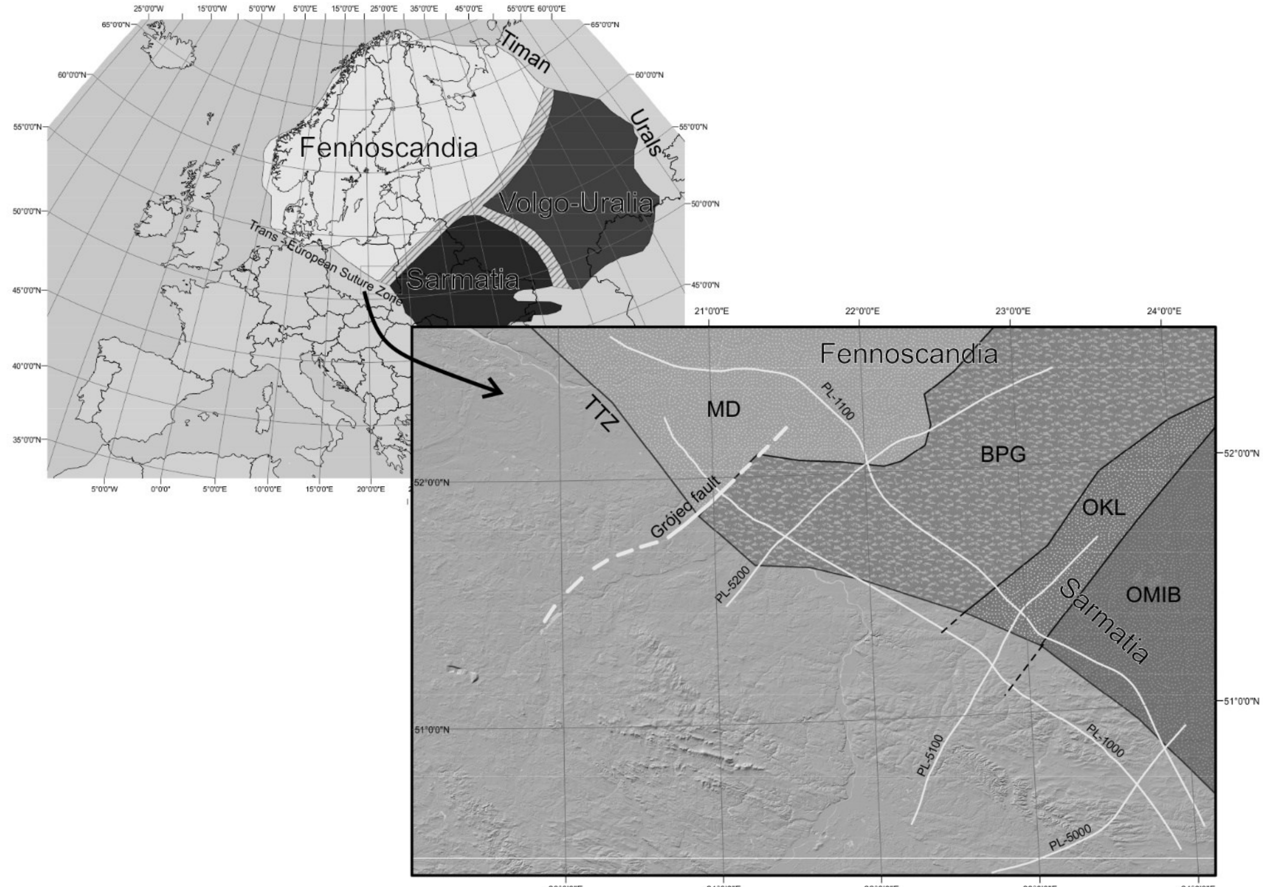

Figure 1: Location of study area overlaid on the map of Europe and the zoom-in of the study area with main geological structures and PolandSPAN seismic lines marked.
Dash lines indicate a possible extension of faults and boundaries. TTZ - Teisseyre-Tornquist Zone , MD - Mazowsze Domain, BPG - Belarus-Podlasie Granulite belt, OKL - Okolovo Belt , OMIB - Osnitsk-Mikashevichi Igneous Belt.

Acknowledgement: This work has been funded by the Polish National Science Centre grant no UMO-2017/25/B/ST10/01348

A strongly disturbed contact zone of the Pieniny Klippen Belt and the Central Carpathian Paleogene Basin (northern Orava): diastrophic breccias, post-tectonic sedimentary cover and backthrusting

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The Pieniny Klippen Belt (PKB) is formed by strongly dismembered formations with chaotic internal structures. In Orava region, such tectonosedimentary breccias occur in the Záskalie beds, belonging to the Upper Cretaceous formations of the Kysuca Unit. A freshly renewed outcrop in a route slope between Kňažia and Bziny, together with another section in the village of Beňova Lehota provide a good possibility to study the relationships between the Záskalie beds, overlaying formations and flysch sediments of the Central Carpathian Paleogene Basin (CCPB).

The Záskalie breccias near Kňažia form steeply dipping beds with block-in-matrix fabrics. They are in overturned position, comprising of Albian grey marlstones, Cenomanian greenish marlstones and Senonian variegated marlstones. Large-sized blocks represent the rafted clasts, detached slumps and other broken beds embedded in shaly matrix with generally southvergent orientation. Sedimentary mélange of the Záskalie beds is overprinted by shear deformation with secondary schistosity and S/C fabrics. Mélange-type beds are disconformably overlapped by calcareous breccias and calcarenites, which comprise of globanomalinid, praemuricid, acarininid, globigerinathekids and rzehakind foraminifers. This microfauna provides an evidence of the Paleocene – Eocene age of the superposed beds, belonging probably to the Proč Formation (not to the basal formation of the CCPB, as was considered before). Transgressive beds of the Proč Formation reveal a mass resedimentation of rotaliporid and globorotalid foraminifers derived from the Záskalie beds. Erosional contact between Senonian and Paleocene-Eocene formations corresponds to „Laramian“ unconformity, which was an expression of the Late Cretaceous tectonogenesis of the Pieniny Klippen Belt.

We also documented a body of Záskalie breccia together with layers of Proč Formation in a seasonal creek in the village of Beňova Lehota. The layers are steeply inclined to the NWW and are in reversed position. Sediments of the Záskalie breccia comprise of dark grey marlstones, variegated marlstones, grey marly limestones, monomictic breccias and polymictic conglomerates. Important is the presence of sandstones and conglomerates of Upper Paleocene – Eocene in age, belonging to the Proč Formation. Litho-biostratigraphical and tectonic situation at the outcrop resembles the section in Kňažia.

The olistostrome and sandstone beds of the Záskalie and Proč fms near Kňažia are disturbed and imbricated by south-east verging reverse faults, formed in response to backthrusting of the Pieniny Klippen Belt over the marginal zone of the CCPB. Another group of younger steep faults was measured. These are oriented in NW-SE direction, without determinable kinematic indicators. Upper Cretaceous formations of the PKB are thrusted over the upper Eocene – Oligocene formations. North dipping formation below the PKB thrust stack is formed by mudstone-sandstone sediments of the CCPB, which contain microfauna of globigerinid, dentoglobigerinid, pseudohastigerinid, catapsydraxid, and other groups of Late Eocene – Early Oligocene foraminifers. Erosion of the backthrust wedge of the PKB was still evidenced by rich Cretaceous microfauna reworked in the Oligocene formations of the CCPB. The backthrusting of the PKB implies an important role of backstop orogenic wedging of the Western Carpathians.

Acknowledgements: The research was supported by projects of the Slovak Research and Development Agency (APVV-17-0170; APVV-20-0079) and Grant Agency for Science, Slovakia (VEGA 2/0013/20).

Geochemical analysis performed using handheld XRF – composition of radiolarites from selected units of the Western Carpathians

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X-ray fluorescence spectroscopy is a well-established technique for determining the chemical composition of rock samples. A few years ago, developments in this field have resulted in miniaturized portable handheld-XRF (hXRF) instruments, that allow measuring of samples out of laboratory settings. Furthermore, they are easy to use and can provide rapid, less financially burdening and on spot, reliable (when correctly used) measurements comparable to XRF laboratory results. In our research, we used hXRF Niton XL3T GOLDD Plus device for measurement of major oxides and elements in non-mineralized siliceous rocks from various tectonic units of the Western Carpathians. These results were compared with traditionally used whole rock geochemical analysis performed at Bureau Veritas Mineral Laboratory in Vancouver, Canada.

For evaluation of this method five samples were selected – radiolarites from the Pieniny Klippen Belt, Silica and Meliata units. To increase precision for the data measured with hXRF, multiple measurements (duration of 60s) of different points on the sample were executed. Points were selected on the flattest portions of the samples – surfaces after cuts for thin sections. Raw data were recalculated from elements to oxides and compared to whole rock analysis. Due to lower beam energies in hXFR it is more challenging to detect and measure lighter elements and impossible to measure trace elements and REE. Therefore, these groups of elements could not be compared, and attention was targeted on major oxides which bare important information about the origin of the sediment and the paleoenvironment.

Results from the geochemical analysis of radiolarites are compared in Table.1. Data for every sample are conformable in both methods and are sufficient and suitable for interpretations of the conditions during sedimentation, as position in the paleo basins, depth of water, etc.

Altogether 420 measurements on approximately 120 samples were performed. They are the base for geochemical study of the deep-sea sediments from the Western Carpathians. These analyses are an important addition to stratigraphical data that have been already acquired from radiolarites. The results and interpretations from geochemical data will be processed and released continuously.

Acknowledgements: The research was supported by projects of the Slovak Research and Development Agency (APVV-17-0170; APVV-21-0281) and Grant Agency for Science, Slovakia (VEGA 1/0435/21).

	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	Cr_2O_3
MBR-4B	75.9	3.8	2.9	1.79	6	0.12	0.83	0.17	0.04	0.18	0.004
MBR-4B hXRF	71.2-78.9	2.16-2.45	1.95-2.42	-	4.94-12	-	0.49-0.7	0.08-0.14	-	0.12-0.18	0.002-0.003
MBR-11-1	95.55	1.78	1.06	0.31	0.09	0.1	0.4	0.07	0.04	<0.01	0.003
MBR-11-1 hXRF	84.2-93.6	1.4-2.5	0.27-0.47	-	0.04-0.07	-	0.37-0.46	0.06-0.08	0.15-0.26	0.01-0.02	-
CLP 6.3	79.26	9.1	4.48	0.87	0.22	0.59	2.42	0.43	0.06	0.01	0.009
CLP 6.3 hXRF	77.5-82.3	6.3-8	3.8-4.5	0-1.2	0.06-0.1	-	1.3-1.8	0.4-0.5	0-0.19	0.02-0.03	0.007-0.012
LES-3	68.02	0.73	0.72	0.16	16.25	0.07	0.17	0.03	0.03	0.04	<0.002
LES-3 hXRF	69-79	0.48-0.55	0.15-0.2	-	4.66-15.5	-	0.17-0.19	0.02-0.03	-	0.02-0.04	0.003-0.004
SIR-1	86.53	4.78	4.17	1.2	0.16	0.18	0.65	0.19	0.06	0.05	0.004
SIR-1 hXRF	83.5-88.6	3.2-3.69	4.19-5.12	0-1.1	0.093-0.12	-	0.44-0.56	0.18-0.22	0-0.18	0.04-0.07	0.003-0.008

Table 1: Comparison of geochemical analyses (major oxides) performed by whole rock analysis and handheld-XRF, measured in selected samples. LES-3 – Pieniny Klippen Belt; CLP6.3, MBR-4B, MBR-11-1 – Meliata Unit; SIR1 – Silica Unit.

Vertical motion patterns in inverted sedimentary basins: competing effects of contraction-induced tectonic uplift, post-rift thermal subsidence and surface processes

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Basin inversion is usually associated with compressional uplift and erosion of the exhuming sedimentary succession, while the resulting uplift rates are predominantly governed by variable convergence rates and structural inheritance. Some basins, however, record continuous basin-wide subsidence and deposition of anomalously thick sedimentary successions during its inversion. In this study, we investigate the controlling processes behind the subsidence and uplift patterns during the structural inversion of rifted basins.

We conducted a series of high resolution 3D numerical experiments to simulate the successive rifting and inversion stages of the Wilson cycle. The applied I3ELVIS-FDSPM allows for two-way coupling between the thermo-mechanical evolution of the lithosphere and surface processes, like erosion and sedimentation (Gerya & Yuen, 2007; Gerya, 2013; Munch et al., 2022). The code is based on staggered finite differences and marker-in-cell techniques to solve the mass, momentum and energy conservation equations for incompressible media, and it also takes into account simplified melting processes.

The models show successively formed sedimentary depocenters during the extension. The variability of crustal and mantle thinning below the depocenters leads to spatial and temporal variations of subsidence rates during the syn-rift phase. At the onset of convergence, inversion localizes where the inherited lithosphere is the hottest and thus the weakest. High convergence rates (i.e. 2 cm/yr) lead to localized uplift of the basin center above the asthenospheric upwelling, which also results in the flexural subsidence of the basin margins. This evolution ultimately leads to intraplate orogen formation and overprinting the former basin structure. In contrast, with low convergence rates (i.e. 2 mm/yr), post-rift thermal subsidence of the inherited lithosphere hinders the effects of contractional deformation, resulting in continuous basin-wide subsidence during inversion. In this case, partial reactivation of the inherited extensional crustal fault zones is more dominant, while inversional structures are only visible along the basin margins.

The modeling results are compared to the thermal and subsidence evolution of the Pannonian Basin during its Middle to Late Miocene rifting and Late Miocene to recent inversion.

Jurassic-Cretaceous transform faults in the Northern Calcareous Alps of Austria?

Hugo Ortner

In this contribution we attempt to demonstrate that folding in the Northern Calcareous Alps (NCA) foreland fold-and thrust belt was not only controlled by transport direction during shortening, but also by inherited older E-W faults that localized folding. Several previous models for the geodynamic evolution of the Austroalpine inferred such faults (Frank & Schlager, 2006; Kövér et al., 2018; Schuster, 2015; Stüwe & Schuster, 2010). We present direct evidence for the existence of such faults.

We show three examples from the western NCA. (1) We demonstrate that the Karwendel-Thiersee synclines are most probably controlled by E-W strike-slip faults and stepovers with N-S normal faults. (2) The Puitental zone S of Zugspitze is another E-W zone along which basanitic sills and dykes are found that are sourced from the subcontinental mantle. (3) The structure of the Cenoman-Randschuppe (the tectonically deepest marginal slice that accompanies the northern margin of the NCA) in the western NCA suggests the existence of a transform margin.

Foreland fold-and-thrust belts are typically stacks of thrust sheets, that were transported toward the foreland. In the NCA, this foreland has been largely removed in the course of Cretaceous subduction of the Piemont-Liguria ocean, that had opened during the Jurassic and had separated the Adriatic microplate from Eurasia. Only the Cenoman-Randschuppe is a remnant of this foreland (Sieberer & Ortner, 2022).

Ad (1) The transport direction during Cretaceous nappe stacking in the western NCA are generally to the NNW. NNW-directed transport would create ENE-WSW fold axes, which is the case west of Zugspitze, however east of Zugspitze some of the major fold systems are oriented E-W (e.g., the Karwendel-Thiersee synclines, Bavarian synclinorium), but transport directions are still NNW-directed. In such a case folding should be localized at preexisting structures. In the Karwendel-Thiersee synclines it has been demonstrated that Jurassic sedimentary facies changes across the syncline (Nagel et al., 1976). Maximum thickness of Upper Jurassic pelagic deposits is found in the stepover zone between the left-stepping synclines. If the synclines were localized by faults, an extensional bend with N-S normal faults between two sinistral E-trending faults may be a reason for this depocenter (van Kooten et al., 2023). Analogue modelling shows that inversion of these fault system may cause the observed 90° bend of a recumbent fold (van Kooten et al., 2023).

Ad (2) The Puitental zone is a zone of Upper Triassic to Lower Cretaceous rocks below one of the major thrust sheets of the NCA south of Zugspitze. Within this zone the Hauterivian thrust is offset by an E-W-trending sinistral fault uplifting the southern block. S and C planes related to a penetrative sinistral s-c' fabric in lower Cretaceous marls are intruded by basanitic dykes, and the dykes are also sheared within the shear zone. We interpret the dykes to be syn-shearing. These intrusions are widespread in the Puitental zone, in the Karwendel, where they are also found within the overthrust unit (Jerz & Ulrich, 1966), and have been observed in the vicinity of Landeck (Mutschlechner, 1954). Most intrusions are sills, and have been dated to ca. 100 Ma (latest Albian) (Trommsdorff et al., 1990).

Ad (3) In the Cenoman-Randschuppe SE of Kempten we observe penetrative sinistral shearing in incompetent rocks at the northern margin of the NCA SE of Kempten, combined with local S-directed backthrusting. Transtensive sinistral shearing separated the Falkenstein klippe (FK of Fig. 1) from the main body of the Karwendel thrust sheet, that had already been emplaced in the Albian. Subsequent transpressive sinistral shearing locally superimposed the FK onto adjacent units (Sieberer & Ortner, 2022).

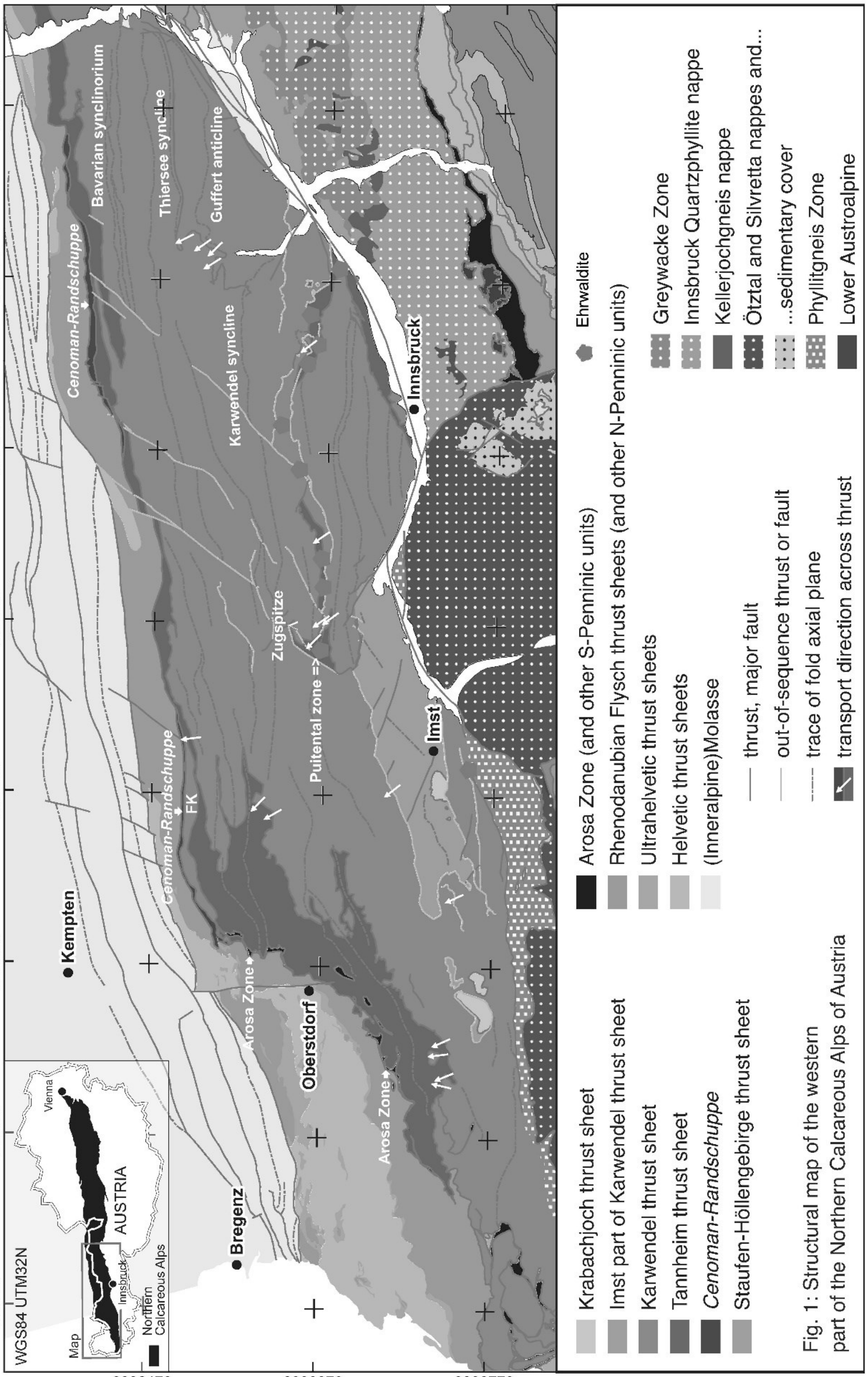

Fig. 1: Structural map of the western part of the Northern Calcareous Alps of Austria

We conclude that sinistral sinistral shearing across E-W faults was intermittent with Cretaceous shortening. Basanitic intrusions sourced from the subcontinental mantly are comparable to volcanites at other intracontinental transform fault systems, such as the Atlas mountains (Harmand & Cantagrel, 1984) or the Dead Sea transform (Weinstein & Garfunkel, 2014). Therefore the NCA had not yet been detached from the underlying continental crust in the Albian, even if the fold-and-thrust belt had started to form. In parts of the thrust belt, localization of folding was controlled by Jurassic-Cretaceous fault pattern.

On a larger scale, the northern margin of the NCA might well have been a transform margin. Large strike-slip faults might have cut out the breccia-rich successions and the thinned continental crust of the Lower Austroalpine, and the South Penninic Arosa Zone related to a Cretaceous accretionary wedge locally.

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Slope sedimentation, syn-orogenic stretching and post-orogenic collapse in a tectonic window along the Vlora–Elbasan–Dibra transfer zone, Albania

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Introduction

The poorly studied Okshtuni tectonic window is located along a major transverse zone that affects the Hellenic orogen. It exposes Late Jurassic to Eocene siliciclastic sediments in two thrust sheets attributed to the Krasta nappe. Reconnaissance field work was carried out in remote eastern Albania in order to (1) describe the sedimentary characteristics of the flysch successions in the two Krasta thrust sheets, and (2) constrain the evolution of the orogen and the exhumation of the tectonic window.

Geological setting

The Krasta nappe consists of the Okshtuni and Ostreni thrust sheets. The tectonically lower Okshtuni thrust sheet makes up the core and most of the tectonic window, and consists of Maastrichtian – Eocene siliciclastic sediments. The overlying Ostreni thrust sheet occurs on the flanks of the window, and consists of Tithonian – Cenomanian slope sediments. The Krasta nappe is overlain by the Korab and West Vardar Ophiolite nappes around the Okshtuni window, and, in turn, it overlies the unexposed Kruja and Ionian nappes.

The Okshtuni window forms a dome that is subperpendicular to the general NNW-SSE structural trend of the Hellenides. The window is part of the Vlora–Elbasan–Dibra transfer zone that is interpreted as a major dextral accommodation zone during Neogene thrusting. The NE-SW oriented zone is seismically active with oblique normal kinematics.

Sedimentology

Sedimentary facies within selected intervals of the Okshtuni and Ostreni thrust sheets were examined during field work. Both thrust sheets consist of siliciclastic-dominated turbidites and hemipelagic mudstones. Both, high-density, very thick- to thick-bedded conglomerate and sandstone, and low-density, thick- to thin-bedded sandstone and siltstone turbidite units are present. These most likely represent confined (slope canyon), and unconfined levee or base of slope deposits, respectively. Soft-sediment deformation is present within the succession, indicating rapid deposition and dewatering. A deep-water Nereites ichnofauna is present. Palaeoflow was largely to the south to southwest (i.e. transverse to the current structural grain), although northwest-directed axially draining systems have also been identified. The succession of the Ostreni thrust sheet contains rare calciturbidite intercalations.

Well-cemented sandstones form the main clast type within the Okshtuni thrust sheet. These may have been derived from the Ostreni flysch unit prior to its emplacement onto the younger Okshtuni thrust sheet. Hundreds of metres to kilometre-scale carbonate olitholiths are also present within the Okshtuni thrust sheet. These are likely to be derived from the contemporaneous Kruja platform. Volcanic and ophiolitic clasts are rare suggesting that the advance of the ophiolitic nappe occurred after the termination of deposition in the Eocene.

Structural geology

The tectonically lowest Okshtuni thrust sheet is moderately deformed. Open folds are characteristic, but tight to almost isoclinal folds occur in the stratigraphically, and also tectonically, deepest parts of the window. Thrust faults, semibrittle shear zones with S-C fabrics, and asymmetrical folds indicate a generally western-southwestern vergence. This D1 phase reflects nappe stacking within the Hellenic orogen. A weak cleavage is usually developed in the mudstones of the Okshtuni thrust sheet, but does not affect the sandstones. The relation of cleavage to regional folding is questionable as the often shallow cleavage planes do not always align with the axial planes of upright or inclined folds.

Low angle normal faults, asymmetrical boudinage structures, and shear bands indicate dominantly SW-directed extension at semibrittle conditions. We interpret this D2 phase to have been synchronous with orogenic deformation. Asymmetrical flattening might have occurred in a SW-dipping, i.e. foreland-dipping, tectonic setting.

Steep normal and/or strike-slip faults affect the flysch of the Okshtuni thrust sheet, but also occur in cemented coarse Quaternary debris near the margins of the tectonic window. These faults crosscut the D1 and D2 structures, and are most likely related to late, at least partly Quaternary, oblique dextral extension along the Vlora–Elbasan–Dibra transfer zone (D3 phase). The exhumation of the tectonic window is attributed to this phase. In the central and south-western part of the window, steep slopes are often covered with cemented coarse talus breccias, and probably indicate active uplift.

The tectonically overlying Ostreni thrust sheet is much more deformed than the Okshtuni thrust sheet. Tight to isoclinal folds with ubiquitous, locally penetrative, low angle axial planar cleavage are common. This thrust sheet is weakly metamorphosed and resembles the Vermoshi–Beotian flysch unit in character and tectonic position.

Conclusions

The tectonic evolution of the Hellenic orogen around the Okshtuni window is summarised as follows. Initial nappe stacking (D1) was followed by still syn-orogenic stretching that probably reflects flattening associated with a foreland-dipping duplex or an antiformal stack (D2). Finally, the extensional collapse of the orogen, and the exhumation of the tectonic window, occurred in conjuction with oblique dextral shear along the Vlora–Elbasan–Dibra transfer zone (D3).

Late-Cambrian arc-related migmatitisation in compression – evidence from the southern margin of the Zavkhan Block, Mongolia

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Granulite-facies metasediments and orthogneisses are exposed in the southern margin of the Precambrian Zavkhan microcontinent in SW Mongolia. Field structural analysis, P-T modelling of mineral assemblages, U-Pb monazite and xenotime geochronology and Ar-Ar muscovite and hornblende ages provide a well-constrained evolution from peak conditions to the cooling of the metamorphic complex. Sillimanite-bearing garnet-biotite migmatites yield similar peak conditions around 760–800°C, 6–8 kbar across the area and also give overlapping monazite ages ranging from 503 to 494 Ma. The Ar-Ar ages range mainly from 488 to 470 Ma and are interpreted as cooling ages just slightly younger than the metamorphic monazite ages. The main metamorphic fabric is steep and folded by open to closed post-metamorphic folds with subvertical axial planes and subvertical fold axes. This implies originally steep orientation of the migmatitic foliation prior to the late folding event. Field relations show that partial melting in migmatites is contemporaneous with the formation of the steep fabric, which was confirmed by monazite and xenotime ages (505–497 Ma) in the syntectonic melt. The partial melting is thus coeval or directly follows emplacement of associated arc-related granitoids, recently dated to 503 Ma and considered as equivalents of the Cambro-Ordovician Ikh-Mongol arc system. The whole area can be interpreted as a mid-crustal segment of the former Precambrian Zavkhan margin, which was shortened in Late Cambrian and heated by magma intrusions of the voluminous Ikh-Mongol arc. Our data strongly suggest that in Late Cambrian times the arc system was still in compression.

Evolution of the Rhodopes from suturing of Neotethys to Aegean rollback

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The tectonic units of the Rhodopes can be grouped into four nappe complexes where the Lower Complex is interpreted to be derived from the Adriatic continent (including Pelagonia), the Middle Complex from the Vardar branch of the Neotethys, and the Upper Complex from the European margin. The structurally highest position is occupied by the Circum-Rhodope Belt. In addition to orthogneisses and metasediments, the Middle Complex contains mostly amphibolite-facies metabasic rocks. Such rocks from the Luda Reka Unit, representing the Middle Complex in the Eastern Rhodopes, yield trace element patterns resembling those of MORB and lower oceanic crustal cumulates and LA-ICP-MS U-Pb zircon protolith ages of 163.5±2.6 Ma and 154.2±1.0 Ma. These data indicate that the Luda Reka unit represents former oceanic crust of the Vardar Ocean and thus the suture of Neotethys that was subducted northeastwards under Europe (including the Upper Complex and Circum-Rhodope Belt) since mid-Cretaceous times. Following high-pressure metamorphism in the Middle Complex, that is locally of Lutetian age, the Lower Complex was underthrust northeastward below the Middle Complex. After that, the original thrust contact between the two complexes probably acted as a décollement for a system of Eocene top-to-the-SW low-angle normal faults during the Middle/Late Eocene to Early Oligocene. These normal faults accommodated the exhumation of the Lower Complex in four large dome structures during the onset of Aegean extension. Comparing the position of the Neotethys suture in the Rhodopes with the present-day Hellenic trench, the Hellenic slab has retreated by ~500 km since ~ 40 Ma.

Integrating lithological data (thicknesses for different lithologies, densities, shear and compressional wave velocities) with seismic surface-wave data (period range of 5-150 s) by applying a non-linear inversion procedure, we modelled the lithosphere-asthenosphere structure of the Rhodopes. We obtained multiple solutions for six 0.5° x 0.5° cells. Additional geological and geophysical information was used to select a representative model for each cell and to construct an east-west profile section through the Bulgarian Rhodopes. The Moho depth decreases from 45 km in the Western Rhodopes to 34 km in the Eastern Rhodopes and the lithosphere thickness varies between ca. 55 and 75 km. We attribute this small lithospheric thickness to asthenospheric upwelling caused by fast rollback of the Hellenic slab from below the Rhodopes to its present-day position.

Burial-exhumation cycles of the continental crust: case studies and numerical models

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We address the evolution of continental subduction-exhumation cycles via field-based case studies and thermo-mechanical numerical modelling. Field-based case studies focus on continent-continent subduction settings in the Pelagonian zone (Northern Sporades, Greece) and in the Betics mountains (SE-Spain), while numerical models aim at understanding the subduction and exhumation of continental material below oceanic plates (i.e. obduction).

The formations of the Northern Sporades (Pelagonian zone) record ductile top-SW shearing experienced during their latest Cretaceous-Paleogene burial, in the footwall of the Europe-derived units and the Vardar suture zone. The formations did not subduct to large depth but were accreted to the base of an accretionary wedge at low-grade (generally greenschist, locally blueschist facies) metamorphic conditions by top-S to SW thrusts. The top-SW shear fabrics are overprinted by top-NE shear fabrics, which show a gradual transition from ductile to brittle deformation mechanisms, attesting to cooling during progressive exhumation of the rocks. Top-NE shearing shows a transition to normal faulting, suggesting that the rocks were exhumed under extension. Prevailing extension in the accretionary wedge following the accretion of the formations suggests continuous and substantial basal accretion to the wedge, inducing uplift, and/or the retreat of subduction trench, creating space for the rocks to exhume.

In the Betics mountain range, the Nevado-Filábride complex experienced deep burial (subduction) below the Alboran continental domain. The main thrusts of the Nevado-Filábride complex show a gradual decrease from high to low-grade metamorphic conditions during their activity, implying that nappe stacking was associated with significant exhumation. This exhumation via thrusting was coevally accommodated by the localization of a major extensional detachment at the brittle-ductile transition zone, above the exhuming rocks. Hence, exhumation was driven by contraction in the deeper part of the subduction zone and simultaneous extension in the upper and middle crust of the orogeny.

For the modelling of continental subduction below oceanic plates, we combined data collected from ophiolite belts worldwide with thermo-mechanical simulations. Our results reveal that buoyancy-driven extrusion of subducted crust triggers necking and breaking of the overriding oceanic upper plate. The broken-off piece of oceanic lithosphere is then transported on top of the continent along a flat thrust segment and becomes a far-travelled ophiolite sheet separated from its root by the extruded continental crust.

The field-based and modelling studies (and the extensive literature of the studied regions) point towards general patterns of continental subduction-exhumation processes that are similarly valid for continent-continent subduction settings as well as obduction settings. Such general features are the buoyancy-driven exhumation and the related migration of extensional and contractional portions of the evolving orogen, accompanied by trench retreat.

From rifting and subduction to accretionary wedge – origin and tectonometamorphic history of the Meliatic Bôrka Nappe (Western Carpathians)

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The Meliata Unit (Meliaticum) is a tectonic superunit of the Western Carpathians that incorporates the blueschists-facies Bôrka Nappe and the low-grade polygenous mélange – Meliata Unit s.s., both occurring as scattered tectonic slices overlying the Gemer superunit (Gemericum). The views on the Bôrka Nappe have been changing over time until today's relatively stable opinions.

The lowermost part of the Bôrka Nappe is formed by mylonitized Permian conglomerates (Jasov Fm.) and acid volcanics (Bučina Fm.). In the past, they were often included in the underlying Gočaltovo Group of the Gemer Unit. However, their significantly different deformation character was pointed out. These rocks represent the syn-rift phase. The Lower Triassic members of the Bôrka Nappe consist of marly to sandy calcareous slates (Werfen Fm.), which were transformed by intense deformation into calcitic phyllites. With continuing spreading of the rift area, the breakup and origin of the Meliata Ocean commenced in the early Middle Triassic. The Middle to Upper Triassic is represented by a thick complex of carbonates, basic volcanics, volcanoclastic and hemipelagic sediments.

The incoming northern passive margin of the Meliata Ocean brought the later Bôrka Nappe into the subduction channel where it underwent high-pressure metamorphism. Based on the monazite EMPA age data, the beginnings of the metamorphic processes started in the Late Jurassic, with a peak around 160 Ma. The high-pressure mineral association is characterized by Gln, Prg, Cld and Grt. As a result of the subduction-related deformation, metamorphic foliation S1 originated (more or less parallel to the primary sedimentary foliation), associated with development of columnar and lobate calcite microstructures in marbles.

The second deformation stage was related to exhumation, formation of the Meliatic accretionary complex and its gradual thrusting over the Gemericum. The early exhumation stage was dominated by the formation of thrust structures and segmentation into sheets accompanied by significant shear deformation. Through successive thrusting processes, the accretionary complex thickened and fold structures associated with compression and collision with the Gemericum began to dominate. This stage formed the main group of measured monazite ages at the boundary between the Jurassic and the Cretaceous (ca 150–130 Ma). The high-pressure metamorphic paragenesis, which arose during subduction processes, underwent a retrograde overprint in the greenschist facies. In these conditions, newly formed fine-grained calcite microstructures were formed, gradually replacing the original, higher-grade ones.

Exhumation continued subsequently in the compression mode by thrusting of the Gemericum onto the lower basement unit (Veporicum) with the piggyback Meliatic accretionary complex (ca 130–100 Ma). During the next deformation stage, the continuing thickening due to thrust stacking brought about a change in the deformation regime from the compression mode to the extension mode, which was associated with the exhumation of the Veporic metamorphic dome. The extensional tectonic regime during the structural unroofing of overlying Gemeric–

Meliatic thrust stack initiated the development of the S-C structures, which are connected with the new monazite blastesis (cca 90-80 Ma).

The last deformation stage is interpreted as the final phase of the nappe stacking in the contact area of the Central and Internal Western Carpathians, up to the emplacement of the overlying Silica Unit nappes. The process of the final phase of thrusting in the area conditioned the development of the cleavage associated with the advancement of a north-west vergent fold structure recorded mainly in the Bôrka Nappe and the Silica Unit complexes.

Funded by the National Science Centre of Poland, (project 2021/43/B/ST10/02312); Slovak Research and Development Agency (project APVV-17-0170) and Grant Agency for Science, Slovakia (project VEGA 1/0435/21)

(Li,Na)-P substitution in garnet as an indicator of UHP metamorphism in metagranites of the Eger Crystalline Complex (Bohemian Massif)

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Findings of coesite and diamond in quartzo-feldspathic rocks confirmed the idea that continental crust, despite its buoyancy, can be subducted into ultra-high pressure (UHP) conditions. In addition to these index minerals, UHP conditions can be potentially reflected by specific minor elements incorporated in major minerals, which was confirmed by experimental works and demonstrated to some extent in mantle rocks, but it was poorly explored in natural samples coming from the continental crust. Here, we investigate garnet containing coesite inclusions from subducted metagranites of the Eger Crystalline Complex in the Bohemian Massif. The garnet shows chemically distinct concentric domains with elevated mutually correlating contents of P, Na, and Li. From the correlation of these elements with the other elements present in the garnet, we infer the following coupled heterovalent substitution: (Na,Li)1P1M2+-1Si-1, where the Na deficiency is partially compensated by Li in a ratio close to 1:2. The identified coesite inclusions are systematically located in these Na, P, and Li-rich zones, supporting the interpretation that the defined substitution is directly related to UHP metamorphic conditions, which is in line with known experimental data. This is the first time that such coupled substitution in garnet has been defined and clearly connected to UHP conditions in natural samples, confirming itself as a useful tool to reveal UHP conditions in garnet even in the absence of index minerals like coesite or diamond. In addition, the correlation of UHP conditions with substantial amount of Li incorporated into the garnet structure (highest contents exceed 200 ppm of Li in garnet) confirms that garnet needs to be considered as an important Li carrier in subduction zones, able to transport significant amounts of Li into the Earth's mantle and influence its Li budget.

Peri-Siberian Cambrian to Devonian tectonic switching in the Olkhon terrane (southern Siberia): implications for the geodynamic evolution of the Mongolian collage during Baikalian orogenic cycle

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The Olkhon Terrane is believed to preserve records of the initial accretion collision of the Siberian Craton with its peripheral orogenic system during the early Paleozoic. However, the related tectono-metamorphic process and its time-scale remain obscure. To address this issue, new structural observations combined with petrological analysis, U-Pb zircon and monazite and 40Ar/39Ar biotite geochronology were conducted in the granulitic Chernorud and migmatitic-granitic Anga-Sakhurta Zone of the terrane. An earliest syn-collisional event associated with the development of a c.530–500 Ma sub-horizontal migmatitic fabric is confirmed. This event is characterized by prograde PT path reaching peak conditions of c. 0.80 GPa and high temperature up to 900°C in the Chernorud zone granulites while peak metamorphic conditions around 0.60–0.80 GPa and 700–770°C were achieved in the Anga-Sakhurta Zone paragneiss and migmatites. The early metamorphic fabric was affected by later extensional doming in the Anga-Sakhurta Zone in association with emplacement of c.470–445 Ma granite sills parallel to the sub-horizontal mechanical anisotropy. This event is connected to a second HT metamorphic event characterized by pressure of 4 -5 kbar and temperatures at 700°C. The HT metamorphism, crustal melting and emplacement of mafic veins are related to formation of numerous core complexes in the central part of the Olkhon Terrane. Subsequent upright folding led to amplification of extensional domal structures and heterogeneous vertical transposition of composite horizontal fabric soon after the doming, as indicated by intrusions of residual melts into the axial planes of the upright folds. This stage is dated as early Silurian c 440-430 Ma as indicated by numerous ^{40}Ar-^{39}Ar hornblende ages. The latest episode of deformation was marked by development of greenschist-facies sinistral shear zones surrounding the Anga-Sakhurta Zone at c. 415–400 Ma constrained by ^{40}Ar-^{39}Ar biotite ages. An updated tectonic model involving 1) Early Cambrian crustal thickening associated to collision of the arc and back-arc units with the Siberian Craton. 2) The collisional event is followed by Middle–Late Ordovician crustal thinning associated with horizontal crustal flow due switch of subduction system marked by long-lasting oceanic roll-back, 3) Silurian crustal shortening related to northwards movement of late Cambrian oceanic arc of the Birkhin Complex to the south, and 4) Early Devonian lateral extrusion and sinistral shearing associated with progression of the Birkhin Complex promontory. Results from this study are compared with the tectono-thermal events affecting south part of the Mongolian Collage. The presented results can be interpreted as a result of accretionary-collisional process affecting the peri-Siberian domain during the early-stage evolution of the Central Asian Orogenic Belt.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (42022017, 42021002), the International Partnership Program of Chinese Academy of Sciences (132744KYSB20190039), and by the Czech Science Foundation (grant number 19-27682X).

Development and destruction of the Neotethys margin – hints from the Eastern Alps

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With respect to their lithological content, the tectonic units of the Eastern Alps developed from two continental and two oceanic realms. While there is a well-defined oceanic suture of the Penninic (Alpine Tethys) realm between nappes composed of continental rocks from Europe in the footwall and Adria in the hanging wall, a suture of the Neotethys Ocean is missing. This creates problems when reconstructing the tectonic history of the Eastern Alps and argues for a complex scenario. In this contribution, we highlight the significance of the Neotethys remnants in the Eastern Alps and discuss why its record is that scarce.

Remnants of the Neotethys Ocean occur as tectonic slices or detrital components within Austroalpine nappe piles composed of Permo-Mesozoic sedimentary sequences. They include the following rock associations:

(1) Slices of the Meliata unit consisting of Triassic radiolarite and carbonate rocks within an unmetamorphosed matrix of dark grey Jurassic slate appear at the eastern margin of the Eastern Alps. They are situated on top of the Tirolic-Noric nappe system and below the Juvavic nappe system. Some of the carbonate rocks of the Meliata units as well as some Triassic carbonate sequences at the base of Juvavic nappes show a weak metamorphic overprint, which predates the Cretaceous Eoalpine regional metamorphic imprint. It may be Triassic and/or Jurassic in age. The emplacement of the Meliata slices in their present position is expected to be due to Early Cretaceous out of sequence trusting. Their tectonic position is the same as in the Western Carpathians, where the Meliaticum appears above the Gemericum and below the Tornaicum and Silicicum.

(2) Bodies and blocks of serpentinite, Permian gabbro and other exotic material are present in a tectonized zone composed of Permian Haselgebirge and Lower Triassic Werfen Formation. They are in the same tectonic position as the Meliata slices but can be traced towards the west for more than 200 km. With respect to a recent interpretation, the serpentinite derived from a harzburgitic mantle, which was exhumed during earliest stages of Neotethys opening in the Carnian. Subsequently, the sea floor was overridden by Permian to Carnian sedimentary sequences from the continental margin (Juvavic Schneeberg and Hohe Wand nappes), due to gravitational gliding in the course of salt tectonics. During Early Cretaceous compressional tectonics, they reached their present position between the Tirolic-Noric and Juvavic nappe systems. In the Western Carpathians the gabbo at Talomos hill is in an equivalent position as the serpentinite bodies. It is embedded within an evaporitic melange of the Telekes odal nappe.

(3) Pebbles eroded from nappes with a Neotethys origin are present in the basal conglomerates of the Gosau Group in the Northern Calcareous Alps. Further, chromespinell detritus occurs in other Austroalpine sedimentary units from the Early Cretaceous onwards. Pebbles represent Triassic and Jurassic radiolarite, serpentinite, basic volcanic rocks and amphibolite of a metamorphic sole. The formation age of the granulite facies metamorphic amphibolite pebbles is ca. 160 Ma, similar to the metamorphic sole of the Vardar zone in the Dinarides. The occurrence of the pebbles in the basal Gosau conglomerates of the Northern Calcareous Alps, but their absence in the Gosau Group sediments on top of the Austroalpine units further south argues for their origin from nappes on top of the Juvavic nappe system. These nappes must have been completely eroded already in the early Late Cretaceous.

Based on the described Neotethys remnants and other observations, the following assumptions can be made about the Neotethys margin evolution in the segment of the recent

Eastern Alps: The first oceanic crust of the was formed by mantle exhumation in Ladinian or Carnian time. A passive margin developed and subsequently blocks of the most distal carbonate platform glided down the continental slope and onto the exhumed mantle rocks due to salt tectonics. In the Middle Jurassic, intraoceanic subduction initiated and in the Late Jurassic ophiolitic nappes and melange zones were obducted onto the Adriatic continental margin. During this process, also the carbonate blocks (e.g. Schneeberg nappe) and some slices of the exhumed mantle rocks were in-cooperated in the initial Alpine nappe stack. To the southeast, the Neotethys Ocean stayed open until Late Cretaceous times. However, the missing of an oceanic suture within the Austroalpine unit as well as at the border to the adjoining Southalpine unit argues against the existence of oceanic lithosphere in this position during Eoalpine contraction in the Early Cretaceous. To solve this problem and to explain the recent distribution of Triassic facies zones in the Austroalpine unit latest Jurassic to earliest Cretaceous sinistral strike slip faults are proposed by a number of authors. These cut the northern part of the Adriatic continental lithosphere and removed the oceanic areas of the Neotethys Ocean from the Adriatic continental margin. The oceanic realm was replaced by continental lithosphere, from which the present Southalpine unit was formed later on. In the Early Cretaceous a south-dipping intracontinental subduction zone developed along the strike slip faults and the Austroalpine nappe stack developed. During this process, the Neotethys derived nappes on top of the Juvavic nappes were eroded and the material was filled into the surrounding Gosau basins in the early late Cretaceous.

New K-Ar dating of metasedimentary rocks of the Urgamal Zone of the Zavkhan terrane (Khasagt Mountains, Mongolia)

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The geological structure of the western part of the Khasagt Mountains (Gobi-Altai Province) is important in analyzing the evolution of the Mongolian part of the Central Asian Orogenic Belt. The study area is located north of the Main Mongolian Lineament in the domain dominated by Precambrian and Lower Palaeozoic rocks (Badarch et al., 2022). We pay attention to the structure of the SW margin of the Zavkhan terrane (cratonal terrane) in order to reconstruct the tectonic events connected with the collision with the Lake terrane (island arc terrane). The basement of the Zavkhan terrane exposed in the Khasagt Mountains is divided into two units separated by the Intra-Khasagt Fault Zone (IKFZ; Sikora et al., 2021). The autochthonous Khasagt Zone is on the north side of the IKFZ and the para-autochthonous Urgamal Zone is on the south side. We have studied the Neoproterozoic metasedimentary rocks (quartz-muscovite-chlorite slates) of the Shar Shoroot Member (Yargait Formation) located in the Urgamal Zone. They were metamorphosed in greenschist facies and deformed into tight, upright or NE-wergent folds. We have determined three metamorphic foliations, that correspond to the following phases: buckling folding, shear folding and faulting. The superposition of different metamorphic foliations is visible in the outcrop scale and the thin-section. The S1 foliation is parallel to S0 sedimentary surfaces. Slaty cleavage S2 is oblique to S1 and cleavage S3 is perpendicular to it. We obtained several dates from K-Ar dating that vary from 593.1+/-20,2 Ma to 401.9 +/-37.2 Ma. Their comparison with the our structural data and results published by Štípská et al. (2010), Bold et al. (2016) and Kilian et al. (2016) allowed us to determine the sequence of deformation on the SW margin of the Zavkhan terrane during late Neoproterozoic and Palaeozoic.

The research was financed from statutory resources of the Polish Geological Institute – National Research Institute project 62.9012.1974.00.0.

Multi-phase development of the faults in the Malužiná Fm. (Hronic Unit, Western Carpathians): reconstruction based on kinematic analysis of multiple fault structures

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The thin-skinned Hronic nappe system represents the structurally highest tectonic unit in the Late Cretaceous thrust-stack of the Central Western Carpathians. Structurally, the Hronic Unit is an internally complicated nappe system with numerous partial nappes. It mostly comprises a Permian volcano-sedimentary sequence and Triassic carbonate sediments that crop out in different parts of the Central Western Carpathians. The basal part of the Hronic nappe system is represented by the uppermost Carboniferous-Permian volcano-sedimentary sequence called the Ipoltica Group. The Ipoltica Group comprises the uppermost Carboniferous lowermost Permian Nižná Boca Fm. and the Permian Malužiná Fm. Nižná Boca Fm. consists of a regressive lacustrine-deltaic succession including sandy shales, sandstones and conglomerates. Overlying Malužiná Fm. consists of three upward sedimentary megacycles. These sedimentary cycles are composed of fluvial-lacustrine and alluvial red beds and locally evaporites. Malužiná Fm. is characterized by the presence of large basic to intermediate volcanic rocks with continental tholeiitic magmatic trend. They are related to a regional extensional tectonic regime, which led to the formation of a rift structure. Extensive andesitic to basaltic volcanism was generated during two main eruption phases. The older phase belongs to the first and the younger, huger one to the 3rd megacycle. Triassic sediments directly overlie the Ipoltica Group. The Triassic succession is comparatively thick. It is represented by siliciclastic deposits, like quartzitic sandstones followed by variegated shales and a wide range of carbonates, representing various parts of a shelf environment, from reef platforms up to pelagic intra-shelf basins. The Jurassic and Lower Cretaceous limestones are rare.

This study is concentrated on the paleostress analysis of five localities in the eastern part of Nízke Tatry Mts. The deformation structures were measured and recorded in the Permian volcano-sedimentary sequence of the Malužiná Formation.

Based on kinematic analyses of meso-scale faults (slickensides), several brittle deformation stages characterized by certain properties of the reconstructed stress field have been discerned. We have employed the program Win_Tensor for the computation of stresses and the separation of the faults into homogenous groups. Relative superposition of individual paleostress states was derived from field structural relationships. An observed chronology of deformation phases can be divided into the five different palaeostress fields. Evolution is characterised by continuous change of the orientation of principal maximum axis σ_1 from the W–E through N–S to NE–SW position. The kinematic analysis of fault-slip data confirmed predominant strike-slip nature of the fault during the whole history.

The oldest deformation phase is characterized by compression in the W–E direction that was generated during the strike-slip to transpressional tectonic regime. This event was accompanied by the formation of the sinistral faults trending in the NW–SE dominating over the dextral faults. N–S trending oblique-slip reverse faults generated in a pure compressive regime are superimposed on older fault structures. Next deformation stage represented by faults generated by a compressional regime with the NNW–SSE maximum horizontal stress axis SHmax. It resulted in formation of the conjugate strike-slip faults, including the NNW–SSE oriented dextral strike-slip faults that predominate over the sinistral faults. For this event, the formation of a great number of W–E striking reverse faults is typical. Compression continued with NE–SW oriented SHmax axis. Generally, the number of reverse faults decreased. The dextral strikeslip faults oriented N–S prevail over the sinistral strike-slip faults. Fourth stage is characterized by the onset of a general extensional tectonic regime, dominated by an extensional component of the stress field oriented in the NW-SE.

Extension continued with NNE–SSW oriented σ_3. Number of conjugate normal faults is as the result of a purely extensional tectonic regime

Acknowledgement: This research was supported by the Slovak Research and Development Agency under contracts No. APVV 19-0065 and KEGA 033UMB-4/2021.

Age, petrogenesis, and metamorphic evolution of the metavolcano-sedimentary complex of the Staré Město Belt, the Sudetes

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The Staré Město Belt (SMB), the Sudetes, is a narrow tectonic zone that separates the Orlica-Śnieżnik Dome, a part of the Saxothuringian terrane and the Velké Vrbno Dome, a part of the Brunovistulian terrane. New whole-rock geochemical (major and trace elements, Nd isotopes) and zircon analyses (typology; trace element composition; and U–Pb, Hf and O isotopes) provide new data on the age and provenance of the SMB, as well as magma generation and evolution during the late Cambrian thermal event in northern Gondwana. Moreover, structural and microprobe data, thermodynamic modelling, and U–Th–Pb dating on monazites, titanites, and zircons were used to reconstruct the Variscan history of the SMB as a suture of the Saxothuringian–Brunovistulian convergence zone.

Field relationships of SMB rocks suggest joint effusions of mafic and felsic lavas of the bimodal volcanic sequence. U–Pb zircon dating from the mafic and felsic metavolcanics and from the adjacent metasedimentary rocks indicates that the studied volcano-sedimentary succession developed at ca. 495 Ma. The source areas of the sedimentary basin were dominated by Neoproterozoic and Palaeoproterozoic crystalline rocks that were presumably located near the West African Craton of Gondwana, which indicates that the entire SMB forms the eastern termination of the Saxothuringian terrane.

Whole-rock geochemistry and trace elements (U=111-4584 ppm, Nb=0,59-48,81 ppm, Ti=2,09-82,22 ppm, Y=35-6993 ppm, U/Yb=0,232-231,067, Nb/Yb=0,001-0,352) in zircon suggest that the formation of the bimodal sequence of the SMB took place in an active Gondwanan continental margin (continental arc/back-arc). Zircon oxygen isotopic compositions of felsic ($\delta^{18}O_{zrn}$ = 1-10.5‰) and mafic metavolcanic rocks ($\delta^{18}O_{zrn}$ = 4.3-6.1‰) correlate with εHf values ranging from -27 to 6 in zircon from felsic rocks and εHf values ranging from -28 to -2 in mafic rocks, respectively. The above results point to complex (crust/mantle) magma differentiation most probably in a suprasubduction environment (possibly fore-arc). Eight whole-rock samples of mafic metavolcanites yield positive values of εNd from +2,6 to +10,8, and seven samples of felsic metavolcanites yield comparable values ranging between +0,8 and +10,7 These data may suggest a common mantle source of magmas that later evolved in the continental crust.

Structural observations, microprobe data, thermodynamic modelling, and isotopic mineral dating confirm the presence of two main Variscan metamorphic episodes at ca. 370-360 Ma and ca. 340 Ma that are related to the polyphase Saxothuringia/Brunovistulia collision. During the main folding stage, rocks of the upper and lower SMB units were buried to depths corresponding to 6-7 kbar, while the middle unit was extruded from depths corresponding to 10-11 kbar. The structure of the SMB (large-scale fold) was modified by dextral transpression event at 340 Ma, during which tonalite magmas were emplaced.

Acknowledgment: The research was financed by a grant from the National Science Center, Poland No. 2018/29/B/ST10/01120.

Tectonic reconstruction and HC trap types of the North Hungarian Paleogene Basin (NHPB)

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The North Hungarian Paleogene Basin (NHPB) is located within the Carpathian arc, at the central part of the Pannonian Basin. The sediments of NHPB were deposited from Eocene to Middle Miocene in deep marine to terrestrial environments in several depositional cycles (Tari 1994, Vakarcs 1997). Beside eustasy the tectonic had a significant role in basin geometry and facies distribution due to local changes of accommodation space (Tari et al. 1993, Fodor et al. 1994, Palotai 2013).

The NHPB is one of the focus areas of hydrocarbon exploration in Hungary. Recent years exploration resulted a relatively good quality onshore seismic dataset. This study would like to summarize the results of seismic interpretation analyses of that data, focusing on tectonic framework. The main driver of that evaluation was to visualize the structural development of the southern part of the NHPB from Eocene to recent time. Based on seismic observations and mapping study – which includes fault geometry and thicknesses analyses of the defined tectonostratigraphic units- a tectonic model was created to summarize and conclude all these results above. The showed tectonic model contains 3D paleo-reconstructional models for all include 7 stages: Eocene, Oligocene, early Miocene, Early Badenian, Late Badenian-Sarmatian, Early Pannonian, Late Pannonian-Pliocene steps.

The earlier published transpressional model of Palotai (2013) was validated here as well. The paleo-geomorphology was mainly defined by syn-depositional tectonic structures. The analyzed seismic data suggests transpressional settings from Eocene, Oligo-Early Miocene to Early Pannonian, which could be correlated with the observations of outcrops in the Buda Hill also (Fodor et al. 1994). In the tectonic regime a significant inversion occured where the previous ENE-WSW right-lateral transpression changed to left-lateral. This study presents observations which indicate Badenian timing for that inversion at the study area.

A second initial goal of the study was to understand the HC trap development phases of the known hydrocarbon fields. At the second part of the presentation a trap class definition will be presented based on its tectonic styles. Three trap development phase was identified based on known HC field trap geometries. The first trap related tectonic phase is connected to Eocene thrusting. Some trap geometry suggests the role of strike slip deformation related tectonic which is defined as second type. The most significant structures in trap point of view are related to post inversional normal faulting, occurring at northern part of the study area.

Keyworlds: Paleo-reconstructional model, North Hungarian Paleogene Basin, transpressional basin

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Hidden metamorphic discontinuities in the NE Baidrag block, Mongolia, reveal anticlockwise metamorphic paths at c. 890−790 Ma indicating peri-Rodinian back-arc compression followed by c. 560–520 Ma burial

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The Barrovian type metamorphism affecting the Precambrian microcontinents of peri-Siberian tract of the Central Asian Orogenic Belt is mostly dated indirectly on zircon from (syn-tectonic) magmatic rocks as Late Proterozoic – Ordovician. However, in-situ monazite geochronology in micaschists and migmatite gneisses at the northern part of the Precambrian Baidrag block, central Mongolia, revealed that the Baikalian Late Proterozoic – Early Cambrian cycle overprints an earlier Tonian phase of metamorphism. The apparent Barrovian-type zoning ranging from garnet, staurolite, kyanite to kyanite/sillimanite migmatitic gneisses is thus false and points to hidden metamorphic discontinuities and mixed metamorphic histories from different times. Therefore, to decipher and interpret the record of different tectono-metamorphic events it is necessary to unravel complete P–T–t paths from individual samples. Two localities with Tonian-age monazite show anticlockwise P–T paths: 1) Grt−Sil−Ky gneiss records burial to the sillimanite stability field (~720°C, 6.0 kbar) followed by burial to the kyanite stability field (~750°C, 9 kbar) and, 2) The Grt−St schist records burial to the staurolite stability field (~620°C, 6 kbar), further followed by almost isothermal burial (~590°C, 8.5 kbar). Based on monazite textural position, internal zoning, and REE patterns, the time of prograde burial under a thermal gradient of 27–32°C/km is estimated at c. 890−853 Ma and further burial under a geothermal gradient of 18–22°C/km is dated at c. 835−815 Ma. On the other hand three localities with Late Proterozoic to Cambrian monazite ages show clockwise metamorphic paths at variable P–T gradients: 3) P–T conditions of the Grt schist reaches ~5 kbar and 500 °C and 4) the Grt−St−Ky schist reaches conditions of 9 kbar and 670 °C, indicating burial under a geothermal gradient of 20–26 °C/km. 5) Grt–Sil gneiss shows peak of 6–7 kbar and 700–750 °C, indicating melting conditions at 30–32 °C/km gradient. Monazite included in porphyroblasts and in the matrix indicate that these P–T conditions reached under variable geothermal gradient were semi-contemporaneous and occurred between 570 and 520 Ma. By correlation with published zircon ages of 600–530 Ma from granitoid magmatic rocks we suggest that the areas with higher geothermal gradient may be explained by closer vicinity of magmatic intrusions. These P−T and geochronology data from a continuous Barrovian metamorphic section suggest that anticlockwise P–T evolution from c. 930 to 750 Ma can be interpreted as a result of thickening of peri-Rodinian supra-subduction extensional and hot edifice. This metamorphic event was followed by a clockwise P–T evolution from c. 570 to 520 Ma possibly related to shortening of the northern Baidrag active margin and incipient collision with with peri-Siberian continental mass further north.

Recrystallized zircon in anatectic metagranite dates eclogite-facies grain-scale melt migration process, the Snieznik dome, Bohemian Massif

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Augen to banded metagranite from the Snieznik dome have been modified locally to have stromatic, schlieren or nebulitic textures typical of migmatites. The rock varieties were mostly interpreted as resulting from variable degree of deformation and migmatization, but the metamorphic conditions, the relation of migmatite formation to the structural succession, and the age of migmatization remain controversial (Redlińska-Marczyńska et al., 2016; Štípská et al., 2019). For example, Turniak et al. (2000) considered the migmatite formation as a HT–LP event incompatible with eclogite boudins and Lange et al. (2002) suggested that the migmatization overprinted the strain gradient and therefore is syn- to posttectonic. In contrast, Chopin et al. (2012) interpreted melting as syntectonic with continental subduction. The age of 340–360 Ma, was interpreted as the age of HT–LP anataxis, and was determined from zircon rims in metagranitic migmatites (Turniak et al., 2000; Lange et al., 2005) and on zircon in leucosomes and granitoid mobilizates (Štípská et al., 2004; Brocker et al., 2009).

In Štípská et al. (2019), former presence, and increasing role of melt in transformation of migmatite types towards nebulite is inferred from interstitial phases along grain boundaries in the dynamically recrystallized monomineralic feldspar and quartz aggregates, and from textures of fine-grained plagioclase and quartz replacing K-feldspar. These features are interpreted as resulting from dissolution-reprecipitation along grain boundaries due to grain-scale melt migration, being pervasive at the grain-scale, but localized at hand-specimen to outcrop scales. The new minerals crystallized from melt are in textural equilibrium with phengite. All the rock types have the same mineral assemblage of Grt−Ph−Bt−Ttn−Kfs−Pl−Qz±Rt±Ilm, with similar garnet, phengite and biotite composition, leading to modelled equilibration conditions of 15−17 kbar and 690–740 °C. Retrograde zoning in phengite, garnet and plagioclase, and biotite replacing phengite and garnet indicate decompression to 7−10 kbar. Because the mineral compositions in the assemblage of interest are independent of the amount of melt, the modelling did not allow to estimate melt quantities in individual rock types. However, migmatite textures suggest that increasing degree of melt-rock interaction occurred from the banded to the nebulitic and schlieren types. The initiation of melt migration is related to gently dipping structures related to continental subduction to eclogite-facies conditions, and more pronounced melt migration is related with vertical fabrics leading to exhumation of the continental subduction wedge from eclogite-facies to mid-crustal conditions.

Zircon in augen to banded types shows oscillatory zoning and gives Cambro-Ordovician age of the protolith. In schlieren to nebulite types, zircon shows domains of blurred oscillatory zoning to structure-less textures. These metamorphic domains are located along grain boundaries, form embayments, form straight or curved linear structures cutting through the oscillatory zoned domains, or are affecting the whole grains. The domains with sharp oscillatory zoning tend to give Cambro-Oridovician ages, while the metamorphic domains tend to give Carboniferous age. Zircon shows also numerous apparent "inclusions" of phengite, K-feldspar, quartz, plagioclase, rare garnet, rutile and biotite. However, the "inclusions" of phengite, garnet and rutile are located in the metamorphic domains of the zircon grains. In places, these inclusions are aligned, and these structures are interpreted as former cracks, along which these metamorphic phases crystallized and zircon (re)crystallized. As the assemblage of phengite-garnet-rutile is compatible with previously inferred eclogite-facies conditions, we interpret the Carboniferous zircon (re)crystallization as dating the eclogite-facies grain-scale melt migration process.

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The origin and conditions of pure compaction bands formation in the naturally deformed Otryt Sandstone (the Silesian Nappe, SE Poland)

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Tabular strain localization structures known as deformation bands are a common form of deformation found in sandstones. However, naturally occurring deformation bands that primarily localize compactant failure, also known as pure compaction bands, have only been documented in a few locations to date. The rare observations of naturally occurring pure compaction bands are attributed to the special combination of lithological and stress conditions that must be present.

The pure compaction bands are found in the Oligocene flysch sequence of the (Lower) Krosno beds within the Otryt sandstones of the Silesian Nappe, the Outer Carpathians (SE Poland). The pure compaction bands are perpendicular to the bedding planes and occur within the folded strata. The pure compaction bands were formed in very fine-grained to very coarse-grained sandstones of moderate or poor sorting. The density of pure compaction bands is on average 140 bands/m and the thickness of a single band is below 1 mm. The microstructures of pure compaction bands are a result of several mechanisms, including pore collapse leading to compact packing of grains, as well as disaggregation such as kinking and cataclasis. The resulting microstructure is highly dependent on the textural properties of the host rock. Cataclasis occurs more frequently with coarser-grained sandstone, whereas kinking is associated with moderately sorted foliated sandstone. The structural restoration of beds to their original horizontal position indicates that the pure compaction bands were formed prior to folding and documented the SW-NE-directed shortening, which is in line with the subsequent folding. The distribution pattern of the pure compaction bands indicates that their growth could be associated with the nucleation of back-thrusts, given their proximity to such structures and their presence in the hanging walls. According to the results of mechanical modelling and stratigraphic constraints, the formation of pure compaction bands took place at relatively shallow burial depths (<1 km) when the host rocks still exhibited porosities of around 20%.

The presence of hydrocarbons and calcite veins in certain fractured pure compaction bands suggests that these structures could have played a significant role in fluid transport during the evolution of the fold-and-thrust belt in the Outer Carpathians.

Acknowledgements: This research was funded by National Science Centre, Poland (grant number: 2018/31/N/ST10/02486) and AGH-UST statutory funds (No. 16.16.140.315).

Geometry and kinematics of the Mikulov fault, Outer Western Carpathians, revealed by LiDAR, ERT, and deep-seismic interpretation. Subrecent activity controlled by thrusting or from the crystalline basement?

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The Outer Western Carpathians are fractured by several syn-thrust and post-thrust faults. One of them, the Mikulov fault, was documented and studied. The fault has previously been partially interpreted as a two-system fault. This study examines the Mikulov fault using the combination of a LiDAR-derived digital terrain model and aerial photograph analysis, with subsurface ERT profiling and 2D deep-seismic interpretation. Two-dimensional deep-reflection seismic profiles were interpreted in the Petrel software in combination with boreholes. Combining these methods, we document a distinct N-S directed fault zone that intersects or delineates the majority of Pavlov Hills Jurassic limestone nappe outliers. Data revealed almost continuous fault zone in the north-south direction, which ranges from Horní Věstonice in the North to Mikulov in the South, and extends further south to Austria. The thrusted Jurassic limestone bodies are cut by the fault zone, which tectonically crushed the limestone in its core and the cores of the secondary fault branches. The map pattern of the fault zone suggests branching and re-attaching with the production of lenticular tectonic slices. We interpret the fault as a prominent sinistral shear zone. This is indicated by block displacement on the Svatý kopeček Hill and also by the orientation of the accompanying subvertical Riedel shears with identified horizontal lineation. The activity of the fault zone begins tightly after the nappe thrust in the formation of the final stages of the accretion wedge, as suggested by the observed sinistral kinematics. Thus, the main movement along the fault is probably of the late Miocene age. However, there are some indications that the tectonic activity might be subrecent. Based on offsets of the known stratigraphy and the fault's position on the ground surface, we aim on determining the causative processes of these young faults.

The research was funded by the Grant Agency of the Czech Republic (GC22-24206J).

Tectonic frames and changing structural styles of the Gorzów block (NW Poland) at successive structural levels.

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An ongoing discussion, though not a very lively one, has been taking place since at least the 1950s about the delimitation and definition of the tectonic units that underlie the Polish Lowlands - an areally extensive informal geographical unit, covering Poland north of the belt of the uplands and mountains concentrated in the south part of the country. Geologically, the Polish Lowlands are roughly equivalent to the Palaeozoic-Mesozoic basin system (the Polish Basin) developed on variable basement, represented by eroded Precambrian, Cadomian, Caledonian and Variscan orogenic belts. The earlier mentioned discussion concerns, among others, the northern extent of the Fore-Sudetic Homocline (Fig. 1) and the location of the boundary line between the Homocline and the south-western part of the Mid-Polish Anticlinorium (also know as the Mid-Polish Swell). One of the proposals of a tectonic division was presented by Dadlez (1974) and, after later modifications (Narkiewicz & Dadlez, 2008). It is functioning today as a generally accepted idea, where a separate tectonic unit, named the Gorzów Block (fig. 1) is distinguished in the western part of the Permo-Mesozoic succession of the Polish Basin. Geographically is located on the line between Gorzów Wielkopolski and Poznań.

Being currently engaged in the revision of the tectonic map of Poland, we suggest that the idea of the Gorzów Block as a separate individualized tectonic unit should be carefully re-examined. Some of the assumed tectonic boundaries of this block in the Permo-Mesozoic fill of the Polish Basin can be put into question, whereas such boundaries in the Pre-Permian, Variscan-tectonized basement are difficult to follow using seismic data due to the screening effect of the upper Permian evaporates (mainly rock salt formations) on seismic waves.

In our presentation we overview of the existing tectonic concepts concerning the Gorzów Block and confront them with the then- and currently available information. Based on the most recent studies, including an advanced 3D structural-parametric model, we attempt to define the tectonic boundaries of the Gorzow block and discuss the difficulties encountered while trying their delineation.

Geometric and hydrogeological properties of the fracture network of the Boda Claystone Formation, Hungary

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Fractures can significantly impact fluid flow in impermeable rocks like the Boda Claystone Formation. The Boda Claystone (BCF) is a prospective host rock for nuclear waste storage in Hungary; hence it is crucial to examine the geometry of the fracture network and evaluate the fractures hydrogeologically. The geometry of the fracture network was modelled using the discrete fracture network (DFN) modelling approach in wells BAF–2, BAF–3, BAF–3A and BAF–4. Each well intersected the BCF for hundreds of meters, with nearly 100% core recovery. Based on the geometric characteristics of the individual fractures, such as orientation, fracture length, aperture, and fracture density, the DFN modelling approach allowed the geometry of the communicating fracture clusters to be modelled. Identifying the fracture aperture with aperture calibration based on hydraulic well testing is the basis for the hydrogeological evaluation of the fracture network. The flow zone index (FZI), which depends on the covariation of porosity and permeability and determines hydraulic units, is frequently used to describe reservoir rocks. The fluid flow controlling characteristics within hydraulic units are uniform.

The basis for a spatial correlation between the wells in the BCF is fracture density. Fracture density can be described as the number of fractures per meter (P10 parameter). The fracture density pattern is highly similar along BAF–3 and BAF–4. In both situations, the fracture density rises steadily with depth without any noticeable leap. However, the fracture density of borehole BAF–2 differs strongly from that of the other two boreholes investigated. The rock body can be separated into two blocks, the boundary of which is located at 400 meters, based on the fracture density log of the BAF–2 well. The borehole's upper section is heavily fractured, whereas the lower portion has a substantially reduced fracture density. This difference in the fracture density is not visible in BAF–3 and BAF–4 wells.

The geometry of the fracture networks in all three wells displays a similar pattern regarding their connection despite the variations in fracture density between wells. In borehole BAF–2, the main horizons are at 100, 400, and 700 m, where the connectedness of the fracture system varies. Weathering could change the top 100 m of the formation in this well. Based on the change in fracture density pattern and other features, a large-scale structural boundary is presumed at a depth of 400 m. Coarsening of the average grain size is the primary factor influencing fracture formation at 700 m, but the influence of a large-scale structural boundary cannot be completely ruled out.

The FZI was used to describe the hydrogeological properties of the fracture network. Most of the rock body in all wells aligns with an average trend; only a few zones deviate from this trend to exhibit increased FZI values. The high FZI values in boreholes BAF–2 and BAF–4 are around 100, 400, and 700 m, respectively. In borehole BAF–3, only the 400 m horizon can be detected based on the FZI log.

Older wells usually lack BHTV data, the base for determining fracture density. However, conventional geophysical log data are often available in these wells. The relationship between the geophysical log data and the fracture density can be established using multiple linear regression analysis. This method can predict fracture density without BHTV using conventional geophysical logs.

The main factors influencing the fracture density in the BCF are the resistivity (e10, e40) and the density values based on multiple linear regression analysis. The fracture density could be accurately predicted using a regression function computed in the upper section of the BAF–4 well in both the BAF–2 and BAF–4 boreholes. However, the accuracy of the prediction could fall in some parts where the lithology deviates from the typical lithology of the formation due to an anomalous shift in the well log data.

By merging the predicted fracture densities of older wells with the available fracture network models from BAF–2, BAF–3, BAF–3A, and BAF–4, it is possible to locate and analyse communicating fracture clusters and large-scale fracture zones. In addition to the fracture network models of the BCF, the predicted effective porosity and permeability could one day be used as a base for hydraulic and transport modelling of the formation.

Acknowledgement

The Public Limited Company provided access to the data for Radioactive Waste Management (RHK Kft.) and the Mecsekérc Zrt. Zoltán Máthé and Péter Mucsi are thanked for their comprehensive assistance. The research was financially supported by the National Research, Development and Innovation Office (grant no. K-138919).

Paleomagnetic contribution to the tectonic evolution of the Drina-Ivanjica Unit, Internal Dinarides

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The Drina-Ivanjica Unit belongs to the internal part of the Dinaric collisional belt, situated between the Vardar Zone and the Durmitor Nappe. Cretaceous-Paleogene collision resulted in the overthrusting of the Durmitor Nappe by the Drina-Ivanjica Unit, which in its turn was overthrusted by the Western Vardar Zone. The basement of the Drina-Ivanjica Unit is made up of Paleozoic metamorphic rocks and sediments and are overlain by Triassic clastics and carbonates, Jurassic limestones and ophiolites, and following a large statigraphical gap, Upper Cretaceous transitional sediments and flysch. Oligocene extension produced small sedimentary basins and activated Miocene volcanism in the area, which resulted in the Golija intrusion and in extrusive magmatic rocks.

The tectonically complicated Drina-Ivanjica Unit was in the focus of several geodynamical and geological study, but this is the first paleomagnetic research in the area, involving Miocene magmatic rocks, Upper Cretaceous siliciclastic formations and limestones, Jurassic and Triassic sedimentary rocks.

Standard laboratory processes resulted in well-defined directions for most of the igneous sites and sedimentary localitites. The site-mean paleodeclinations of the Miocene magmatic rocks are well-clustered, suggesting a moderate, 30° CW vertical axis rotation after about 20 Ma. Some inclinations are highly variable, which can be explained by non-separable, composite natural remanent magnetizations (NRM) of the rocks. The Campanian – Maastrichtian flysch, close to the magmatic bodies in the Golija area, showed similar CW rotation before tilt correction. Thus we interpret them as remagnetized during the Miocene magmatic events.

Upper Cretaceous (Albian to Santonian) limestones elsewhere in the Drina-Ivanjica Unit exhibit minor CW rotation after tilt correction, but the age of this magnetization is questionable as the tilt test was indeterminate. Thus we tentatively suggest a maximum 15° CCW rotation, probably of the whole Drina-Ivanjica Unit after the Upper Cretaceous and before 20 Ma. The Jurassic and Triassic results indicate CCW (30-60°) rotation during the Mezozoic.

Earlier paleomagnetic directions had been published for Oligocene–Miocene igneous rocks from the adjacent Vardar Zone. These studies document about 30° clockwise rotation for the area, after 23 Ma, which is in good agreement with the new Miocene results from the Drina-Ivanjica Unit, suggesting co-ordinated vertical axis CW rotation in the Miocene.

The paleomagnetic results so far obtained for the Triassic and Jurassic sediments are fairly scattered, thus insufficient to constrain the magnitude of a possible general CCW rotation affecting the Drina-Ivanjica unit. Further investigation is needed to decide if the variations in declinations are due to local tectonics or the changing orientation in time of the whole unit.

This work is supported by the ÚNKP-22-2 New National Excellence Program of the Ministry for Culture and Innovation from the source of the National Research, Development and Innovation Fund and by the National Development and Innovation Office of Hungary, project K 128625.

Alpine evolution of the Gemeric basement rocks (Central Western Carpathians) revealed by low-temperature thermochronology ($^{87}Rb/^{86}Sr$ isochron data on biotite, zircon and apatite fission track data)

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The Western Carpathians are the north-easternmost segment of the European Alpine Orogen and are divided into Internal, Central, and External Western Carpathians. The Central Western Carpathians consist of a nappe stack of thick-skinned crustal-scale basement nappes/units (Tatric, Veporic, and Gemeric), incorporated into the Upper Cretaceous collisional wedge and overlain by thin-skinned nappes. The thick-skinned nappes are composed of Variscan crystalline basement and upper Palaeozoic to Mesozoic cover sequences. The research is focused on the late stages of the Carpathian orogenic evolution and especially on the internal Gemeric part. $^{87}Rb/^{86}Sr$ biotite ages (regression ages calculated from biotite and corresponding whole rock) as well as zircon and apatite fission track (ZFT and AFT) thermochronology have been used to derive quantitative constraints on the low-temperature evolution of the Gemeric basement. According to previous studies Alpine peak metamorphic conditions were reached in the Early Cretaceous (~ 140 – 115 Ma). This overprint is related to Late Jurassic subduction followed by Early Cretaceous N–S convergence forming the Eo-Alpine nappe stack with the overlying Meliata subduction-accretionary complex. The basement rocks, predominantly composed of Permian granite, yield $^{87}Rb/^{86}Sr$ biotite ages in the range of 114.8 ± 1.1 Ma to 94.5 ± 1.1 Ma, which are interpreted as cooling ages below 300 °C. Zircon fission track ages are between 108.2 ± 7.0 and 73.0 ± 4.5 Ma and apatite fission track ages are ranging from 62.5 ± 7.3 to 59.3 ± 6.1 Ma. The Permian to Lower Triassic siliciclastic deposits of the Northern Gemeric cover sequences yield zircon fission track ages from 94.6 ± 9.1 Ma to 83.3 ± 7.4 Ma and apatite fission track ages are between 72.8 ± 8.0 Ma and 61.3 ± 7.3 Ma. The basement rocks of the Gemeric Unit as well as the Permian to Lower Triassic cover sequence of the Northern Gemeric subunit were heated up to temperatures of approximately 350 °C or slightly more during the Alpine metamorphism. According to the geochronological ages presented above, the Gemeric Unit stayed in a crustal level with 350 – 200 °C at a depth level of 10 – 6 km at about 115 – 73 Ma ago. During exhumation and accompanied cooling it reached a near-surface level at less than 80 °C at 73 – 60 Ma. The cooling of the Gemeric Unit began after the collapse of the overlying Meliata accretionary prism and Silica-related nappes at approximately 130 – 115 Ma. Cooling of the Gemeric Unit throught the temperature interval of 350 – 200 °C at 115 – 73 Ma occurred in the same time interval as the metamorphic peak in the underlying Veporic crystalline basement (~ 115 – 105 Ma). Therefore, it is interpreted to be related to overthrusting of the Gemeric thrust sheet onto the Veporic crystalline basement. Cooling of the Gemeric Unit below the apatite partial annealing zone is practically the same age as final cooling of the Veporic Unit (~ 70 – 60 Ma).

Acknowledgement: This work was supported by the Slovak Research and Development Agency under contracts Nos. APVV-21-0281 "Alpine geodynamical evolution of the Western Carpathian inner zones", APVV-17-0170 "Early Alpidic tectonic evolution and palaeogeography of the Western Carpathians".

Influence of caprock on the growth dynamics of salt diapirs in the southeastern Zagros mountains, Iran

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We present a new joint international (DFG and GAČR funded) project of the Ludwig-Maximilians-Universität München (LMU), the Institute of Geophysics of the Czech Academy of Sciences, the Charles University in Prague, and the Deutsches Zentrum für Luft- und Raumfahrt in Oberpfaffenhofen (DLR), which focuses on structure, composition and deformation of caprock on salt diapirs in southern Iran. Caprock consists of insoluble remnants of the original evaporite sequence (e.g. gypsum or carbonate) that remain after the diapir boundaries have reacted to unsaturated fluid flow. Mechanically, caprock is a highly porous and brittle domain with a high potential for migration of fluids and deposition of mineral resources. The Zagros Fold-and-Thrust Belt (ZFTB) in southern Iran represents one of the few regions in the world, where salt diapirs and their caprocks are exposed at the surface and can be studied directly.

The overall objective of our project is to gain a better understanding of the mechanical behavior of the caprock and how it depends on the units' thickness, composition, deformation of the underlying rock salt, and surface effects. We aim to decipher the influence of caprock properties on the morphotectonics of diapiric extrusions and the overall kinematic evolution of salt diapirs. This will be addressed by integrating results from our 1) detailed field mapping, 2) remote-sensing analysis including persistent scatterer interferometry (PSI) using Sentinel-1 (C-Band) and TerraSAR-X (X-Band) data (to be) processed by the DLR, and 3) analogue, numerical and stratigraphical-geological modeling.

Geological field work includes structural mapping across selected diapirs that show different morphologies reflecting the pre-shortening and active growth stages. This part includes petrological and geochemical characterization (e.g. stable isotopes) of collected samples. Different dating techniques will be applied to constrain ages of sediments and growth dynamics of the investigated diapirs. Sentinel-1 and TerraSAR-X satellite radar images, processed by the DLR, are employed to detect subtle displacements on several diapirs, using the PSI method. Analogue modeling was carried out to understand fundamental deformation processes of the caprock during tectonic shortening and extrusion as well as surface strain pattern around shortened diapirs. The models will simulate lateral squeezing of pre-shortening diapirs including the caprock. We tested the effect of various initial diapir shapes, caprock rheologies and thicknesses and cover layer compositions on extrusion morphology, uplift rates and style of caprock deformation. In summary, the project aims to improve the understanding of the deformation mechanisms of the caprock, the uplift and degradation rates of the salt diapirs in Iran, their subsurface shapes and their kinematic evolution during their reactivation in frame of the ZFTB.

keywords: Caprock, Iran, salt diapir, uplift rate, diapir reactivation, gypsum