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Abstracts

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Tectonic interpretation of Miskolc Geothermal Field

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INTRODUCTION

The drilling of wells of Miskolc Geothermal Field at the vicinity of Bükk Mountains (NE Hungary) started in 2010. Since 2013 the geothermal heating system is operating two production and three injection wells and producing approx. 700.000 GJ thermal energy annually. Based on the original conceptual model all five wells are operating in the same karstified thermal aquifer, which's carbonate formations of Triassic age are outcropping in Bükk Mountains, where the recharge of the system takes place. Unfortunately, the concept on the identical aquifer was not verified satisfyingly by interference and tracer tests right after the completion of the wells (Tolnai et al. 2012). The operators of the system published (Révi et al. 2017) the observed well head temperatures of production wells over 4 years duration, which indicates unbalanced cooling of the production wells. One of the well was cooled three times more than the other, which feature hardly supports the concept of identical aquifer. Based on the interpretation of drilled layers in the wells and the surface distribution of geological formations of Bükk Mountains, the forecasted presence of a thrust fault between the production wells might be a plausible explanation for the observed difference in cooling of wells.

RESULTS OF DRILLINGS

The area of town of Miskolc was a known geothermal field, because of the natural phenomena of Miskolc-Tapolca thermal spring and the thermal wells drilled in the town during 20th century. The location of deep thermal wells for heating purposes was designed in the wider vicinity of the town, this way higher outflow temperature was forecasted due to larger distance from the recharge area, and less effect was expected on the existing springs and wells, which receptors enjoyed certain privilege and protection against new developments. The first exploratory drilling (MAL-PE-01) was made in the outskirt of town of Mályi (Fig. 1). The well is 2311 m deep, and it is producing thermal water of 105.3°C from the 2275–2311 m depth interval. The drilling explored a 0.8 m long open fissure at 2275 m, which triggered a total mud loss resulting the complete lack of cuttings. Unfortunately, the attempt of getting cuttings by junk basket tool was failed, so the rock of aquifer is not known accurately. The expected rock of aquifer is Bükkfennsík Limestone Formation (BLF) of Triassic age (rock of lagoonal facies, Less et al. 2005). Above the aquifer Répáshuta Limestone Formation of Triassic age (pelagic basin and slope facies; Less et al. 2005), Lökvölgy Shale Formation of Jurassic age and Szépvölgy Limestone Formation of Eocene age were recognized. The drilled sequences of the well are indicated on Figure 1. A year later in 2011, the first injection well (KIS-PE-01) was drilled near town of Kistokaj (Fig. 1). The distance between the two wells (MAL-PE-01 and KIS-PE-01) is 1.9 km. The KIS-PE-01 well drilled into the BLF right under the tuff of Miocene age at 1065 m depth. If one compares the drilled sequences of the two wells (Fig. 1), the missing cap rocks of Triassic, of Jurassic and of Eocene age above the water-bearing fissure at KIS-PE-01 are observable. In 2012, the second production well (MAL-PE-02) was completed at 600 m distance from MAL-PE-01. The drilling interestingly explored very similar layers as at KIS-PE-01, the water-bearing BLF was right under the tuff of Miocene age at 1395 m (Fig. 1).

SURFACE ANALOGIES FOR DRILLINGS

The outcropping Mesosoic sequences of Bükk Mountains provide an opportunity to find analogies for the drillings. The Figure 1 shows a surface geological map of the area as well. The area indicated with black circle (as part of SE Bükk area) consists of formations reported above the BLF at MAL-PE-01 drilling. The area indicated with red circle (as part of Répáshuta-Tapolca area) is, where BLF is outcropping, or tuff of Miocene age is overlying it. Based on Less et al. (2002) a fracture zone is interpreted between the two above-mentioned areas (indicated with brown ellipsoid).

CONCLUSION

Comparing the absolute levels of BLF in MAL-PE-01 and in MAL-PE-02 840 m long vertical difference is observable along 600 m horizontal distance. This thought provoking difference was not explained by tectonic features previously, because the fully continuous, identical aquifer concept was interpreted. The observed difference in rate of cooling indicates a kind of barrier between the two wells, which provides additional protection for the deeper well against the invading cooling front. This barrier might be a hidden tectonic feature, which's analogy might be the structure described between the Répáshuta-Tapolca and SE Bükk area. This tectonic element could be verified by further analysis and tests, especially by the help of tracer tests.

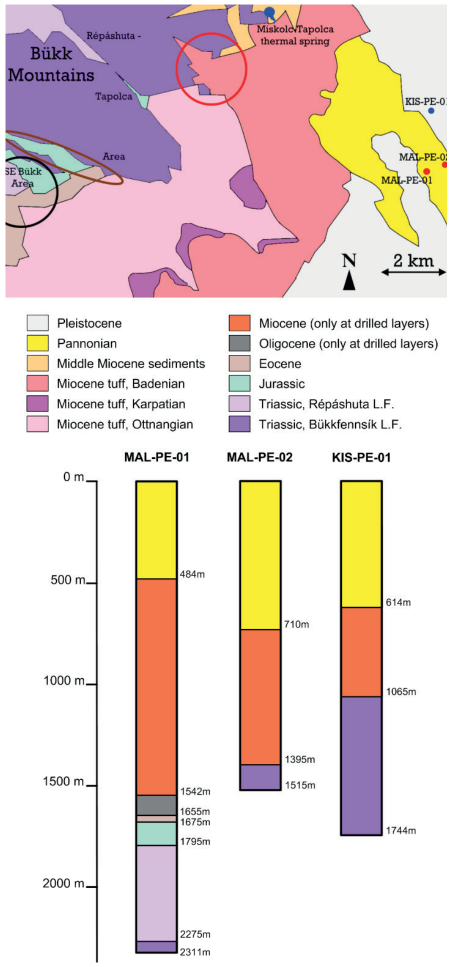

***Fig. 1.** Geological map of Miskolc Geothermal Field (Gyalog & Síkhegyi 2005) and interpretation of drilled geological layers in geothermal wells*

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Evaluation of basement reservoirs for geothermal utilization at southern part of Pannonian Basin

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In the last decade successful and costly geothermal developments happened in the Pannonian basin, e.g. heating projects in Hungary (town of Győr, Miskolc, and Szeged, the total built-in capacity of geothermal part is around 130 MW), and power plant projects in Tura (3 MW), Hungary, and in Velika Ciglena (10 MW), Croatia (under completion). Most of the new developments are producing geothermal energy form fractured basement reservoirs. Compared to basin fill reservoir (e.g. Upper Pannonian sandstone aquifer) the basement reservoir is less predictable during exploration, but it can provide hotter fluid, sometimes in enormous amount (above 100 l/s) and it is less sensitive for reinjection. During the completion of DARLINGe project (co-funded by the European Regional Development Fund and by the Instrument for Pre-Accession Assistance II) an attempt was made to evaluate and to locate those part of basement reservoirs along the project area, which might represent a realistic target for further geothermal exploration. The realistic targets should fulfil several conditions, like desired depth range for expecting reasonable amount of stored heat energy, presence of tectonic features and of permeable or brittle faulted rocks, which increase the likelihood of having pores and conduits within the rock or fault framework. The highest likelihood of having suitable conditions is connected to carbonate formations, where the karstified top surface, if it was sufficiently karstified in the past, together with sub-vertical fractures might create a highly permeable resource, in which convective heat-flow is expected efficiently conveying thermal conditions of deeper zones. The project area is located along six countries (Bosnia-Herzegovina, Croatia, Hungary, Romania, Serbia, and Slovenia) and the results of the evaluation are presented by countries. Most of the located targets are suitable for heating purposes only, but at some places electricity production is possible as well. The exploration of basement reservoirs should follow a system-level approach, where one successful well is not enough to ensure the success of an expansive geothermal utilization system. In this respect the existence of well data which proves the water bearing property of basement reservoir is only a good indication of a resource, but for ensuring successful further exploitation, the accurate picture and characteristics of tectonic features are indispensable, because of the need of adequate reinjection. The system-level approach of exploration of fractured basement reservoir was successfully applied at geothermal development of town of Szentlőrinc along the South-Mecsek line, SW Hungary. Since 2011 the system is running problem-free selling approximately 23.000 GJ annually. The geological risk is hanging like sword of Damocles above any exploration activity, which risk could be mitigated by detailed geological evaluation, measurements, design and completion. In case of under-performance of exploratory wells, there are several stimulation methods, like thermal, chemical and hydraulic stimulation, which might be used successfully for increasing productivity at basement reservoirs if the open hole section of a newly drilled geothermal well is exclusively set in a brittle rock environment. The evaluation of basement reservoirs along six countries in the frame of DARLINGe project will provide support for creation of an adequate exploration method for fractured reservoirs.

Geochronology and tectogenesis of the Late Ordovician-Silurian K-bentonites from the Baltic basin

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Bentonites, being a result of violent and short lasting volcanic eruptions, serve as one of the most useful time markers enabling correlations of regional as well as global scale events. Except for their stratigraphic value, bentonites often witness plate tectonic reorganization, cause faunal or climatic changes which makes them valuable tool in paleo-tectonic or paleo-environmental reconstructions.

The Late Ordovician-Silurian sedimentary sequences in the northern part of the Baltic Basin in northern Poland contain over 100 K-bentonites strata which provide an excellent record of volcanic activity witnessing the collisional process between Laurentia, Avalonia and Baltica. Vast majority of the previous studies attempted to constrain their petrogenesis using primarily petrographic and geochemical methods. These, however, are handicapped due to high degree of syn- and post-depositional alterations of the original tephra which may lead to inaccurate results. In this study, except for the "traditional" geochemical and isotopic whole rock analyses, we conducted *in situ* U–Pb zircon dating combined with *in situ* Hf isotope composition measurements using LA (MC) ICP-MS. An obvious advantage of this approach is a well acknowledged high resistance of zircon to post-crystallization alterations which allows a better inside into magmagenesis of K-bentonites. Furthermore, analyses of the detrital components in zircons provide additional constraints on provenance of the volcanic ash deposits.

Trace element composition of the studied K-bentonites points to the mixed, crust derived and juvenile magmas originating from sub-alkaline magmatism generated in the subduction zone. The Late Ordovician-early Silurian K-bentonites involve larger juvenile component in magmagenesis, and most likely, their magma source developed within the northern margin of the Avalonia volcanic arc as indicated by the U–Pb ages of the inherited domains in zircons. We correlate magmagenesis with the early stages of collision between the southern Baltica and Avalonia. The younger K-bentonites deposited in Wenlok and Ludlow were generated predominantly by partial melting of continental crust with only minor addition of a juvenile component. The U–Pb inherited age distribution in zircons indicates their source still within Avalonia. The change in geochemical and isotopic signature is explained by tectonic plate reorganization associated with the end of subduction of oceanic crust of Tornquist sea below Avalonia and with the beginning of the Caledonides formation due to collision of Laurentia with Baltica.

A possible mechanism of normal faulting in the western part of the Polish Outer Carpathian revealed by seismic data and surface geology

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Based on outcrops and seismic data a prominent fault zone was identified within the area of the Magura Unit in the westernmost part of the Polish Outer Carpathians. By referring to the structural style of this area (Starzec et al. 2014, Starzec et al. 2017), it can be interpreted as a normal or transtensional fault system with general N-S strike direction. Preliminary studies suggest that formation of this zone might be associated with development of duplexes below the Magura Unit. The research area is located south of Wisła and Żywiec towns, bordering with the Czech and Slovak Republics on the west and south, respectively. Interpretation of the recently acquired seismic data, combined with surface geology, shed a new light on the structure of this region. Starzec et al. (2017) suggest an abrupt termination of the Silesian Nappe just below the Fore Magura thrust and presence of the Fore Magura / Dukla Unit (here and after named as a Dukla Unit) below the Magura Nappe. One of the most prominent features, previously anticipated based on well data and surface geology, and recently confirmed by seismic investigation, is so called the Sól structure, which is defined as an anticlinal stack formed within the Krosno and Inoceramian type beds of the Dukla Unit. The structure is covered by the Magura Unit. Its culmination lies at depth of about 400 m bgl that increases along strike of the structure as well as transversely to it.

Recent geological mapping campaign (Starzec et al. 2014) provided much more detailed outlook on the surface geology in the studied area. The general picture of the area shows that the Magura Unit is composed of series of second order thrust related folds that propagated towards the north-west. Mostly the youngest, i.e. the Late Eocene / Oligocene sandstones of the Magura Formation are exposed in its middle part (the Raca zone). They form the back limbs of the thrust related folds. In folds' hinge zones older, Upper Cretaceous to Early Eocene formations crop out. Distinctive feature of this area is lateral variability regarding both the width of the hinge zones and the rock formations exposed along them. In this respect, the area is clearly divided into two parts: the western part with at least three thrust related folds with relatively broad hinge zones in which the oldest Upper Cretaceous formations are exposed, and the eastern part with much simpler tectonic style and with the oldest formation in the folds' hinges dating back only to the Early-Middle Eocene. The earlier mentioned fault constitutes a boundary between these two parts. The fault can be identified by a presence of distinct linear features in the topographic image derived from LiDAR data. It is confirmed by field observations of brittle rocks. At many places along the fault zone a several meters sized blocks of sandstones or packets of sandstones and shales of the Magura Formation with joints, striated micro-faults and slickensides are visible. Faulted sandstones display an evidence of alteration resulting from fluid flow along fractured medium, i.e. many calcite veins, change of their mechanical properties and colour from the original yellow gray to almost white. Two of the folds on the western part of the area are cut off by the fault and do not continue on its eastern side, whereas another fold extends over its both sides. The most striking feature of the last one is curvature of its axis. With respect to the regional W-E trend of the strike of fold structures, the arcuate (or even sigmoidal) shape of its axis suggests an occurrence of a fault zone with strike-slip component. Although, the seismic data shows a strong throw component of the fault movement.

Interpretation of pre-stack depth migrated seismic sections reveals the existence of the large normal fault, with accompanying second order antithetic and synthetic faults. The décollement surface of the main fault dies out at the base of Carpathians' nappe system. Based on our observations it can be said that the strike slip component might be connected with development of the lateral ramp formed during thrusting, whereas extension and normal faulting was associated with formation of the previously mentioned anticlinal stack of the Sól structure, which caused uplifting of the western part (now the foot wall) and gravitational sliding of the eastern part (the hanging wall).

The presented study was carried out within the framework of the research NCBiR BLUEGAS II ShaleCarp grant and partially financed by statutory works (11.11.140.332 and 11.11.140.005). Processing of the seismic data was performed with the Halliburton's SeisSpace software, while interpretation and structural modelling was performed with the Move software (Midland Valley).

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Orogenic collapse recorded in Benešov granodiorite, Bohemian Massif

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Magmatic rocks in the NE part of the Central Bohemian Plutonic Complex known as the "Benešov type" were affected by strong deformation during the Variscan orogeny. These rocks are represented especially by amphibole-biotite granodiorites. To determine deformation fabric of the "Benešov type", anisotropy of magnetic susceptibility (AMS) was used. AMS data were compared with similar structures found in the Bohemian Massif.

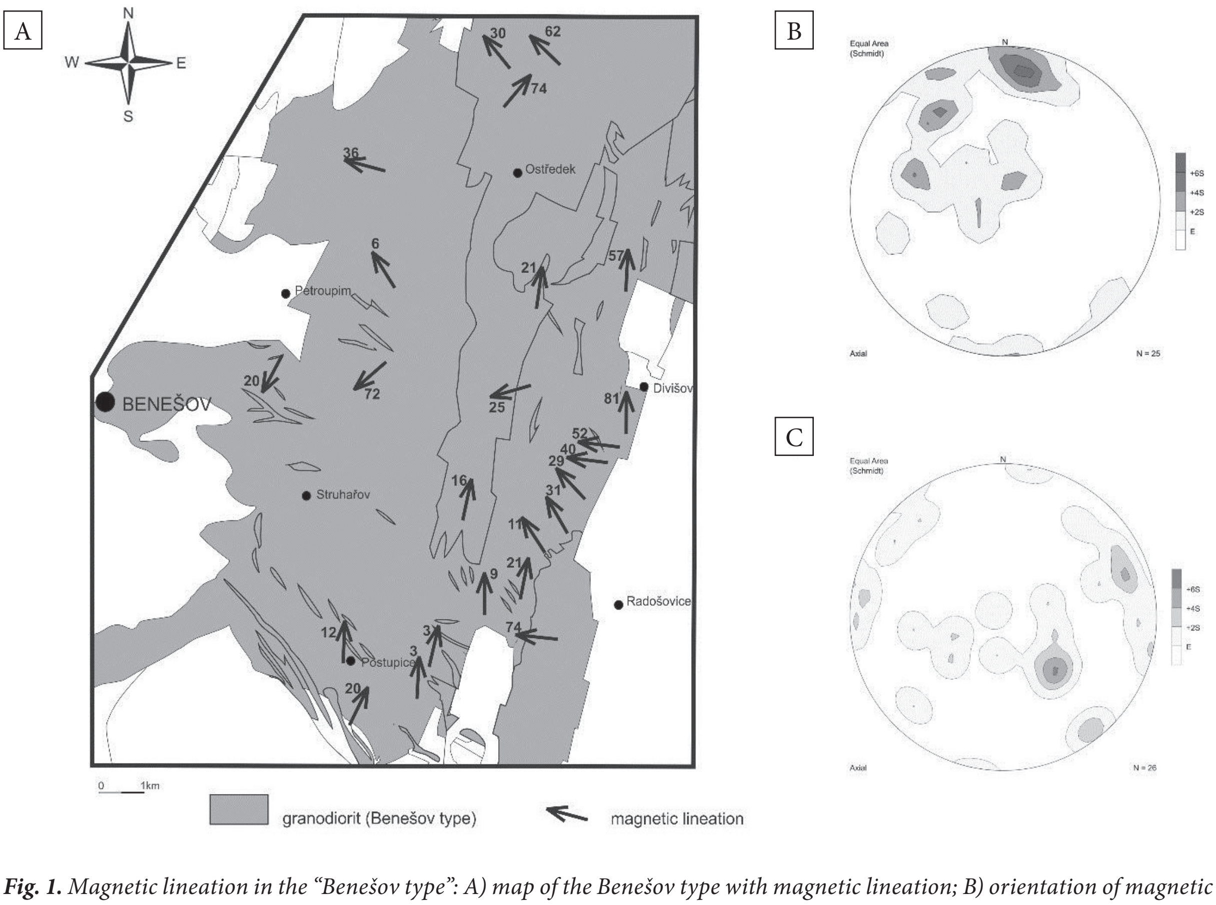

Fig. 1. *Magnetic lineation in the "Benešov type": A) map of the Benešov type with magnetic lineation; B) orientation of magnetic lineation in azimuthal projection on lower hemisphere; C) orientation of poles to magnetic foliations in azimuthal projection on lower hemisphere*

Over 450 samples were collected. Recognized magnetic fabric is more-or-less homogenous through the study area. Magnetic lineation dips to the NW or N at low angles (Fig. 1). Magnetic foliations are less homogeneous but it trends to dip to the W-NW. The most of samples have prolate ellipsoid of AMS. The degree of anisotropy varies from 1.033 to 1.132. Relatively low bulk magnetic susceptibility of measured samples (from 0.23×10^{-4} SI to 4.08×10^{-4} SI) suggests that the AMS signal is caused by paramagnetic minerals. Microstructural observation confirmed top-to-the north tectonic movement. Equivalent shear zones with similar orientation as well as with similar sense of movement were found in this part of the Bohemian Massif in other units, such as Čertovo břemeno type, Miřetín pluton, Nové Město durbachite among others. Considering lithology, dating and tectonics of the surrounding units, these shear zones might be interpreted as ductile to brittle-ductile detachments originated during gravitational collapse of the Variscan orogenic belt.

Structure of durbachitic rocks in the southern part of the Třebíč Pluton

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Studied area is situated in southern part of the Třebíč Pluton, which is a plutonic body consisting of durbachitic rocks situated in the Bohemian Massif. The pluton intruded into the Variscan orogenic root (Moldanubian Unit) before 335–340 Ma (Kotková et al. 2010). Internal structure of the body was investigated using anisotropy of magnetic susceptibility (AMS), which well reflects magmatic- and strain-originated preferred orientation of magnetic minerals.

Over 162 samples were taken using a portable drill at 25 sampling sites covering the area under study. Results of AMS analysis were compared with mesoscopic structural observations (compass data).

Essentially, there are four groups with different directions of magnetic foliation. The degree of anisotropy varies from 1.013 to 1.154. The value of degree of anisotropy increases from south to north. The shape parameter T varies from strong prolate (–0.820) to medium oblate (0.510). Vectors K1 show magnetic lineations developed in NW-SE direction and plunging to the NW or N under low angels. Vectors K3 are normals to magnetic foliation, which is steeply dipping mostly to the W. There was also used an analysis of temperature dependence of magnetic susceptibility. This method showed that all fabrics in these rocks in southern part of pluton are controlled by paramagnetic minerals such as amphibole and biotite.

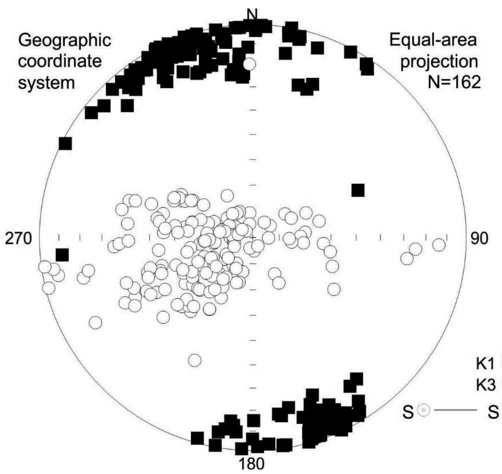

Fig. 1. *Orientation of magnetic lineation K1 and poles to magnetic foliation K3 in durbachitic rocks from the southern part of Třebíč pluton*

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Regularities of failure of migmatized gneiss with metamorphic foliation

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The research is focused on exploration of the mechanical anisotropy and fracture process of a rock with planes of weakness.

In this study, the strength behaviour of migmatized gneiss with weakened planes, i.e. metamorphic foliation is evaluated. Metamorphic foliation with a specific orientation of rock grains may results that the mechanical behaviour, and the mechanical properties, i.e. strength, are changed in different directions of loading. The strength anisotropy and the direction of weakening are in geomechanics not sufficiently clear until now.

For these purposes, series of uniaxial compressive strength tests were carried out on the five groups of specimens of migmatized gneiss based on the different angle *α* between foliation and loading. The measured results have shown that mechanical properties of the migmatized gneiss have different values concerning foliation. U-shaped anisotropy was obtained, in accordance to Ramamurthy distinguished curve of anisotropy (Ramamurthy 1993) with the minimum average strength at α = 30° and the maximum average strength is reached when α = 90° (Fig. 1).

Next, an intensity of deformation, an orientation of new-created fractures due to foliation and a shape of fractured specimens were characterized. An extension failure parallel or subparallel to the loading and a shear failure were also recognized on the fractured rock specimens.

The characterization should be a contribution to understanding of that, how an orientation of weakness planes influences the strength and the fracture formation of the rock. The knowledge of the problem is useful information for stability ensuring of underground construction, mine workings and for other geotechnical application.

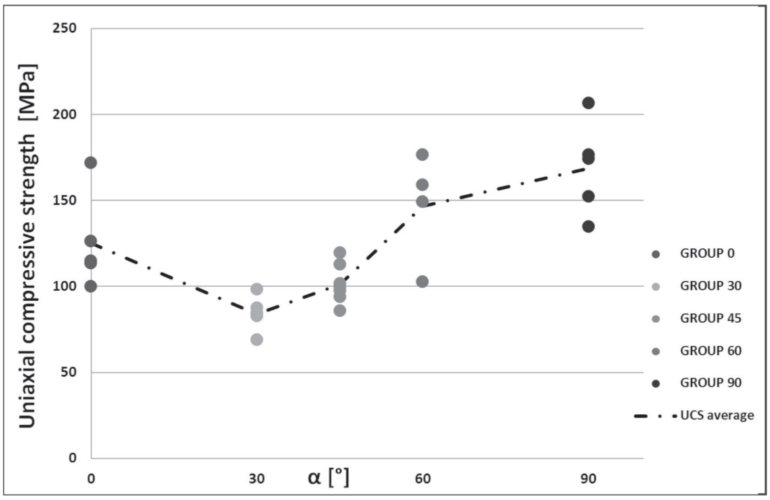

Fig. 1. *Graphic plot showing values of uniaxial compressive strength of five groups of migmatized gneiss (based on the different angle α between foliation and loading). The dotted line results U-shaped strength anisotropy*

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Geochronology and Nd-Hf isotope constraints on petrogenesis of teschenites – alkaline lamprophyres from type locality in the Outer Western Carpathians

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Teschenite Association Rocks form a suite of alkaline volcanic rocks in the Outer Western Carpathian flysch sediments where *teschenite* was first defined. They represent continental intraplate volcanism, which produced a wide range of melano- to mesocratic lamprophyres emplaced during Early Cretaceous rifting within the southern margin of the European Platform. Geochemical modelling indicates that they are probably a product of ~2–5% partial melting of metasomatized, amphibole- and/or phlogopite-bearing, asthenospheric mantle. Variations in trace elements (e.g. La_N/Yb_N = 11–34) are consistent with the presence of residual garnet in the mantle source. Teschenite Association Rocks were subjected to two-stages of fractional crystallization; initially mainly of olivine followed by clinopyroxene + amphibole fractionation. Initial Nd-Hf isotope composition ($\varepsilon(Nd)_i$ = 5.0–6.3, $\varepsilon(Hf)_i$ = 4.9–10.0) preclude significant crustal involvement. Instead, a linear trend in Nd–Hf isotopic compositions points to a genesis from mixed enriched, HIMU type OIB source with less fertile OIB component. Mantle metasomatism was most likely caused by subduction-related fluids associated with the Variscan subduction–collision processes as indicated by depleted-mantle Nd model ages. Isotope and trace-element composition is characteristic for European Asthenospheric Reservoir (EAR) – the common mantle end-member for widespread Tertiary-Quaternary volcanic rocks from Europe. It suggests a long-term occurrence of EAR mantle component beneath the Central Europe. *In situ* laser-ablation ICP-MS U–Pb dating of titanite (124–119 Ma) indicates short duration (ca. 5 Myr) of the alkaline magmatism. It is correlated with maximum lithospheric thinning which triggered adiabatic decompression and partial melting of the asthenospheric mantle. Rapid transition from extensional climax to compressive regime directly preceding the Carpathian-Alpine Orogeny could have ceased magmatism in the Silesian basin.

Two separate orogen-parallel extension events in the Tauern Window revealed by crystallization-deformation relations

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

In the studied area, the Venediger duplex is composed of nappes of late Variscan/Permian Tux Gneiss and Zillertal Gneiss with its post-Variscan (Permo-Carboniferous and Mesozoic) cover sequences (Veselá et al. 2010). The Subpenninic nappes in the hanging wall are represented by the Modereck and Wolfendorn nappes which are overlain by the Glockner nappe being part of the Penninic units (Schmid et al. 2013). The nappes alltogether were previously named as Lower Schieferhülle, Upper Schieferhülle and their P-T conditions of up to blueschist facies were described by Selverstone (1985, 1988).

We present results of detailed structural and petrological study focused mainly on the cover sequences represented by the post-Variscan cover and Subpenninic nappes and their tectono-metamorphic evolution with respect to the Central gneiss complexes. The cover sequences consist mainly of schists, amphibolites, marbles and quartzites and they show dominant W to NW-dipping fabric (S1) in the western and central parts of studied area and S to SW-dipping fabric in the southern part. The observed stretching lineation (L1) plunges generally to the W. This dominant fabric was later folded by open to tight folds F2 with steep E-W trending axial planes (S2) and gently SW- to W-plunging axes (L2). Subsequently, the western part of the Tauern Window was heterogenously affected by development of discrete gently westward dipping cleavage S3 with dip-slip lineations L3. The geometry of the cleavage as well as the development of synkinematic folds with their axes perpendicular to L3 suggest normal sense shearing associated with this deformation. These later structures are only present in schists and orthogneiss, while they are absent in quartzites. The overlying Glockner nappe (former Upper Schieferhülle) is composed of deformed greenschists, calcschists, micaschists and marbles, which are together folded by large-scale open folds with W-SW trending fold axes and lineations (L2) and steep NW dipping cleavage in fold planes (S2). Western part of studied area is affected by late folding F2 with fold axes trending N-S and fold planes dipping to W or NW (S3).

The metamorphic overprint observed in the Venediger duplex cover sequences, Subpenninic nappes and Penninic nappes is characterized by occurrence of garnet in generaly syn- to post-kinematic position with respect to S1. These garnets show decrease in spessartine and sometimes also grossular component, while almandine and pyrope increase towards the rim. The core to rim increase in XMg documents the overall prograde growth of these garnets. PT conditions were estimated using thermodynamic modelling in Perple_X (J. Connolly, ETH Zurich). The compositional zoning of garnets in the calculated pseudosections confirmed their prograde PT evolution with an increase in both temperature but mainly pressure and show prograde evolution of garnets.

From our data, we conclude that the tectono-metamorphic evolution of Tauern Window comprises two independent E-W orogen-parallel extension events. The first one related to the nappe stacking responsible for formation of the dominant S1 fabric which was later overprinted by formation of S3 during the N-S shortening and westward lateral escape associated with exhumation of the nappe stack of Venediger duplex.

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The Iberian Massif: Variscan evolution and terrane correlations

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The Iberian Massif is the outcrop of the Variscan basement in the western half of the Iberian Peninsula. It is divided in six zones, of which two are external and one is significantly allochthonous. All zones and units are derived from the northern margin of Gondwana or oceanic peri-Gondwanan realms. The autochthonous and part of the allochthonous tectono-metamorphic units derive from an extended passive margin of early Paleozoic age. There are two sutures, both related to the closure of the Rheic Ocean. The tectono-metamorphic evolution is particularly complex in the NW Iberian Allochthon, and includes large thrust sheets, recumbent and upright folding, and high-, medium- and low pressure-metamorphism of Cambro-Ordovician and early Variscan age. The Autochthon registered poly-phased deformation of Variscan age, including large transcurrent shear zones, orocline development and abundant syn- to post-kinematic granitoids.

The aim of the presentation is to give a snapshot of the structure and structural evolution of the Variscan belt in Iberia, and to review the correlations with other Variscan massifs in Europe preserved from Alpine deformation, namely the Armorican, Central and Bohemian massifs. Among the several possible interpretations regarding how many terranes where involved, a conservative hypothesis of two relatively large ensembles is preferred. These are respectively described as the Autochthon and the Allochthon, according to their relative structural position. They form the essential part of the Variscan belt in Central Europe, and their superposition formed one of the sutures identified in Iberia, the one that will be described in detail. The other is Rhenohercynian suture, which represents the collision of these terranes with the supercontinent Laurussia.

The deciphering of mixed tectonic pattern based on characterization of structural data from boreholes obtained using acoustic televiewer

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The acoustic televiewer (Zemanek et al. 1969) records structure of borehole by transmitting ultrasound pulses from a rotating sensor and by recording the time and the amplitude, which it returns from the reflected signals walls. Amount of energy, which reflected wave carries back to the probe sensor, is dependent on quality of the borehole wall.

Each joint, bedding or foliation surface or any similar anisotropic planes is indicating by decreasing of reflected-wave amplitude. Due to its principle, the probe contains a group of three magnetometers and accelerometers. Output of the probe is continuous information about value and azimuth of borehole inclination, which allows us to define the dip direction and dip of planar structures. The structural data obtained were submitted in matrix showing depth of inhomogeneity, dip direction and dip.

Orientational analysis was used for detailed interpretation of inhomogeneities from the borehole. Directional data were visualized by equal-area Lambert projection on Lower hemisphere and statistically analyzed by Spheristat software.

Foliations, joints and/or zones of joints (eventually shear zones) were interpreted by cluster analysis across the borehole profile. Four significant clusters were defined in the contour plot for borehole A-025. Slightly rotating orientation of dominant cluster seems to be result of inclined to subhorizontal foliation. It is spread throughout the borehole profile without any significant cumulation. Inhomogeneities striking in N-S direction and dipping to the East under low angles (25–30°) are less dominant. These structures are also spread almost uniformly throughout the borehole profile. They represent a joint system, which appears in the entire borehole length.

Remaining two clusters have steeper orientation. The first of them represent tiny inhomogeneities striking in the ENE-WSW direction. These structures have appeared in several sets from depth of 13.28 m and deeper (see Fig. 1B). I interpret these structures as zones of intensive jointing.

The last directional cluster represents the inhomogeneities with strike NE-SW and steeply dipping to the NW. These structures appear in two discontinuous zones in depth between 47.75–52.81 m and 62.25–77.74 m. As these zones were found in adjacent borehole with different rock type, I prefer shear zone interpretation.

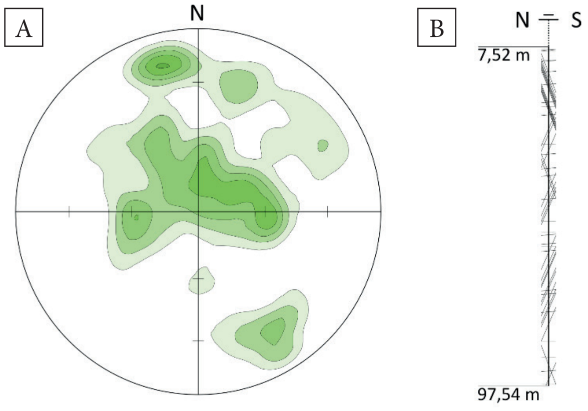

Fig. 1. *Orientation of planar inhomogeneities from A-025 borehole: A) azimuthal projection of poles to planes; B) borehole profile*

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Devonian magmatic rocks of the Mariánské Lázně Complex and Čistá pluton (Bohemian Massif)

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Eclogites from the Mariánské Lázně Complex (MLC, Bohemian Massif) show peak eclogite-facies metamorphic conditions at c. 390 Ma and are affected by HT extensional shearing at c. 375 Ma connected with granulite-facies overprint and migmatization (Collett et al. 2018). To understand a geodynamic context of such rapid transition from cold subduction to hot extension, rocks within the several tens of meters wide extensional zones were studied. These rocks are dominated by amphibolite migmatites and contain unfoliated, fine to coarse-grained rocks in which magmatic textures including euhedral crystal shapes, magmatic bedding or dykes are preserved. In places, the unfoliated structure of magmatic rocks passes into magmatic foliation and locally to solid-state amphibolite-facies shear zones. The nature of these magmatic rocks ranges from amphibole gabbros to trondhjemites, the latter being previously dated to a Devonian age (Timmermann et al. 2004). This magmatic event in the deep crust has possibly an upper crustal equivalent in the granitoids of the Čistá pluton, intruding the hangingwall Teplá-Barrandian domain (Žák et al. 2011). This study provides new whole rock geochemical data including major, trace element and Sr-Nd isotopes, combined with zircon study, for the extension-related magmatic rocks of the MLC and the supracrustal Čistá pluton. Calc-alkaline nature of the rocks, a pronounced negative Nb-Ta anomaly, relative enrichment of fluid-mobile elements (including large ion lithophile elements, LILE), a strong fractionation of LREE over HREE and depletion of high field strength elements (HFSE) is evidence for an active continental margin origin. Low values of εNd data suggest either the presence of variable mantle chemistry at the base of the magmatic system, and/or implication of the lower crust. Zircons of the gabbros to trondhjemites show magmatic overgrowths with ages ranging from 390 to 370 Ma and strong inheritance between 480 and 560 Ma. Zircons from the Čistá pluton show two peaks, a younger one with a range of ages 350–380 Ma and an older one with a range from 380 to 410 Ma, together with a weak inheritance between 500 and 530 Ma. The results are interpreted in terms of a long-lasting magmatic activity covering most of the Devonian. During this period, magmas intruded the lower crust during Middle and Late Devonian and were emplaced in the upper crust during Early Carboniferous. Magmas show strong involvement of the Cambrian lower crustal material concerning also the eclogites, and, based on variable relative enrichment of mobile elements (LREEs and LILEs) among the samples, a possible heterogeneous contribution of the subduction component in the system.

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Previous concepts and new data on the structural and magmatic evolution of the Bükk Mts., NE Hungary: first step toward the reconsideration of geodynamic models

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The Bükk Mts. are displaced fragments of the Inner Dinaric nappe system (Schmid et al. 2008). Two major concepts described their structure; one suggests four stratigraphic units as continuous, slightly deformed units (Less et al. 2005), while others considered these units as distinct nappes (Balla 1983, Csontos 1999, 2000). In our contribution we list some new, preliminary observations which may challenge both concepts and will hopefully provide a new one.

The Bükk Complex records the disintegration of the Triassic platform and deposition of Middle(?) Jurassic pelagic radiolarite. It is covered by the Lökvölgy distal turbidites, a slate with siltstone to sandstone intercalations. The overlying Mónosbél sequence contains shale, limestone intercalations, olistostromes and radiolarites. The Szarvaskő Complex is a Jurassic basaltic to gabbroic magmatic suite intruded in or flowed onto fine siliciclastics (Balla 1983). Finally, the Darnó Complex represents a mélange unit, composed of shales and embedded clasts of Triassic-Jurassic sediments and magmatic rocks (Kovács et al. 2011). All units were slightly metamorphosed and folded, the degree of alteration decreases upward. In the nappe-stack concept, the Mónosbél, Szarvaskő and Darnó Complexes are nappes, partly derived from the Neotethyan ophiolites (Csontos 1999, 2000):

– Newly described syn-diagenetic faults, slump folds can be connected to the passive margin setting of the Mónosbél Complex.
– Most, if not all olistolithes can be originated from the passive Adriatic margin, very few could have been scrapped off the Triassic part of the Neotethyan downgoing slab. Limestones are rich in clasts originated from coeval Bajocian-Bathonian carbonate platform.
– The Darnó Complex contains clasts from the overriding upper plate: blocks of Triassic and Jurassic radiolarites as well as Triassic basalts of advanced rifting origin (with peperitic red limestone) and Jurassic basalts similar to those occurring at Szarvaskő (Kiss et al. 2010, 2016, Kovács et al. 2011). We suggest that this is the only ophiolite-related tectono-sedimentary mélange in the Bükk area.
– There is a clear structural boundary at the top of the Lökvölgy Fm. (base Mónosbél Complex); folds are overturned, closed and have regular axial-plane foliation, while folds are open and have layer-parallel foliation, below and above the boundary. In addition, foliation, faults, or boudins form sigmoidal geometry, resembling to S-C foliation/sigma-clasts/faults in duplex; all indicating simple shear. Part of the shearing

with SSE to ESE vergency occurred in sub-horizontal bed position and probably characterise original tectonic emplacement. New fission-track zircon ages (140–134 Ma) would constraint this deformation as earliest Cretaceous.
- The geometry and magma-flow direction of the Szarvaskő Complex may point to a ring dyke-pillow basalt complex. New Sm-Nd dating on garnets from the contact of gabbro and plagiogranite yielded an age of 164.7 ± 1.6 Ma, in agreement with previous K–Ar ages (Árva-Soós et al. 1987; 166 ± 8 Ma on magmatic amphibole and 165 ± 5 Ma on muscovites of the contact hornfels), confirming a Callovian age of the magmatic rocks.
- Whole-rock geochemical data of the magmatites display MORB-like characteristics with subduction-related imprints, therefore previous authors (Harangi et al. 1996, Aigner-Torres & Koller 1999) suggested that the Jurassic magmatism of the Szarvaskő Complex is related to the opening of a back-arc/marginal basin. The differences from a real mid-oceanic ridge setting are also supported by the observed limited submarine hydrothermal processes and the lava-unconsolidated sediment interactions, i.e. the presence of the siliciclastic peperitic facies (Kiss et al. 2016).
- However, there is a strong connection between the Szarvaskő and Bükk Complexes, as the clastics hosting the magmatites have strong affinities to the Bükkian Lökvölgy Fm. and to the Vaskapu Sandstone Fm. It seems to be unrealistic to consider Szarvaskő as part of the upper plate ophiolite nappe system.

Our suggestion is that all complexes of the Bükk Mts. were derived from the same basin, situated on the downgoing slab. Their original position was within the distal continental margin, possibly approaching the trench of the intra-oceanic subduction. Some exotic clasts could be detached during incipient thrusting and redeposited immediately. The Darnó complex, as a mélange, could be linked to the once overlying ophiolite.

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3D structural model of Miocene depositional environment and faults for a future LBr-1 pilot CCS in the Vienna basin

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The LBr-1 is an abandoned oil and gas field Lanžhot – Brodske located at the Czech and Slovak border in the Vienna basin. The Lanžhot block forms a southern part of the Hodonín – Gbely horst in the Czech part of the

Vienna Basin, adjacent to the Moravian Central Depression on the W and Kúty Depression on the SE. This area has been recently revisited with an effort to evaluate potential CO_2 storage (CCS) and EOR. The well log data along with the seismics, petrophysics and stratigraphy served as basis for construction of a new 3D/2D model of the Badenian to Pannonian and younger strata (Fig. 1). The oil and gas field LBr-1 was explored and exploited from 1956 to 1976. The new well log correlations introduced marker horizons, sequence stratigraphic features, such as upward coarsening or fining, pinchouts and transgressive phenomena. The well log data are tied up with the 3D seismics and principal surfaces are interpreted with lithological patterns and petrophysical properties in maps and profiles in addition to the previous works (Prochác et al. 2012). The key intervals include 4 partial sand horizons within the Lab resrvoir, top of the Middle Badenian regional seal and base of the reservoir. Faults are mapped in the seismic lines and modeled in 3D. They are situated mainly outside the reservoir and do not represent a major risk for the storage integrity. The overburden model includes top of the Sarmatian, Pannonian coal seam strata, and the base of the Quaternary. Compartmentalization and reservoir continuity is shown in 3D and provides basis for improved understanding of the porosity and permability distribution in the storage complex.

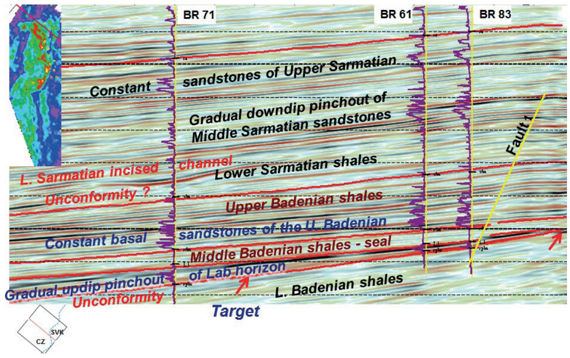

Fig. 1. *Seismic line with major sedimentological features of the evolution of the depositional setting during Badenian and Sarmatian with minor growth faults. Insert shows the restored shape of a Sarmatian channel*

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Shortening partitioning across the Variscan orogen in SE Poland

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Long discussion on the foreland extent of the Variscan orogen in Central Europe entered a new phase with the discovery of a Late Carboniferous fold-and-thrust belt overlying the SW slope of the East European Craton (EEC) in Poland (Krzywiec et al. 2017). A hinterland of this fold belt is formed by the Malopolska Block (MB), from which it is separated by the Holy Cross Fault (HCF). This fairly rectilinear fault has been considered a subvertical terrane boundary inherited after early Paleozoic wrenching. This remains at odds with a dozen-or-so up to >20 km of shortening absorbed by thin-skinned structures in the more platform-ward position. How was this shortening transferred across a fixed terrane boundary?

Using surface data from the Holy Cross Mountains (HCM) we have built a series of local and regional cross-sections that depict geometries of the HCF's hanging- and footwall. Fault-slip analysis provided additional constraints on regional kinematics. Finally, integration of seismic and gravimetric constraints resulted in a crustal-scale tectonic model that addresses the question on partitioning of the Variscan shortening along the SW perimeter of the EEC.

We demonstrate that the HCF is an S-vergent thrust that carries a ~7 km thick thrust sheet detached along middle Cambrian shales over the margin of the MB. The hanging wall of the HCF maintains a constant 40–45° dip angle along most of its strike. This corresponds to the dip of the HCF at depth. The footwall features a series of thin but tightly stacked imbricates related to the foreland thrusting propagation. These are as rule detached along Lower Silurian shales although a deeper intra-lower Cambrian detachment is also evident in the central sector of the HCM. Outcrop-scale record in the footwall of the HCF indicates plane-strain thrusting conditions with the σ_1 perpendicular to the HCF. On the contrary, the HCF's foreland located beyond the thin-skinned front is less deformed, mostly via rejuvenation of pre-Variscan structures. There, we identified syn-sedimentary normal faults inherited after pre-Variscan extensional tectonics and to a various extent reactivated during the Variscan shortening. Outcrop data indicate a progressive clockwise rotation of the shortening direction from N-S during the layer-parallel shortening to NE-SW during terminal phases of folding.

The fold-and-thrust fabric is overprinted by strike-slip tectonics, although reshaping of older map-scale structures occurs only locally. In particular, neither map- nor cross-section geometries contain any univocal evidence on a major strike-slip reactivation of the HCF. Despite of this, strike-slip record in outcrops is often dense and comprises three superposed populations of strike-slip faults. The most visible is the Alpine subset that obliterates two older subsets that potentially may represent a late Variscan post-folding signature. The older of the two yields a NE-SW σ_1 direction oblique to the Variscan structural trend in the HCM and compatible with late-folding directions. The younger one yields a NW-SE σ_1 direction.

Inversion of gravity data yielded a continuous top of the EEC basement descending gradually down to ~21 km b.s.l. beneath the HCM. The continuous top-basement excludes any source of tectonic shortening (i.e. basement-involved thrusts) north of the HCM. In addition, thin-skinned structures documented by Krzywiec et al. (2017) north-east of the HCM display a general vergence towards the foreland (EEC), hence opposite to the thrusting polarity in the HCM. The S-vergent thrusts and folds in the HCM must therefore have originated in the general back-thrust context. Given the propagation of thrusting in the HCM from a structural depression in the north toward a structural high of the MB in the south, we propose a triangle-zone geometry and kinematics for the Variscan structures of the HCM. On a crustal scale, the postulated triangle zone is related to the indentation of the MB leading edge into the sedimentary cover of the EEC. The resultant shortening of the sedimentary cover is partitioned between the foreland-vergent fold-and thrust belt north of the HCM and passive-roof backthrusting along the HCF.

Kinematic coupling between the Variscan orogen proper and peri-EEC Variscan units in SE Poland is not obvious. Our kinematic analysis from the HCM indicates N-S to NE-SW σ_1 directions during Variscan shortening, while the proven Variscan orogen is situated W-SW from the HCM. This discrepancy may be explained through an eastward escape of the MB from the zone of Variscan convergence and strain partitioning between strike-slip and thrusting components over an oblique slope of the EEC. However, scattered Variscan massifs (e.g. Matte 1986) and sediment provenance (e.g. Poprawa et al. 2005) in the Carpathian-Balkan area evidence an additional branch of the Variscan orogen south of the MB. This segment of the Variscides, disintegrated in the course of Mesozoic rifting and reworked during the Alpine orogeny is a suitable candidate as a source of shortening for the peri-EEC Variscan assemblage. If true, then the zone of Variscan deformation along the SW perimeter of the EEC would represent the most external, and the only preserved member of the southern branch of the European Variscides.

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The North European Platform suture zone in Poland

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The authors interpret the structure of the Central Carpathian-North European plates suture zone in Poland, where three main Carpathian tectonic units: the Central Carpathian, Pieniny Klippen Zone (PKB) and Outer Carpathian are present. In general, the PKB follows this zone. Several deep bore-holes were drilled in this region and the seismic lines were tied to bore-hole data and geological maps. The Polish PKB belongs to the complex geological structure stretching from Vienna in Austria to Romania. The rocks included in the PKB tectonic components were deposited within the paleogeographic realm known as the Alpine Tethys, mainly during the Jurassic-Early Cretaceous times. Both strike slip and thrust components occur within the Polish section of the PKB. The strongly tectonized, few kilometer wide PKB zone is limited by a flower structure marked by two major faults, linked to the strike-slip zone. These faults reach the North European Platform (part of the North European Plate).

The flysch sequences, arranged into a series of north-vergent thrust-sheets, constitute the main component of the PKB in the survey zone. They contain olistoliths, which are mainly Jurassic-Early Cretaceous in age. The PKB tectonic components of different age, strike-slip, thrust as well as toe-thrusts and olistostromes are mixed together, giving the present-day mélange character of this belt, where individual units are hard to distinguish. Two olistostrome belts (mélange units) exist within the PKB structure. The seismic lines show the Central Carpathian Paleogene rocks covering the Paleozoic Central Carpathian Basement south of the PKB. The Subtatric covers the High-Tatric autochthonous and allochthonous rocks. The Central Carpathian Plate is thrust over the North European Platform in the Podhale region. The allochthonous Outer Carpathian consists of several nappes (thrust-sheets) verging northward. They are thrust over each other and over the North European Platform which dips gently southward.

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Structural style of basin inversion at the base Zechstein level in the copper and silver deposit of "Polkowice-Sieroszowice" mine (Fore-Sudetic Homocline, SW Poland)

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Along with exploitation of copper and silver in mines located on the Fore-Sudetic Homocline, newly mined portions of the ore body, provide valuable structural data. We present here an analysis of tectonic structures uncovered in mine galleries and provided by cores from mining wells (drilled from inside the mines) as well as interpreted from archival mining structural maps. Our structural investigations were carried out in the Polkowice-Sieroszowice mine, along a profile that started few hundred meters from the Middle Odra Fault Zone, where the sedimentary cover had been elevated and eroded, and continued up to 10 km away of the fault zone. Near the border of the Fore-Sudetic Homocline with the Fore-Sudetic Block, the tectonic style of the ore body is dominated by compressive structures, such as minor thrusts, reverse faults and gentle folds striking mainly in NW-SE direction. The net slip on thrust faults reaches up to 70 m, with throw up to 20 m. Moreover, at the base Zechstein level in the Zechstein Limestone (Ca1), we have documented very common compressive meso-scale folds and thrusts. The thrusts sometimes are rooted in the Kupferschiefer shale (T1) which is smeared along fault surfaces. In places we have noticed Rotliegend sandstones wedged into the ductile T1 shales.

Pre-inversion structures, mostly grabens and horsts, developed at a broadly understood extensional stage of basin's development (from Triassic to Cretaceous times), were locally modified by the end-Cretaceous inversion-related tectonic shortening. We have observed the horsts that are cut and horizontally displaced along the Kupferschiefer (T1) horizon from their previous position. In tectonic grabens, we have documented horizontal displacements along the T1 shales, which cut the tectonically lowered strata in grabens. In such places, the tectonically displaced ore-bearing T1 shales and Ca1 carbonates rest on top of the Lower Anhydrite (A1d). Also, in the Kupferschiefer shales (T1) compressive deformations structures are common and represented by e.g. centimeter-scale fault propagation folds, thrusts and duplexes.

What we have also observed that farther north from the Middle Odra Fault Zone, the compressive deformation structures become less intense and those related to an extensional brittle deformation regime start to prevail. We farther suggest that the zone of intense brittle tectonic deformation (extensional and compressive) seems to be related to the SW extent of the Oldest Salt (Na1). It might be considered peculiar that the intense brittle deformation ceased at the line marked by the current Na1 extent, and where the Na1 salts are present in the overburden, the observed brittle tectonic imprint on the Zechstein base is not so intense or is absent.

Based on our research, we indicate that the compressive structures related to the Cretaceous/Paleogene basin inversion are much more common and widespread than it was previously documented (Dumicz & Don 1977, Salski 1975, 1977, Markiewicz 2007) especially at the border zone with the Fore-Sudetic Block.

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Remarks on the structure and evolution of the Skole Unit in the eastern part of the Polish Outer Carpathians

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In the middle part of the Polish segment of the Skole Unit new seismic data has recently been acquired by the Polish Oil and Gas Company (PGNiG) that together with geological mapping campaign allowed performing a comprehensive description of the geological setting in this region. Integration of seismic, well and the surface data enabled construction of the regional cross section throughout the Skole Unit showing its subsurface structure that allowed interpreting the deformation history of this part of the Outer Carpathians.

The new 2D seismic campaign covered an area over 800 km^2 extending on both sides of the San River valley. The area belongs mostly to the Skole Unit, but also includes marginal part of the Silesian and Subsilesian Units. So far, its subsurface structure has been rather poorly documented, especially in comparison to more northern parts of the Skole Unit. There are only few exploration wells and very limited geophysical data of good quality.

The map-scale structure of the Skole Unit in this area involves several NW-SE striking thrust sheets, verging north-eastwards. They are laterally continuous although, as revealed from a detailed map view, they vary along strike in terms of the geometry of structures and their stratigraphy. Lateral variation of stratigraphy is due to plunging of fold's axes and/or facies changes of the stratigraphic units. The most distinct feature is difference in stratigraphy across extend of the thrust sheets. The south western structural elements (like Wańkowa Wieś and Witryłów Anticlines, Tyrawa Wołoska Syncline), adjacent to the front of the Silesian and Subsilesian Units, are largely built of the youngest deposits, i.e. the Oligocene to Miocene Krosno Beds which are accompanied by the Menilite Beds. The latter directly underlay the former ones in sedimentary succession of the Skole Unit. Locally along anticline axes the Eocene formations crop out, manifesting in a form of narrow belt in the map view. In this part of the area structural elements are very steeply dipping, some of them showing chevron like geometry (e.g. the Witryłów Anticline). To the north east, starting with the prominent Wara Thrust, the older Upper Cretaceous formations constitute the dominant component of the structural units. In north-eastern part of the area and beyond it, toward external part of the Skole Unit, numerous, tightly stacked, thrust sheets are even devoid of deposits younger than the Upper Cretaceous. Variable dip data measured in the field reveals their complex internal geometry, however, thrust sheets herein are less steepen than in more southern parts of the Skole Unit. Fold and thrust structures of the Unit are cut by normal or strike-slip faults on several scales with strike perpendicular to the NE tectonic transport direction. The faults usually manifest by a significant topographic expression.

Interpretation of seismic sections combined with surface geological data suggests that Skole Unit in the area of research can be split into two compartments. Those compartments are separated by the Wara Thrust which is one of the major tectonic features in the area, both in terms of coverage and the amount of material transport. The northern compartment exhibit more simple structural development and better seismic data quality, than the southern one. In the northern part strong and continuous seismic reflections show moderately dipping strata that are folded in the near surface zone. In the southern compartment seismic data quality is poor, but the visible reflections suggest very steeply dipping strata.

The basement of the Carpathian deposits as well as the main detachment level is well imaged by the seismic data in the northern part of the section. Both the seismic and the magnetotelluric data suggest the occurrence of sub-vertical faults which affect the basement. One of those faults may have facilitated steepening of the Wara Thrust and piling up of deposits to the south. To image the whole Skole Nappe, the interpretation of seismic data was combined with cross-section provided with *Detailed geological map of Poland in the scale of 1:50 000 – 1006*. Interpretation results were examined using tectonic modelling and section analysis techniques available in Move software.

We would like to thank the Polish Oil and Gas Company (PGNiG) for providing seismic data and department's seismic processing group for putting an outstanding effort in data preparation. Interpretation and modelling was performed with the Move suite by Midland Valley. Seismic data processing was performed with the Halliburton's SeisSpace software.

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Neoproterozoic history of the Brno Massif: geology, age and geochemistry of the magmatic rocks of the Central Basic Belt

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The Brno Massif is the largest exposed part of the Brunovistulicum, a Precambrian crystalline geological unit at the eastern margin of the Bohemian Massif. Brunovistulicum is covered by Devonian to Carboniferous sediments and, further east, by the Outer Western Carpathian Flysch nappes. The Brno Massif is composed of two Cadomian plutonic belts, a geochemically primitive Eastern and more evolved Western, separated from each other by the Central Basic Belt (CBB) (see Finger et al. 2000a, Leichmann & Höck 2008 for review). The CBB is the N-S trending zone of dominantly mafic igneous rocks formed by two largely independent segments: bimodal metavolcanic Metabasite Zone (MBZ) in the East and metaplutonic Metadiorite Zone (MDZ) in the West.

Primary textures in the MBZ have been mostly obliterated by deformation and low-grade metamorphism. Therefore, massive metabasalts passing to greenschists dominate and pillow lavas or amygdaloidal basalts are only exceptionally preserved. Subordinate metarhyolites primarily occurred as massive lavas, dykes, tuffs and ignimbrites. Meta- gabbros and (quartz) diorites with cumulate fabrics dominate the MDZ. Subvertical N-S trending contact of the MDZ with the MBZ is tectonic and masked by a body of granodiorite/trondhjemite known as "Jundrov tonalite" that shows intrusive contacts with MDZ in the southern CBB.

Massive rhyolite associated with tholeiitic metabasalts of the MBZ was dated using a Pb–Pb zircon evaporation method to 725 ± 15 Ma (Finger et al. 2000b). Our LA ICP-MS U–Pb zircon dating of massive rhyolitic lava yielded a well-defined concordia magmatic age of 733 ± 5 Ma. Second sample representing ignimbrite shows a detrital zircon age pattern dominated by a prominent Neoproterozoic age maximum at ca. 726 Ma.

Meta-quartz diorite of the MDZ yielded a well-defined concordia magmatic age of 655 ± 3 Ma, identical to the mean age of a trondhjemite apophysis in metadiorite (655 ± 4 Ma). The LA ICP-MS U–Pb data of the Jundrov tonalite are more complex. Zircon rims yielded a cluster of magmatic ages between ca. 660 and 631 Ma with concordia age of 648 ± 5 Ma, while cores are slightly older with cluster of magmatic ages between ca. 673–685 Ma.

Subalkaline basalts to basaltic (trachy-) andesites from the MBZ (46.0–52.4 wt. % SiO_2) form two distinct groups. First shows flat, slightly LREE-depleted chondrite-normalized patterns (La_N/Yb_N = 1.1–1.2, La_N/Sm_N = 0.87–0.96). The second group is characterized by slightly fractionated trends (La_N/Yb_N = 1.6–2.3, La_N/Sm_N = 0.99–1.44). The acid member of the MBZ bimodal association corresponds to subalkaline rhyolites. Taking into account the associated mafic rocks, they can be collectively interpreted as a part of a single tholeiitic trend in the AFM plot. The NMORB normalized spider plots feature a general enrichment in LILE, Th and U as well as marked depletions in Nb, Ta, Sr, P and Ti. Rocks of the MDZ are ultrabasic to basic (37.8–52.5 wt. % SiO_2), often cumulates as demonstrated not only by their textures but also by the frequent presence of positive Eu anomaly in chondrite-normalized REE spider plots (Eu/Eu* = 0.99–2.16). The MDZ rocks classify as low- to normal-K calc-alkaline series in the SiO_2–K_2O diagram. The NMORB-normalized spider plots display patterns with a marked enrichment in LILE and depletion in Nb and Ta ± Zr and Hf.

Also, the Jundrov tonalites (63.9–73.9 wt. % SiO_2) correspond to the low-K calc-alkaline series. The NMORB-normalized spider plots display variable enrichment in LILE (especially Cs and Ba, less so Rb), Th, U, Pb and Sr. Characteristic are also shallow troughs for Nb and Ta, variable depletion in P and Ti, and slight enrichment in Zr and Hf.

The Nd isotopic data point to geochemically primitive sources of the magmas (ε^{i}_{Nd} = +9.1 to +3.5) with little scope for contamination by a mature continental crust. Thus, the parental magmas were derived directly from a variably depleted mantle, a juvenile metabasic crust with a short mean crustal residence (T^{Nd}_{DM}.2stg = 0.53–0.96 Ga), or both.

Submarine as well as subaerial volcanic activity is indicated by textures of bimodal tholeiitic volcanic rocks of the MBZ and this, together with the within-plate geochemistry and inferred primitive source of the magmas, points to an extensional, perhaps rift-related setting. It is tentatively ascribed to the Rodinia supercontinent break-up at the Tonian/Cryogenian boundary. Younger plutonic rocks of the MDZ evolved in a Late Cryogenian primitive magmatic arc, hallmarking the onset of intermediate-acid continental arc plutonism, products of which are preserved, *inter alia*, as the two large Cadomian plutonic belts of the Brno Massif. Missing geological data do not allow us to interpret relationships between MBZ and MDZ in a more detail; nevertheless, the view of CBB as a dismembered ophiolite belt (Leichmann & Höck 2008 for review) seems untenable.

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Source and evolution of the two-pyroxene quartz syenitic magmas parental to the Tábor and Jihlava plutons (Moldanubian Zone of the Bohemian Massif)

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Visean ultrapotassic magmatic rocks constitute several large and numerous smaller plutons and stocks in high-grade metamorphic rocks of the Variscan orogen's root (the Moldanubian Zone). They can be subdivided into two chemically similar but petrologically and genetically contrasting groups (Holub 1997, Janoušek & Holub 2007): (1) coarse Kfs-phyric amphibole–biotite melagranites to quartz syenites (the durbachite suite – e.g. Čertovo břemeno, Knížecí Stolec or Třebíč plutons), and (2) essentially equigranular biotite–two-pyroxene quartz syenites to melagranites (the 'syenitoid suite' – Tábor and Jihlava plutons). The latter group, characterized by the mineral assemblage orthopyroxene, clinopyroxene, phlogopite, plagioclase, perthitic K-feldspar and quartz, with accessoric zircon, apatite, ilmenite, monazite ± rutile ± chromite, is studied here.

Conventional (ID TIMS) U–Pb ages for zircon (336.9 ± 0.6 Ma) and rutile (336.8 ± 0.8 Ma) from the Tábor Pluton (recalculated from Janoušek & Gerdes 2003), together with the zircon U–Pb age from the Jihlava body (335.1 ± 0.6 Ma; Kotková et al. 2010), provide a precise time bracket for the emplacement and rapid cooling of the syenitoids. Geothermobarometry using mineral compositions of the two pyroxenes, zircon, rutile, plagioclase and alkali feldspar (Watson et al. 2006, Putirka 2008, Ferry & Watson 2007, Tomkins et al. 2007, Benisek et al. 2010), reveals two-stage, polybaric crystallization of a hot (~1200°C), dry melt. The clinopyroxene precipitation commenced early and deep (>12 kbar), perhaps in a putative lower crustal magma chamber. Emplacement (~6–7 kbar) was followed by isobaric cooling below ~850°C and crystallization, indicated by the Ti-in-Zrn and Zr-in-Rt thermometry, two-pyroxene thermobarometry and two-feldspar thermometry. In contrast, calculated saturation temperatures for zircon (< 850°C: Watson & Harrison 1983) and rutile (Ryerson & Watson 1987) based on bulk-rock composition have been compromised by variable degrees of clino- and/or orthopyroxene accumulation. Indeed, petrology and chemical data imply that the main petrogenetic process shaping the chemistry was essentially closed-system fractional crystallization with, or without, crystal accumulation of various combinations of phlogopite and clinopyroxene ± orthopyroxene. This stands in sharp contrast with the volumetrically prevalent durbachite suite, where mixing of contrasting mantle-derived and crustal anatectic melts was clearly much more significant. The syenitoid plutons share mutually comparable mineral- and whole-rock chemical compositions characterized by strong enrichments in lithophile Cs, Rb, Th, U and Pb and deep Nb, Ta and Ti troughs in Primitive Mantle-normalized spiderplots. Crust-like radiogenic isotope signatures with highly radiogenic strontium ($^{87}Sr/^{86}Sr_{337}$ = 0.7119–0.7133), lead ($^{206}Pb/^{204}Pb$ = 17.95–18.04, $^{208}Pb/^{204}Pb$ = 37.86–37.96) and unradiogenic neodymium (ε^{337}_{Nd} = −6.8 to −8.0) are typical.

The preferred tectonic scenario assumes an oceanic subduction transitioning to underthrusting of attenuated Saxothuringian crust beneath the rifted Gondwana margin (Teplá-Barrandian and Moldanubian domains) (Janoušek & Holub 2007; Schulmann et al. 2014). Deep burial of this mostly refractory felsic metaigneous material is evidenced by the abundance of felsic HP–HT granulites in the orogen's core and occurrence of detached UHP slices, mainly exhumed back through the subduction channel. Such a process inevitably brought about contamination of the local lithospheric mantle. Soon thereafter, these anomalous domains yielded ultrapotassic magmas whose major- and compatible-trace element signatures point to equilibration with mantle peridotite, whereas their incompatible-element contents and radiogenic isotope signatures are reminiscent of subducted continental crust.

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Age and provenance of metavolcano-sedimentary basins in the Sudetes, Poland and Czech Republic: LA-ICPMS U–Pb zircon geochronology

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Our new investigations show that the onset of a geological collage in the Sudetes dates back to the Neoproterozoic. In the Palaeozoic, several tectono-stratigraphic units were assembled, mainly with pronounced record of Variscan tectono-metamorphic events written in metasedimentary and metavolcanics rocks. Despite many studies, both number and age of pre-Variscan sedimentary basins and possible source areas for clastic deposits are still debated. New LA-ICP-MS U–Pb zircon dating was applied to specify: 1) the age and provenance of sedimentary successions in different tectono-stratigraphic units that form the Sudetes, 2) their relationships between them and with respect to Gondwana.

New zircon dating (~140 analytical points per metadetrital sample and ~50 points per metaigneous sample) show Cambrian or Cambrian-Ordovician maximum depositional age of metasedimentary units in the Izera-Karkonosze Massif (Szklarska Poręba and Stara Kamienica schists belts), Niemcza Shear Zone, Staré Město Belt, Góry Sowie Massif, Orlica-Śnieżnik Dome (Młynowiec-Stronie Group) and Kamieniec Belt (Kamieniec mica schists, Chałupki paragneisses). These units are accompanied by metaplutonic and associated with metavolcanic rocks with ~500 Ma protolith ages. In contrast, metavolcano-sedimentary successions in the southern part of the Kaczawa fold belt, Nové Město Belt, Zabřeh fold belt, Velké Vrbno Dome, Branná Belt and Desná Dome yielded Neoproterozoic maximum depositional ages. The Desná Dome also contained ~600–620 Ma old igneous rocks. The Velké Vrbno metasediments were also accompanied by Neoproterozoic mafic and felsic metavolcanics rocks and then by Lower Devonian mafic volcanites.

Detrital age spectra indicate that the clastic components of the studied pre-Variscan deposits were delivered by the erosion of rocks consolidated within the Cadomian-Avalonian orogenic belt. The studied rocks revealed source areas with predominantly Neoproterozoic (580–660 Ma) and Palaeoproterozoic (1.9–2.3 Ga) rocks. In addition, samples revealing Neoproteorozic protolith ages occasionally show a Mesoproteorozic zircon age spectrum (1.2–1.7 Ga). The latter ages are especially characteristic for the samples of Kaczawa fold belt and the Velké Vrbno Dome, and they are weekly observed in zircon data coming from paragneisses of the Desná Dome. Slight differences in the detrital age spectra can be taken as indication of some diversification between the source areas and can be translated into the creation of somewhat different Variscan terranes. The new U–Pb zircon data are consistent with the earlier U–Pb zircon studies (Jastrzębski et al. 2015) which suggested that the main terrane boundary in the Sudetes is located east of the Staré Město Belt and west of the Velké Vrbno Dome and at the surface coincided with the outcrop pattern of the Nýznerov Thrust.

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Post-Variscan tectonics of eastern part of the Bohemian Cretaceous Basin (Czechia)

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The goal of this contribution is to characterize tectonic features in a relation to the fluids in eastern part of the Bohemian Cretaceous Basin (BCB) situated in northern-central Czechia. Structural arrangement of eastern part of the BCB is traditionally explained as the system of the synclines and anticlines supplied by the faults (eg. Malkovský 1980, Herčík et al. 2003). The modern research of the basin tectonics frequently brings the results concerning on the role of interconnection of the fold tectonics and the fault tectonics in the frame of a conception of ramp geometry or the sense of transpressional tectonics (eg. Jones et al. 2004). Malkovský (1987) outlined the transpressional arrangement of eastern part of the BCB without direct evidences. Adamovič & Coubal (1999) introduced that tectonic style of the folds combined with reverse or possibly strike-slip faulting indicates that the formation of these structures resulted from an intensive, approx. NE-SW orientated compression.

The BCB is the largest sedimentary unit and the most prominent fluid (groundwater) reservoir in Czechia. The BCB represents shallow water seaway formed during global transgression and subsidence in the Cenomanian-Santonian (Uličný et al. 2009). Sedimentary infill of the BCB was concentrated between two main fault zones – the Lusatian Fault zone and the Elbe Fault zone s. s. included in the Elbe Fault system (Coubal et al. 2014). Tectonic features were recorded in a relationship to a formation of calcite veins in the area of the BCB. The processes connected with calcite crystallization e.g. growth stages, twins or entrapped inclusions are the most excellent reflecting of the tectonics.

The area of research associates nine geological sites in three fault zones documented by striated fault planes: the Jílovice Fault zone, the Semanín Fault zone and the Kyšperk Fault zone.

The researched methods include a construction of tectonograms both the fault planes and the striations, paleostress analysis, microthermometry, cathodoluminiscence, isotopes, analysis of joint sets and reflection seismic survey.

There were determinated thrust faults, reverse faults and strike-slip faults due to oblique or subhorizontal striation. Thrust or reverse faults were formed in the marlstones whereas the strike-slip faults in the sandstones. The distribution of maximal normal stress σ_1 appears in a concordance to continual joints in the direction esp. NW-SE, NE-SW, NNE-SSW, ENE-WSW and E-W. Fluid inclusions were entrapped under the pressures 23–67 MPa according to the line of isochore. This pressure is almost in a coincidence to the range of compressive strenght of the marlstones between 26–70 MPa (Gudmundsson 2011). The average temperature of homogenization was 80°C. Calcite crystallization was probably taken place during one tectonic phase without recrystallization. The origin of fluids was perhaps from the close vicinity. The reflection seismic profile shows positive “flower structure” in e. vicinity of the Semanín Fault zone. Shear fractures were related to the less competent layers built by the marlstones in contrast to the tension fractures developped in competent layers of calcacerous claystones. A combination of the direct evidences of thrust/reverse faults and strike-slip faults gives a conception of transpressional features as a basis of the tectonic conception of eastern part of the BCB. The rotation of bedding planes seems to be indirect evidence of the bending of the layers on the top of the ramp geometry.

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Geodynamic implications of continental red clays, bauxites on carbonatic substrate – the complex story of the Late Cenozoic Vöröstó Formation (Southern Bakony Mts., Hungary)

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The Vöröstó (= Red Lake) Formation is a red clayey-silty assemblage, mixed with up to fist-sized and well-rounded bauxite pebbles, covers locally the karstified surface of Triassic carbonates in the Southern Bakony Mountains, Carpathian-Pannonian Basin. This continental sediment was deposited in an extremely long-lasting apparent stratigraphic gap between the underlying Triassic carbonates / Miocene to Quarternary cover sequences, therefore the age of formation is uncertain. Based on borehole and geophysical data the Vöröstó Formation fills up to 30 m is the diameter and up to 100 m deep sinkholes and dolinas indicating, together with a characteristic oxidized red color, an elevated position before or during the time of accumulation. Weathering processes damaged most of the characteristic extraclasts and prevented the preservation of datable fossils. Due to these reasons, the determination of the exact origin and age of the Vöröstó Formation was challenging and controversial in the past decades (Budai et al. 1999). The formation and deposition of bauxitic continental sediments generally require a tectonically stable, warm and humid environment. They are composed of the mixture of weathered airborne/fluvially transported sediments and the insoluble remnants of the underlying carbonates (Bárdossy 1982). However, the presence of the coarse well-rounded bauxite pebbles in the Vöröstó Formation indicate a dramatic change in the tectonic settings of the area, an elevating hinterland and the appearance of fluvial erosional processes. This can be simultaneous or close to the time with the already well-determined Miocene tectonic events characterized by the development of large-scale fault systems (Fodor 1998). In this study, pebbles, rock fragments and the clayey matrix of the Vöröstó Formation were studied by sediment petrographic methods, x-ray powder diffraction (XRD), scanning electron microscopy (SEM), and X-ray fluorescence whole-rock geochemistry (XRF). Furthermore, heavy mineral composition and zircon single-grain U–Pb age distributions acquired from both the bauxite pebbles and the red clayey matrix separately. The coarse fraction of the Vöröstó Formation consists of well-rounded, mostly oolithic, hard bauxite pebbles, likewise hard, angular to subangular ferricrete fragments and dolomite clasts embedded in a clay-mineral rich matrix (kaolinite, illite, smectite) mixed with silt to fine-sand sized quartz grains and very rare altered feldspar grains. The heavy mineral suite of the pebbles and the matrix are markedly different. The matrix contains a variegated heavy mineral assemblage with staurolite, garnet, pyroxene, ilmenite and epidote being present besides the dominant ultrastable heavy minerals zircon, rutile, and tourmaline. The zircon U–Pb age spectra are composed of distinct components reflecting Ordovician, Variscan, Paleogene (40–27 Ma) and Middle Miocene (18–10 Ma) ages. In contrary, the bauxite pebbles are rather poor in heavy minerals and only contain the ultrastable species. The U–Pb age spectra of bauxite pebbles contain the same pre-Mesozoic age components, additional Triassic ages, while the Cenozoic ages are missing.

Based on their lithology, micromorphology, heavy mineral assemblage and the lack of young zircon ages the hard bauxite pebbles are considered to have been eroded from some of the older Cretaceous bauxite deposits of the Bakony Mts. A probably significant part of the matrix is derived by re-deposition and break down of debris from the Paleogene bauxite deposits, as they contain variegated extraclasts and characteristic, euhedral, volcanogenic zircons with Paleogene U–Pb ages.

We suggest an elevated hinterland supplying the Vöröstó Formation area to the north-northwest. The triggering mechanism can be the development of the Miocene fault systems (Fodor 1998), which should have been active during the interval based on the Miocene zircon ages and ended with the deposition of the Vöröstó Formation's freshwater limestone cover sequence indicating a low topography area. The presence of partly decomposed feldspar grains and the wide age range of Miocene zircons assumes that the continental red clay landscape in the Bakony accumulated air-born ashes during the entire period of the Carpathian-Pannonian Neogene volcanic activity. For more details about this project please check the already published results in Kelemen et al. (2017).

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Stress variation along the Carpathian profile in the light of well data

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Knowledge of the recent stress field is extremely important for understanding tectonics and reservoir management (Meixner et al. 2014). In recent years, as interest in unconventional reservoirs has increased, the construction of geomechanical models has become an indispensable element of the hydrocarbon exploration process. This results directly from the multiple use of such models in the wellbore stability analysis (selection of the appropriate drilling mud, stable trajectory, casing design), trajectory optimization from the viewpoint of possible intensification treatments, and stress analysis of fractures within the perspective intervals (Zoback 2007). The Mechanical Earth Models (MEM) describe the recent stress field and mechanical parameters of rocks for a given volume of the studied rock. MEM is composed of several parameters: pore pressure (P_p), vertical stress, the minimum horizontal stress (S_{hmin}), the maximum horizontal stress (S_{Hmax}), rock strength, friction coefficient (μ) and parameters describing the elastic properties (Young's modulus, Poisson's ratio). In the case of stress distribution, both the direction and magnitude of the principle stresses are important.

The key aim of the study is to present the recent stress variation in the Carpathian profile based on the created geomechanical models for two well locations. The stress field within Carpathians is still poorly researched what is a consequence of lack of direct indicator such as focal mechanisms due to negligible seismic activity (Balling 1992). Analyses of hydraulic fracturing of borehole walls shows that in the area of interest stress regime varies from strike-slip to reverse faulting regime (Jarosiński 2005) but the question about variation along the profile still persists.

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The paleothermal history of the Szaflary Beds (Podhale Basin, Poland) recorded in calcite veins and the maturity of organic matter

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The Lower Oligocene Szaflary Beds are the oldest strata of the Paleogene-Neogene flysch in the Podhale Basin. They comprise shales, medium-thick sandstones and conglomerates. These rocks crop out along the contact with the Pieniny Klippen Belt as well as in the Periklippen Flexure Zone in Poland (comp. Mastella 1975). The present study is focused on: (1) the mineralogical and microtectonic characterization of calcite veins filling joints (2) the recognition of the paleothermal structure of this area and (3) the relationship between calcite mineralization and structural records.

Joints are healed by blocky and drusy calcite. Quartz was noted rarely in the open veins that occurred in the eastern part of the studied area. Synkinematic fibrous calcite was found on the surfaces of some small-scale strike-slip faults as well as normal faults.

Cathodoluminescence studies revealed the occurrence of several generations of calcite filling joints. Calcite crystals are characterized by luminescence in orange, brown and yellow. Some veins contain mosaic crystals with a varying intensity of luminescence of bright and dark orange. This is probably related with cataclasis of the veins and subsequent recrystallization or new crystallization. There is also frequent calcite dissolution at the crystal boundaries. Calcite crystals are dominated by thin twins with high intensity, which indicate crystallization temperatures below 170°C (comp. Ferrill et al. 2004). Thick twins with low intensity related to higher temperature are seldom found. The presence of non-twinned crystals associated mainly with the last generation of calcite filling joints indicates a lower fluid temperature.

For veins $\delta^{13}C$ values range from –4.93‰ to 2.20‰$_{PDB}$. Values of $\delta^{13}C$ for synkinematic calcite collected from normal faults are in the range of –2.37‰ to 7.97‰$_{PDB}$. These points to a mixed source of CO_2 but, on the other hand, $\delta^{13}C$ values between –0.86‰ and 0.10‰$_{PDB}$ indicate one CO_2 source for calcite from strike-slip faults. The same values are noted for veins collected up to 300 m from the PKB boundary.

For veins and synkinematic calcite from strike-slip faults, values of $\delta^{18}O$ are in the range from –10.91‰ to –7.07‰$_{PDB}$ whereas for normal faults the range is narrower (–9.42‰ to –6.72‰$_{PDB}$). There is no systematic variation of $\delta^{18}O$ in the study area. Furthermore, in four exposures two groups of calcites were distinguished based on $\delta^{18}O$ differentiation. These values are about 2‰ higher for group (I) in comparison with group (II). This variation suggests different temperature or/and salinity of fluids. The crystallization of calcite (I) probably took place from water which had been more modified by digenetic processes than calcite (II).

In an exposure-by-exposure comparison, it seems that the isotopic composition of calcite from veins show more genetic similarity with calcite collected from strike-slip faults than from normal faults. The source of fluids responsible for mineralization was external, suggested by the bulk analysis of sandstone. For sandstones, the values of $\delta^{13}C$ vary from –2.84‰ to 0.71‰$_{PDB}$, while $\delta^{18}O$ vary from –9.86‰ to –5.62‰$_{PDB}$. Concavo-convex contacts of grains in the sandstones are common and they point to advanced chemical compaction.

Vitrinite reflectance studies of dispersed organic matter show only slight variations of the obtained results, from 0.46% to 0.70%. Based on formula of Barker & Pawlewicz (1994), paleotemperatures calculated for these values are 73°C and 107°C respectively. The lowest Ro values were recorded in the western part of the studied area whereas the highest was in the eastern part. However, apart from the extreme values mentioned, the paleotemperature affected rocks of the Szafary Beds did not show evident variation and their values are between 85–91°C. These values are in accordance with the low maturity of oil inclusions found in quartz. Oil migration is confirmed by higher reflectance of pyrobitumines (0.79–0.85%) than vitrinite (0.62–0.70%).

The presented results indicate that calcite mineralization has been a multistage process. Calcite crystallized from diagenetically modified waters which displayed different temperatures and/or salinity. Microtextures record multiple episodes of the cracking and opening of calcite veins. Based on isotopic analyses, it seems that the filling of joints occurred mainly in the tectonic regime of the strike-slip faults. The results provide evidence that the Szaflary Beds had a different thermal history than other parts of Podhale.

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Strength of sedimentary rocks near fault structures (Barrandian, Bohemian Massif)

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Within the framework of ongoing projects, a field determination of rock strength was used. The Schmidt hammer was used for measurement of the strength. That is mainly used in civil engineering (especially concrete study), but it can be also used for geological research. The equipment enables indirect detection of compressive strength by measuring scleroscopic strength (e.g., Aydin & Basu 2005). The ADA 225 device, equivalent to the Schmidt Hammer type N with a kinetic energy of 2,207 J, was used for the tests. This device can measure rock strength above 10 MPa. As the device is not used in a standardized manner and outside of the laboratory, the resulting values are not quantitatively accurate. However, the results can be relatively evaluated and monitored.

The aim of the experimental measurement was to determine variability of the strength transversely across significant fault-damage zones. To exclude the influence of degradation and weathering, the locations where the faults are encountered by underground adit were selected. The first one was the Clay Fault – a multiphase strike slip fault (Knížek & Melichar 2015). The data were taken in the "Wasserlauf" level of the Anna Mine in Příbram-Březové Hory mine district. The second one was the Očkov Fault – a thrust fault with flat-ramp-flat geometry (Melichar 2004). The data were obtained in the New Entrance Gallery in the Koněprusy Caves.

Data points were set at regular intervals on both sides of the fault, always at least every 1 m. The strength was studied in two directions – perpendicular and parallel with the bedding surface. At all data points, a set of up to 12–25 strength data was done by the Schmidt hammer. The data were averaged by arithmetic mean. Extreme values below 80% and over 120% percent of the first mean were excluded and, after that, corrected mean was counted. This corrected arithmetic mean was converted to the indicative strength value according to the Schmidt hammer nomogram. The values of strength are not in absolute scale but relations are more-or-less objective. Conversion of averaged strength data were verified by other published conversion algorithms.

The Clay Fault was studied over the entire length of the intersecting damage over 120 m length. The results show decrease of strength of the Cambrian sandstone with increasing strain towards the core of the fault (e.g., from south to north). The core of the fault is made up of a soft tectonic clay with a strength below 1 MPa, reflecting its last Neogene phase of activation. The mylonite rim formed during older Variscan phases of the fault activity showed relatively low strengths with values above 10 MPa. The strength gradually increased towards the north into less damaged Proterozoic shale (see Fig. 1A). The results of the measurements correspond to the reduced mechanical properties of the rocks (Cambrian sandstone and Proterozoic shale) depending on the strain intensity and distance from fault core respectively.

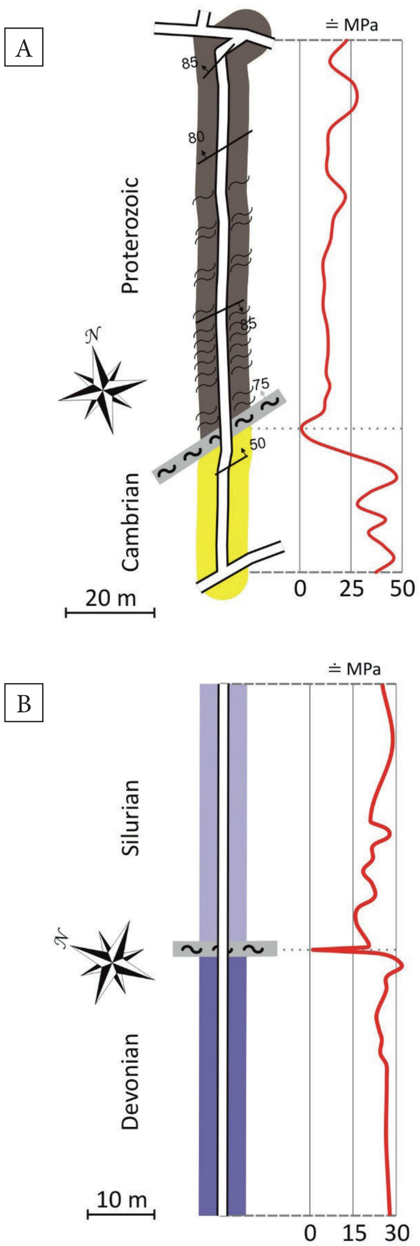

Fig. 1. *Distribution of the relative strength in the fault surroundings: A) Clay Fault; B) Očkov Fault*

The Očkov Fault is a thrust of Silurian limestones over the Devonian Suchomasty Limestone. The data points were arranged along a line with length of about 50 m and the core of the fault was approximately in the central part of the study profile. Comparing to the previous example, the results are not so significant, as the strain in limestones was realized by sliding along bedding discontinuities (see Fig. 1B).

As it was shown above, the method of scleroscopic analysis of rock strength is a very simple, effective and fast tool for rock damage study. It can give positive results in a geologically interesting environment. This simple tool can easily support interpretations not only of structural geology problems.

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Jurassic-earliest Cretaceous tectonic events in the Pieniny Klippen Belt (Polish and Ukrainian Carpathians) and their sedimentary record

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During the whole Mesozoic evolution of the northernmost part of the Western Tethys several tectonic events took place, which resulted in different kind of sedimentary records in the Western Carpathians. Good evidences of such events occur in the Pieniny Klippen Belt (PKB) (both in Polish and Ukrainian part), which are well documented by sedimentological features such as: synsedimentary breccias, neptunian dykes, hard grounds, ommission surfaces, condensed carbonates etc.

One of the first such tectono-sedimentary event has been connected with Toarcian-Aalenian episode of rift-related movements. In the Ukrainian part of the PKB (e.g., Priborzhavskoye quarry) the oldest Jurassic rocks consist of different type of clastic sediments of wide-spread Alpine *Gresten*-like facies (Early Sinemurian) which are overlying by pelagic spotty limestones and marls of *Fleckenkalk*/*Fleckenmergel*-type facies of oxygen-depleted environments (Sinemurian-Pliensbachian) (almost 30 m in thickness). Still younger are condensed limestones (uppermost Pliensbachian-Aalenian) with several omission surfaces, stromatolites, ferro-manganeous crusts and oncoids, and iron-rich ooids in some places, and small neptunian dykes as well. These features indicate the reduced sedimentation rate, and this very thin condensed limestones (maximum to 25 cm) indicate an important change in sedimentry regimes after thick sequence of pelagic limestones and marls. Just above appear the massive, thick (up to 50 m) Bajocian crinoidal limestones. The big contrast between pelagic sedimentation of spotty limestones and condensed deposits reflect an episode of initial extensional, rift-related regime, and episode of condensation could be correlated with uplift effect of tillted blocks originated during first step of rifting process, which is known as Devin rifting phase in the Western Carpathians.

The second tectonic event has been connected with origin of the Bajocian crinoidal limestones in the PKB. They are represented by three lithostratigraphical units (Smolegowa, Flaki and Krupianka Limestone formations), and constitute an important segment of the Middle Jurassic sequence in the so-called Czorsztyn, Niedzica and Czertezik successions. The onset of the crinoidal sedimentation, perfectly dated biostratigraphicaly by ammonites, took place during the late Hebridica Subchron of the Propinquans Chrone of late Early Bajocian and it was preceded by a marked stratigraphical hiatus, which covers the time interval of the Laeviuscula (may be even Discites) Chron and a bulk of the Propinquans Chron of the Early Bajocian. This hiatus corresponds to the origin and uplift of the Czorsztyn Ridge, which separated from this time the Magura Basin (on the NW side) and Pieniny Basin (on the SE side). The evidences of condensation event at the beginning of crinoidal limestones sedimentation are marked by numerous sedimentological features in the lowermost part (10–20 cm in thickness) of these limestones (e.g. phosphatic concretions concentration, pyrite concretions, large clasts of green micritic limestones and numerous rests of ammonites, belemnites and brachiopods as well). Occurrence of such important correlation horizon indicates primary thickness of investigated crinoidal limestones (from ca 10 m up to 100 m), and suggests origin of synsedimentary tectonic blocks and troughs, which influenced on their original, not recently tectonically reduced, differentiation of their thickness. Additionally, the rapid change of sedimentation from dark shales of oxygen-depleted environments (*Fleckenmergel*-type Skrzypny Shale Formation – Aalenian to earliest Bajocian) to overlying light crinoidal grainstones (Smolegowa and Flaki Limestone formations) corresponded to this Bajocian tectonic activity within Pieniny Klippen Basin (so-called Krasin tectonic phase) and corresponds very well with others Middle Jurassic Western Tethyan geodynamic reorganizations.

The third tectonic event within PKB is marked by the earliest Cretaceous (Berriasian-Calpionellopsis Chrone) synsedimentary breccia of the Walentowa Breccia Member of the Łysa Limestone Formation of the Czorsztyn Succession which is very widely distributed (from Polish sections up to Ukrainian part of the PKB – e.g., Veliky Kamenets quarry). This breccia is composed of pelagic limestones containing pinkish and creamy fragments of underlying beds (so-called *Calpionella* limestones – both Korowa and Sobótka Limestone members of the Dursztyn Limestone Formation). Sedimentation of this breccia coincides very well with shallowing-upward movements of the whole Czorsztyn Ridge, including Czorsztyn and Niedzica successions. In the same time in the Inner Carpathians, both sedimentological and age equivalent of the Walentowa Breccia Member occur – so-called Nozdrovice Breccia, as tectonically controlled resedimentation event which produced synsedimentary breccias along submarine scarps distinguished important tectonic phase – Walentowa Phase – during Early Cretaceous evolution of the Western Tethys realm. Simultaneously, in the Ukrainian part of the PKB and within the so-called Kaminnyi Potik Unit (Rakhiv vicinity and the Chyvchynian Mountains) volcano-sedimentary complex occur and is represented by: basalts (basaltic pillow lavas including), volcanic breccias of debris-flows with blocks of the limestones, basalts, within volcanic/tuffitic matrix, peperites and coarse/fine-grained calcareous pyroclastic turbidites ("pyroclastic flysch"). These associations were formed in the earliest Cretaceous (Berriasian) times as calpionellid data indicate. From geodynamical point of view, mentioned above volcanogenic-sedimentary unit is small part of the Severin-Moldavidic Basin developed within the North European Platform as rift and/or back-arc basin. Generally, it was wider effect of the Pangea break-up and origin of the Alpine Tethys, which constitutes important paleogeographic elements of the future Outer Carpathians, developed as an oceanic basin during Jurassic-earliest Cretaceous time.

Retention versus overprint of deformation microstructures in quartzo-feldspathic rocks during polyphase deformation in the Erzgebirge Mountains

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The aim of this study is to characterize deformation microstructures related to distinct deformation fabrics in orthogneisses of the central part of the Erzgebirge Mountains and assess the possible retention of microstructures during the polyphase deformation. The studied area was previously interpreted as a large-scale nappe stack, however our recent investigation revealed a sequence of deformation overprints which comply with the observed microstructural differences and their spatial distribution.

Erzgebirge is composed of mainly Proterozoic and early Paleozoic rocks including various types of orthogneiss, garnetiferous micaschist, quartzite and phyllite. Based on our structural investigation of the studied area, we identified three main deformation fabrics. i) S1 is defined by shape preferred orientation of quartz aggregates intercalating with feldspar porphyroclasts and it is well preserved in the eastern part of the studied area and in relics elsewhere. This deformation fabric of originally steep orientation is isoclinally folded and transposed to, ii) gently NNW- or SSE -dipping S2 fabrics, defined by well-developed monomineralic bands. S2 foliation bears subhorizontal east-west trending stretching and/or intersection lineation associated with relics of cm-scale quartz isoclinal folds. Due to the intense overprint of S1 by S2, both fabrics are subparallel and generally subhorizontal in studied samples. iii) S3 fabrics are represented by ENE-WSW trending discrete/crenulation cleavage with subhorizontal crenulation lineation. Four different microstructural types I–IV associated with subhorizontal S1/S2 fabrics were identified in the orthogneisses of the studied area. Type I is defined as relatively coarse-grained microstructure containing porphyroclasts of K-feldspar with mostly idiomorphic shape. Type II is characterized by recrystallized plagioclase forming aggregates with polygonal grains, elongated recrystallized quartz aggregates with amoeboidal grain shapes and relics of K-feldspar porhyroclasts. Type III shows recrystallized monomineralic bands of quartz and K-feldspar intercalating with bands of mixed plagioclase, quartz and K-feldspar matrix. Type IV microstructure is characterized by elongated recrystallized quartz aggregates, thin bands of recrystallized K-feldspar with locally preserved small relics of K-feldspar porphyroclasts. The matrix consists of mixed K-feldspar and plagioclase.

Quantitative microstructural and texture analysis revealed further differences among the microstructural types I–IV, constrained namely by differences in grain size of dynamically recrystallized quartz and in activity of quartz slip systems. Type I and II reveal coarse grained quartz microstructure with median grain size of 129–208 microns and dominance of prism<a> slip system. In contrast, Type III and IV show fine grained quartz microstructure with median grain size of 77–98 microns. The analysis of crystallographic preferred orientation in Type III and IV quartz microstructures shows combination of prism/rhomb/basal<a> slip systems. Single girdle distribution of quartz c-axes locally shows the cleft girdle distribution suggesting constrictional symmetry of strain.

The spatial distribution of described microstructural types I–IV does not comply with the spatial occurrence of the previously recognized nappes. The quantitative microstructural and texture analyses of dynamically recrystallized quartz allowed us to separate two microstructural groups covering types I–II and types III–IV. These two groups are interpreted to correspond to the two main deformation fabrics S1 and S2, respectively. The constrictional symmetry of deformation observed in Type III microstructures can thus be related to the overprint of S1 by S2. At the same time, the difference between Types I and II, and between Types III and IV is interpreted as a difference in finite strain intensity during formation of S1 and S2 fabrics, respectively.

Investigation of the lithospheric density stratification by modeling of the geoid shape in the area of European Plate

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The paper summarizes results of the geoid undulations modelling for the European Plate by use of topographic and Moho data. Two models assuming linear density stratification in the lithosphere (constant contrast model CCM, constant gradient model CGM) and isostatic balance of the lithosphere were used for calculating the undulation in the flat layer approximation. The results show that the constant contrast model (CCM) can describe the entire oceanic lithosphere, as it indicates the amplitude of thermal density change, which is in very good agreement with the cooling plate model estimation. The constant gradient model (CGM) gives reliable estimations of the lithosphere properties only in smaller geoprovinces of relatively uniform structural properties like the Interior of the East European Craton. For continental and oceanic regions, the resulting values of the density gradient have some average meaning and they are in interpretable correspondence with characteristic mantle heat flow. In the entire area, both models show strong confusion giving not intermediate and unrealistic lithosphere characterization, which is a result of essential differences of thermal constitution, differences in average crustal density and mineral differences of the lower lithosphere, occurring between the two major tectonic provinces (oceanic and continental). The convention of equivalent linear reduction was discussed extensively and applied as an adequate method of lithosphere thickness estimation. This approach leads to thickness determination like other methods (seismic, petrological and thermal). The two concepts allow for the construction of LAB (transitional zone between the lithosphere and asthenosphere) depth maps from topographic and Moho data (Fig. 1).

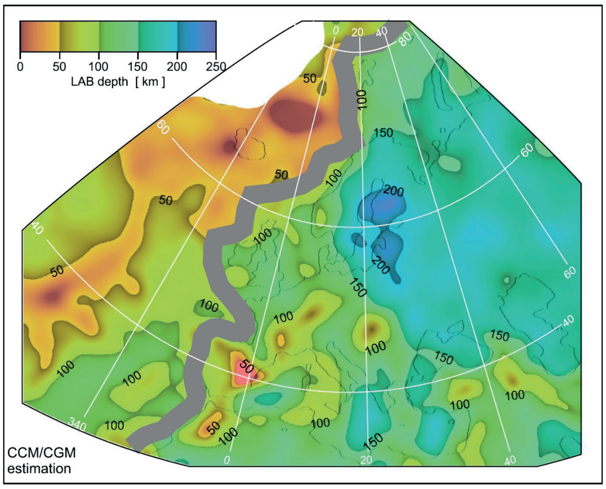

Fig. 1. Lithosphere-asthenosphere boundary (LAB) depth map derived as a combination of LAB using the oceanic part from CCM and continental part from CGM, and the thick grey line indicates the continent-ocean transition (COT)

Crustal-scale detachment/diapiric folding driven by the indentation in hot orogens-insights from analogue experiments investigated by PIV (particle image velocimetry) method

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The indentation deformation of partially molten crust, typical for thickened hot orogenic domains, cause significant material transfers within both solid and partially molten crust. The crustal flow is commonly driven by transient pressure gradients developed during indentation, by folding of competent crustal layers or due to Rayleigh-Taylor instability developed in the thickened crust. The most advanced techniques for prediction of the material transfer in such a system are methods of numerical and analogue modelling.

In our study, we used the particle image velocimetry (PIV) to trace the material transfer within complex analogue models of crustal-scale detachment/diapiric folding above a weak anatectic layer. These models have been set up to simulate the detachment folding, the mechanism proposed to be responsible for the formation of the Eastern Pyrenees, Chandman dome in Mongolian Altai or the high-grade domes in Chinese Altai mountain range. We applied the PIV method and derived dynamical parameters based on the velocity field, such as divergence, velocity components, flow azimuth, strain-rate or vorticity. Results reveal dynamic feedbacks between the ductile flow and topography evolution as well as the deformation of ductile lithospheric layers.

In crustal scale detachment/diapiric folding experiments, we used divergence as a proxy for redistribution rate of the molten material along the mantle-crust interface as well as for transfer of melt into the cores of amplifying fold domes. Negative anomalies of divergence field represent zones of melt inflow parallel with the fold limbs and accumulation zones beneath the hinges of detachment folds. These anomalies are balanced with positive values of divergence field that are situated below the folds in the source layer of partially molten material. The time evolution of divergence is related to the amount of melt as measured from the side-view photographs of progressively evolving models. Difference between detachment style folding and diapiric-like exhumation is driven by time-evolution of rheological parameters and heat distribution in the visco-elasto-plastic middle to lower crust. For investigation of fold dynamics, we studied vorticity of the molten material inside fold core and traced markers in the plastic layer. Tortuosity (ratio of the relative and absolute path of the material element) was used to compare elevation of both fold limbs.

We correlated the divergence, melt volume and tortuosity with strain-rate to demonstrate the polyphase evolution of fold development. The three major stages have been identified: 1) initial slow amplification of the multilayer and coalescence of melt below the hinge zones, 2) rapid amplification and vertical redistribution of melt along the axial zones of the folds, 3) vertical extrusion of the weak hinge domain along steep limbs during further horizontal compression of the locked-up folds. Our results clearly demonstrate advantages and the potential of the photogrammetric methods for post-processing of geodynamic and tectonic analogue models.

Structure and Miocene evolution of the Carpathian orogenic front in Poland – an overview

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The Carpathian orogenic belt consists of three main tectonostratigraphic domains: the Inner Carpathians, the Pieniny Klippen Belt and the Outer Carpathians that were subjected to several shortening and subduction events since the Late Jurassic. The Outer Carpathians in Poland form thin-skinned thrust-and-fold belt composed of several thrust sheets built mostly of the Cretaceous – Paleogene deepwater flysch sediments. To the North it is flanked by the Carpathian foredeep basin filled with predominantly clastic sediments, with important Upper Badenian evaporitic horizons (cf. Oszczypko et al. 2006). Miocene foredeep deposits are presently located both in autochthonous position, either beneath or in front of the Carpathians, or in allochthonous position within the frontal zone of the orogenic wedge (Zgłobice and Stebnik thrust sheets). Foreland (lower) plate of the Polish Carpathians is built of two distinctly different basement units: the East European Craton and the West European Platform that are divided by the Teisseyre–Tornquist Zone that focused intense tectonic movements through the Paleozoic and Mesozoic. The pre-Miocene substratum is inhomogeneous and comprises Cretaceous, Jurassic, Triassic, Permian, Carboniferous, Devonian and Lower Paleozoic rocks, erosionally truncated at various levels and overlying intensely folded and low-grade metamorphosed Neoproterozoic to Early Cambrian and/or medium-grade metamorphosed Proterozoic crystalline rocks. Geological and geophysical data from the area between Kraków and Przemyśl reveal significant along-strike variations in tectonic style of the Carpathian orogenic front that was controlled by two main factors: (1) structure of the foreland plate, and (2) extent of the Upper Badenian evaporites.

In the central part of the Carpathians, in the area between Kraków and Pilzno – Dębica, fairly broad (up. to 10 km) zone of deformed foredeep deposits developed within the Carpathian front. Seismic data allowed for identification of triangle zones and related deformations in this area, characteristic for wedge tectonics (Fig. 1A; Krzywiec & Verges 2007, Krzywiec et al. 2014). Wedge tectonics resulted from a combined effect of the diverse erosional topography of the pre-Miocene basement top surface and of the areal extent and lithological changes (salt → gypsum → anhydrite) of the foredeep evaporites occurring near the base of the foredeep sedimentary infill. The frontal roof backthrust of the triangle zone is overlain by a foreland-dipping frontal monocline, in places disturbed by detachment folds. Some of the tectonic structures inferred in this unit were classified as syn-depositional, coeval with sedimentation of the upper portion of the post-evaporitic siliciclastic foredeep succession. Similar model of wedge tectonics and the triangle zone could be applied for the famous Wieliczka salt mine located within the deformed Miocene rock salt near Krakow. In this area no seismic data are available to testify this concept; however, geological cross-sections presented in previous decades based on mine, outcrop and well data (e.g. Tołwiński 1956) clearly resemble triangular geometry associated with wedge tectonics. According to this interpretation, the Wieliczka salt mine would be located in the axial part of the Miocene triangle zone. Backthrusting of the Upper Badenian-Sarmatian foredeep infill above the evaporites could also be observed at the front of the so-called Gdów tectonic embayment. In this area, numerous wells and seismic data show that thrusting involved also Mesozoic succession of the lower plate. Pre-Miocene substratum of the central Polish Carpathians and their foredeep basin shows only very minor and localised normal faulting related to flexural extension, and its present-day morphology is related primarily to intense Palaeogene localized erosion and incision. Small degree of observed basement reactivation is related to orientation of main basement fault zones – they dip to the NE while compressional stresses generated within the Carpathian collision zone were acting generally S – N, hence hangingwalls of the basement fault zones have not undergo any major reactivation.

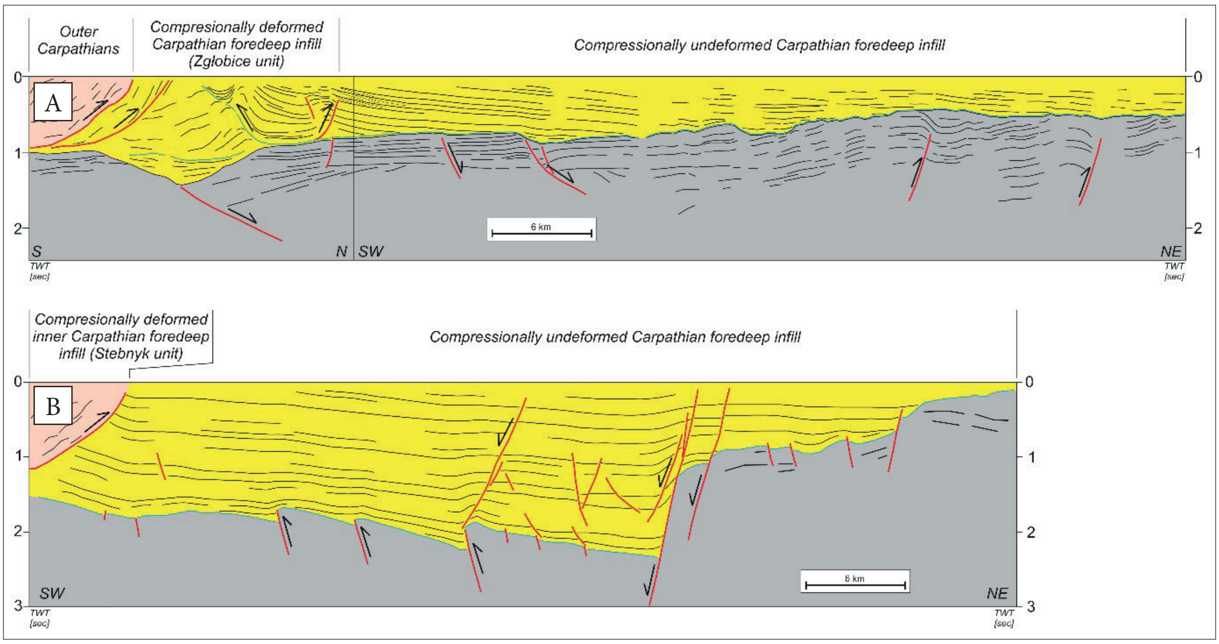

__Fig. 1.__ Interpreted regional seismic profiles from the central (A) and eastern (B) Polish Carpathian foredeep basin. Vertical scale in time, approx. 3–4× vertical exaggeration

In the Eastern segment of the frontal Polish Carpathians and their foredeep basin, superimposed on the Teisseyre–Tornquist Zone, orogenic front shows fairly simple structure, defined by the major frontal foreland-verging thrust that overlies compressionally undeformed Miocene foredeep deposits. Locally, Miocene deposits could be found above the Carpathian thrust sheets that were related to the late / post-kinematic deposition above the thrust front. (e.g. Rzeszów embayment). The basement of the eastern part of the foredeep basin is characterized by a complex system of normal and reverse faults, with throws up to several hundreds of meters or more (Fig. 1B). These faults are older inherited tectonic discontinuities that were reactivated due to the combined effect of the flexural extension of the foreland (lower) plate and compression generated within the continental collision zone. Activity of some of these fault zones included important strike-slip component. Combined effect of significant foreland normal faulting and intense foredeep sedimentation resulted in very minor foreland displacement of the orogenic thrust front during the final stages of emplacement of the Carpathian thrust belt.

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Variscan (late Carboniferous) tectonics of the SE Lublin Basin

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In the last few years several high-quality reflection seismic surveys, including deep seismic profiles POLCRUST-01 (Narkiewicz et al. 2015) and PolandSPAN (Krzywiec et al. 2017a, 2017b; Fig. 1), were acquired in SE Poland, across the Teisseyre-Tornquist Zone, major tectonic boundary that separates the East European Craton (EEC) from the Palaeozoic Platform. All this data provided new information on structure and evolution of two major Paleozoic units: the Radom-Kraśnik Block, a NW-SE elongated structural high where strongly deformed early Paleozoic to Devonian strata subcrop beneath the Permo-Mesozoic cover, and the Lublin Basin, a major Paleozoic sedimentary basin developed above the SW slope of the EEC that corresponds to a SE-trending structural depression marked by occurrence of the Carboniferous strata at the base-Permo-Mesozoic subcrop. Two different structural models have been offered so far based on this newly acquired seismic data. According to model by Narkiewicz et al. (2015), based on POLCRUST-01 profile, subvertical faults cutting the Ediacaran-Palaeozoic sedimentary cover up to the base-Mesozoic unconformity characterize the Radom-Kraśnik Block and the Lublin Basin. However, as it has been recently shown by Krzywiec et al. (2017a), those faults should be re-interpreted as thin-skinned thrusts, detached above the crystalline Precambrian basement (see also Antonowicz et al. 2003). Paper by Krzywiec et al. (2017a) was primarily focused on structural model of the Radom-Kraśnik Block, but results of reinterpretation of POLCRUST-01 profile supported by numerous other 2D and 3D seismic data prove that also SE segment of the Lublin Basin is characterized by thin-skinned thrust tectonics, with major detachment related to Silurian shales (cf. Krzywiec et al. 2017b). Compressional structures, identified within the Lublin Basin and interpreted as the most frontal zone of the Variscan fold-and-thrust belt developed above the SW edge of the East European Craton, continue farther towards the SE, into W Ukraine and Lviv Basin (cf. Khizhnyakov & Żelichowski 1974).

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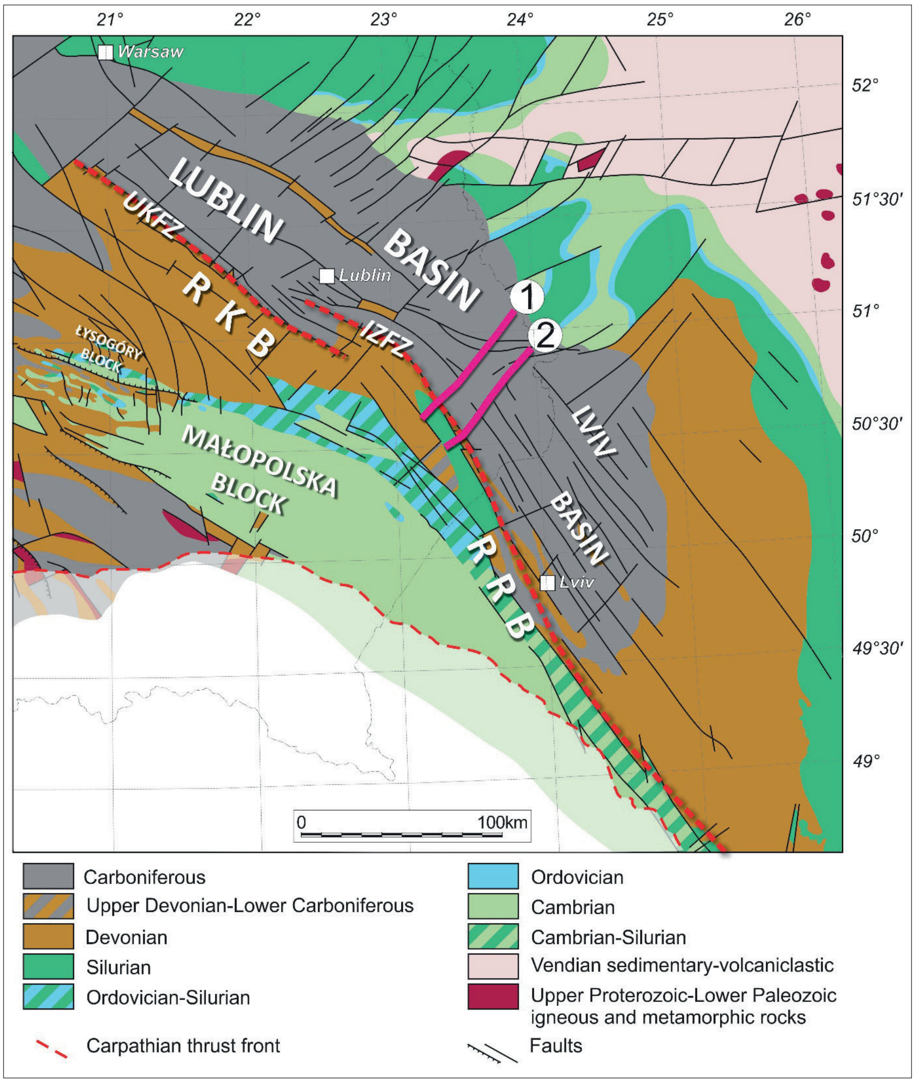

Fig. 1. *Geological map without Permo-Mesozoic of SE Poland and W Ukraine (from Krzywiec et al. 2017a): RKB – Radom-Kraśnik Block, RRB – Rava Russkaya Block, HCM – Holy Cross Mountains, UKFZ – Ursynów-Kazimierz Fault Zone, IZFZ – Izbica-Zamość Fault Zone (its continuation in western Ukraine was shown after Khizhnyakov & Żelichowski 1974); 1 – NE part of POLCRUST-01 seismic profile, 2 – NE part of PolandSPAN® seismic profile*

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Late Paleozoic fracture system in the Lublin Basin: results of seismic attribute analysis and fracture modeling

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The aim of the study was to compare the fracture system derived from volumetric attribute analysis carried out for the intra-Ordovician and intra-Carboniferous using 3D seismic cube. This pattern was subsequently compared to the fracture orientations derived from 3D balanced structural model (Fig. 1). The research area is located in NE part of the Lublin Basin, to the south east from the Kock Fault Zone. The main Paleozoic tectonic events included late Devonian thick-skinned faulting and late Carboniferous thin-skinned folding and thrusting (Krzywiec et al. 2017). Modelled fracture sets correlate well with those derived from volumetric seismic attribute analysis, although significant scatter in strike is observed (Fig. 1). Precise identification of particular fracture sets requires inspection of borehole image logs or core. Acknowledgment: This study was benefited from the BlueGas GASŁUPSEJSM research project funded by NCBiR. MOVE® software, provided by Midland Valley, was used for cross-section restoration and balancing, 3D seismic data were kindly provided by the Orlen Upstream.

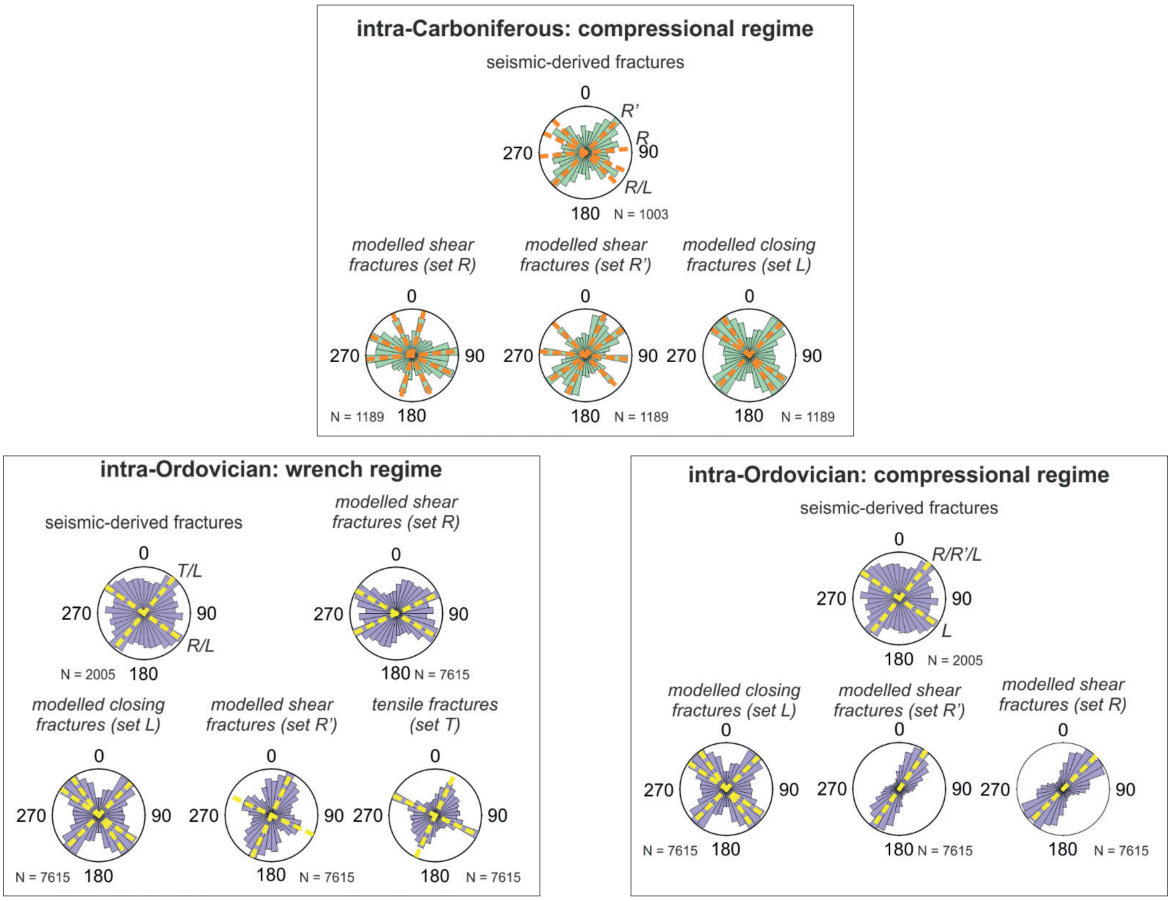

Fig. 1. *Rose diagrams showing main trends for seismic-derived and modelled fracture sets for intra-Carboniferous and intra-Ordovician horizons*

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Subseismic-scale fracture system in Carboniferous strata of the Lublin Basin (Poland): results of seismic enhancement and interpretation

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Modern techniques of seismic data post-processing and attribute analysis allows for tracking sub-seismic scale features such as small-scale faults. Enhanced seismic cube acquired in late 90s in SE part of the Lublin Basin was processed and interpreted in order to analyse geometry of first-order structures and determine sub-seismic fractures developed within the Carboniferous succession.

The Lublin Basin, a structural unit encroaching SW edge of the East European Craton, underwent two major tectonic events: late Devonian basement-rooted reverse faulting and late Carboniferous thin-skinned folding and thrusting. The folds analysed in this study were detached in Silurian fine-grained rocks. Minor thrusts developed due to room problems during bending of stiff Devonian-Carboniferous strata.

Post-stack seismic data conditioning techniques, including the dip-steering and structurally oriented filtering, were applied in order to suppress random noise and to enhance fault detection within the seismic cube. Fault & fractures likelihood seismic attribute volumes derived from the enhanced seismic data were used for the 3D interpretation of the subseismic-scale fracture system in Carboniferous strata.

The fractures derived from the intra-Carboniferous horizon slice show predominantly NE-SW strike, running parallel to the regional thin-skinned structures (Fig. 1). This may suggest their opening coeval with basin inversion.

This study was completed within the BlueGas GAZGEOLMOD research project co-funded by NCBiR. dGB Earth Sciences B.V. is acknowledged for the OpendTect software for seismic data conditioning and attribute analysis. 3D seismic data were kindly provided by the Polish Oil and Gas Company (PGNiG).

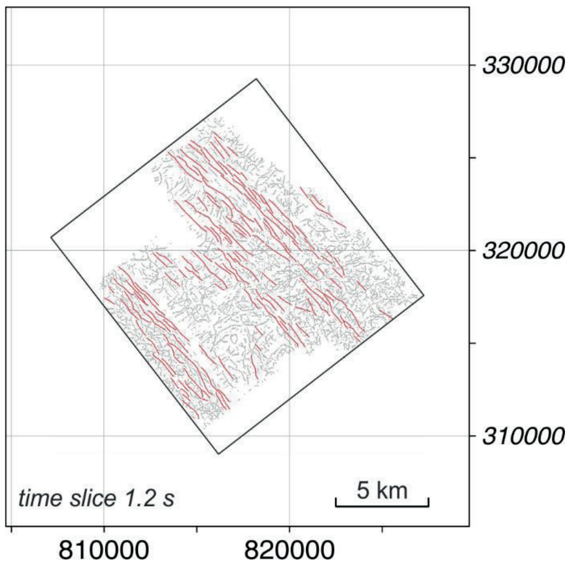

***Fig. 1.** Time slice for the Fault Likelihood volumetric attribute showing straight, long NW-trending fractures*

The Orava Basin inversion in a tectono-sedimentary analysis using anisotropy of magnetic susceptibility

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The present-day Orava Basin straddles across the Inner/Outer Carpathians border. It overlies the neoalpine consolidated basement comprised mainly of the Magura Unit, as well as the Pieniny Klippen Belt (PKB) and Podhale Synclinorium (Fig. 1). The Orava Basin originated in the Middle/Late Miocene (Wysocka et al. in press) and were filled with terrestrial siliciclastic deposits derived predominantly from surrounding uplifted and eroded basement. Around 1 km-thick sedimentary succession, from Neogene up to Quaternary, documents the structural evolution of older structural units during the youngest stage of the Carpathian history corresponding to significant strike-slip tectonics and large blocks uplift (e.g. Tatra Mts.). This study unravels the present-day structural framework of the basin showing the tectonic inversion of its southern part and local aspects of basin tectonics.

This study was based on a few combined methods: field sedimentological and structural analysis, along with laboratory measurements of anisotropy of magnetic susceptibility (AMS). The latter method provided data on possible tectonic deformation directions and the degree of deformation, especially useful in weakly deformed sediments lacking any macroscopic structures.

In case of common massive structure of deposits, the AMS method was used for estimation of bedding orientation and supported the interpretation of sedimentary facies. Prior to the whole basin analysis various AMS fabrics in different types of lithofacies were first established in the case study of the Oravica River section (Łoziński et al. 2015, 2016).

The AMS measurements showed that the whole southern part of the basin underwent considerable tectonic deformation. The general NNE-trending direction of strongest compression, inferred from AMS ellipsoid orientations, was presumably responsible for faulting, fracturing and uplift of this part of the basin. Sedimentary facies revealed band-like configuration along the southern margin. The southernmost deposits, being likely the oldest part of the basin infilling, represent fine-clastics typical for sedimentation far from depression margins, accompanied by tuffite deposition (e.g. Wysocka et al. in press) and abundant organic matter accumulation. Towards the north, deposits become mostly siliciclastic and monotonous. This scheme was interpreted as a result of gradual uplift and erosion exposing deposits from older to younger towards the north. The extent of the inversion of this basin part was restricted in the north by Chochołów-Chyżne-Bobrov-Vavrečka line.

In turn, deposits in the northern area of the basin are predominantly undeformed. This area had a tendency for subsidence, apart from strictly marginal parts where deformations were also noted. These observations suggested that the present-day Orava Basin may have a form similar to a fault-bounded half-graben resulted from the partial inversion and tilting of the former basin which could have had a larger extent, especially towards the south (what was already suggested by e.g. Baumgart-Kotarba 1996, Tokarski et al. 2012, Łoziński et al. 2015).

The detailed studies allowed for identification of a few locally strongly deformed zones, based on either strongly tilted to vertical bedding or deformational AMS fabrics. Zones are located along the southern margin of the present-day basin (Nové Ústie, Kovalinec and Wojcieszacki zones), as well as in central part (Bobrov-Jelešňa and Červený zones). The strike of vertical bedding within the outcrop between Orava lake and Bobrov village followed the straight line of Jelešňa valley, showing that this lineament in terrain morphology had a tectonic origin. Also, the probable location of the Pieniny Klippen Belt (PKB) under the basin infilling seemed to be followed by the valley of Červený stream, where vertical bedding occurred along with strong AMS fabric disturbance. This points to the Neogene/Quaternary tectonic activity of PKB, probably being a preferred zone for uplift or strike-slip movement accommodation.

According to the obtained NNE-trending compression, similar to present-day thin-skinned lithospheric stress, the basin deformation and inversion could have occurred as a result of ALCAPA unit northward movement.

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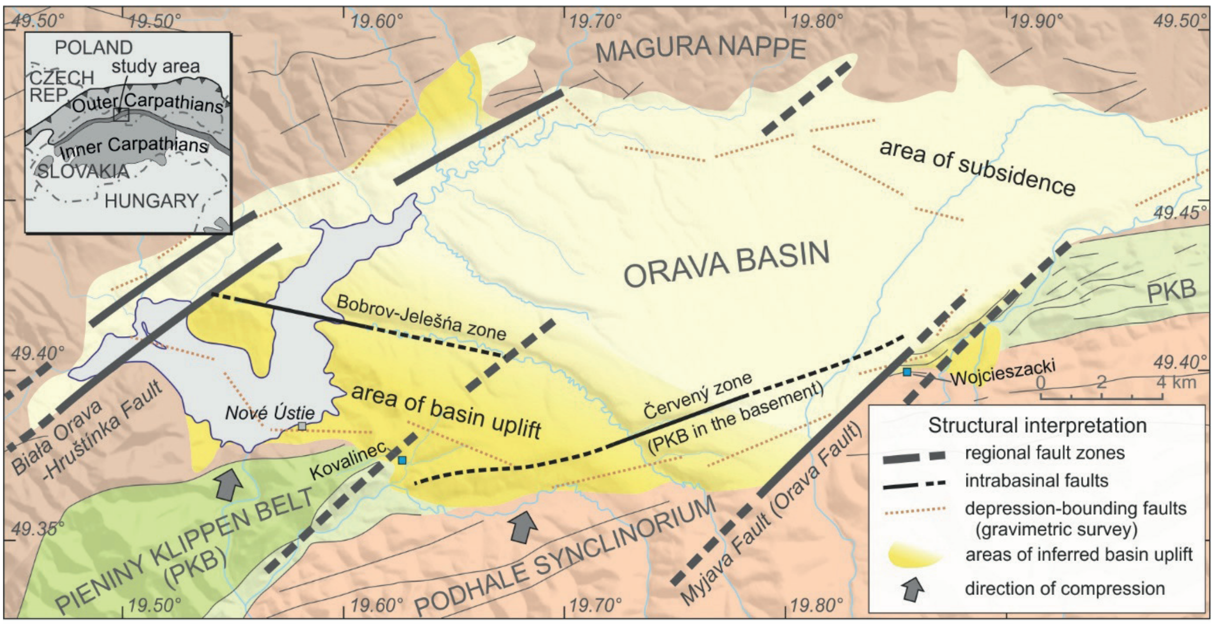

***Fig. 1.** Structural interpretation of the Orava Basin in the present-day shape of fault-bounded depression filled with partially uplifted Neogene deposits (after Łoziński et al. 2017, modified; gravimetric survey after Pomianowski 2003)*

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Thick-skinned deformation in Variscan fold and thrust belt: an evidence from Brunovistulian terrane

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The eastern margin of Bohemian Massif is well exposed part of Variscan Orogenic Front, where the detail structural relations can be studied. The megastructures of the area are results of collision between Brunovistulian terrane and a rest the of Bohemian Massif (Fig. 1A). This work is focussed on processes and structures in the lower block (e.g. Brunovistlicum).

Structural analysis supported by anisotropy of magnetic susceptibility analysis reveals same Variscan deformational origin for mesoscopic and magnetic fabrics in Brno Massif – the biggest uncovered area of Brunovistulicum. The rock fabrics are flexing from NNE-SSW striking and steep western dipping on the north to NW-SE striking with NE dipping on the south. Similar changes in direction is apparent as well in lithological zoning of Brno Massif rocks suggesting a regional fold (Fig. 1B).

Fold axis is slightly plunging to the north enabling profile construction using the down plunge method. Overthrusted fold limb consists of repeated simple sheared thrust sheets with increasing intensity of deformation to the north originated in dextral transpresional regime. These facts lead to a conlusion that there is a large-scale fold as a product of late Variscan deformation developed together with Moldanubian Thrust. This regional structure shows a propagation of orogene to its foreland incorporating the lower block to a megastructure similar to the fabrics in recent orogenes. Proving the same mechanisms and intensity of deformation in Variscan and Alpine orogenes allows the application of known fabrics from current orogenes to the older ones.

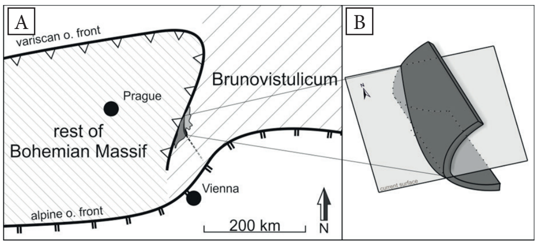

Fig. 1. *Situation of Brno Massif in Central European Variscides. Dashed line is positive magnetic anomaly (continuation of basic rocks of Brno Massif under younger cover) (A). 3-D model of Brunovistulian block (B)*

In search of relics of pre-Variscan oceanic crust: a geochemical signature of the Leszczyniec unit, Sudetes, revisited

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The overall goal of our research is to find out whether the Leszczyniec Unit is a fragment of lower Palaeozoic oceanic crust preserved in the suture between the Saxothuringian and Teplá-Barrandian terranes in the Sudetes. The oceanic affinity of the Leszczyniec unit was suggested by several geochemical studies based on whole rock geochemistry and the presence of the Paczyn Gneiss, a trondhjemite-type rock variety

(Szałamacha & Szałamacha 1991, Narębski et al. 1986). However, radiometric dating of the Leszczyniec Unit (Oliver et al. 1993) yielded the latest Cambrian age typical of rift-related, Cambro-Ordovician volcano-sedimentary and igneous suites that are widely distributed in the Variscan belt. Therefore, an alternative hypothesis is possible linking the protolith of the Leszczyniec Unit with mafic lower crust – a product of syn-rift underplating. The Staré Město Belt (Štípská et al. 2001) and Mariánské Lázně Complex (Štědrá et al. 2002) can provide appropriate regional analogues. Therefore, our study aims at testing and discrimination between two working hypotheses, oceanic crust versus mafic lower crust, for the Leszczyniec Unit, the distinction having an important significance for the European Variscides.

In general, the Karkonosze-Izera Massif is interpreted as a stack of tectonic units assembled by Variscan thrusting during collision between the Saxothuringian and Teplá-Barrandian terranes (e.g. Mazur & Aleksandrowski 2001, Jeřábek et al. 2016). The collision was a consequence of the closure of the Saxothuringian Ocean, possibly representing a branch of the Rheic Ocean, due to a subduction system developed along its eastern termination and operating beneath the Teplá–Barrandian upper plate. The nappe structure of the Karkonosze-Izera Massif recorded continuous subduction and underplating of imbricated thrust sheets, derived from the Saxothuringian lower plate, to the base of the upper plate that has been interpreted as a northern prolongation of the Teplá-Barrandian domain (Mazur & Aleksandrowski 2001, Jeřábek et al. 2016). Only the affinity of the uppermost allochthon, corresponding to the Leszczyniec Unit, remains uncertain. It may represent a vestige of the Saxothuringian Ocean or a slice of the Teplá-Barrandian upper plate.

The Leszczyniec Unit is represented by a differentiated suite of mafic and felsic rocks of volcanic and plutonic origin. Fine-grained schistose and medium-grained massive Leszczyniec metabasites include several large sill-like bodies of the Paczyn Gneiss. The latter comprises a wide range of rock types from felsic to hornblende-bearing gneisses (Kryza et al. 1995) derived from metagranites and metadiorites, respectively. The overall geochemical characteristics points to N-type MORB affinities of the Leszczyniec metaigneous complex (Kryza et al. 1995, Winchester et al. 1995). It is only the metadiorites that are reminiscent of island-arc lavas (Narębski et al. 1986) or, alternatively, have formed through crustal contamination of rift-related magmas (Kryza et al. 1995, Winchester et al. 1995). It is hypothesized (Kryza et al. 1995) that the Leszczyniec complex was emplaced in an extensional rift setting, though the observed large proportion of felsic rocks seems to preclude a mature oceanic rift.

We aim at compiling a set of indicative features allowing the distinction between metamorphosed relics of oceanic crust, missing a typical ophiolite succession, and fragments of mafic lower crust emplaced by underplating and then exhumed in collisional zones. To achieve this goal, we employ a number of geochemical methods including ICP-MS bulk chemistry analyses of major and trace elements. Preliminary results reveal two different primary suites of the Leszczyniec Unit metaigneous rocks based mainly on a distribution of Y in comparison with trace elements, like La and Nb. Two different magma sources seem to be observed also in the rocks diversity. The first suite is composed mainly of the fine-grained metabasites, which indicate N-MORB as a probable source, and metafelsic rocks, whose signatures partially display anomalies suggesting possible accumulation or crustal contamination. The second suite is represented by the hornblende-rich Paczyn Gneisses. Their samples show fairly flat, depleted and uneven REE patterns, relatively enriched in LREE. Strong depletion of Nb and Ta, as well as Zr and Hf is visible. Accordingly, the partial melting of the continental crust is a believable factor. These rocks might be considered reminiscent of island-arc lavas but their origin by crustal contamination of rift-related magmas seems also plausible.

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Structure from motion (SfM) for virtual 3D outcrop modelling and fracture corridors detection on case of SW Poland granitoids.

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Problem of fracture network, fracture corridors and fault zone spatial distribution and internal structure was discussed by many authors e.g. (Hausegger & Kurz 2013, Barani et al. 2014, Bisdom et al. 2014, Cilona et al. 2016) for structural analysis and fluid flow in fractured reservoirs. Our work is trying to fit into research trend presented by above authors.

The Lower Silesian granitoide massifs have potential to be fractured reservoirs of water, but moreover their fracture system can provide deep water circuit, which effects geothermal water occurrence (e.g. Cieplice Śląskie-Zdrój). For precise analysis of deep or shallow water circuit in fractured crystalline rocks detailed data about disjunctive tectonics spatial distribution and internal structure seems to be valuable input.

Structure from motion (SfM) is photogrammetric technique based on digital photography. Basis of SfM is to collect set of images of object form different points of view and reconstruct 3-dimensional colour point cloud representation of measured object. In our study SfM is used to create precise 3d data and orthorectified images, both from quarries and natural outcrops to quantitatively characterize fracture systems. Basing on 3D models and ortho-images tectonic features are detected as 2D trace lines on oriented profiles and 3D surfaces, next 2D and 3D data are combined to create fracture network model. This approach allows describing not only fractures orientation, but also their spatial density and distribution along analysed outcrops. Using such data, we can easily detect and quantitatively describe joint system, fractures corridors, fault zones and mutual relations between these structures.

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Structural mapping, well data and stress field analysis in the surroundings of the Nekézseny Thrust Fault, NE Hungary

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The Bükk and Uppony Mts. located in NE Hungary are two adjacent structural units with different origins: while the nappes of the Bükk Mts. once formed part of the Inner Dinaric nappe system, the Uppony Mts. are correlated with the Western Carpathians (Schmid et al. 2008). The mainly S-SW-vergent Bükk and N-NW-vergent Uppony Units are separated by the Nekézseny Thrust Fault along which the Bükk-type Permomesozoic formations are thrust upon the Uppony-type Paleozoic and Senonian formations (Schréter 1945).

Despite of its obvious structural importance, the structural evolution of the Nekézseny Thrust Fault hasn't been studied in details. The possible timing of its movements is between the Senonian and the Early Miocene.

In their preliminary structural study Fodor et al. (2005) interpreted the results in the lights of the Paleogene deformation of the Darnó Deformation Zone. On the other hand, based on paleogeographic considerations Schmid et al. (2008) consider the Nekézseny Thrust Fault as the suture zone of the Meliata Ocean thus assume that the age of this structural contact is Early Cretaceous.
Consequently, the aim of our study was to understand the deformation geometry and the timing of activity along the Nekézseny Thrust Fault. As part of the study core samples from boreholes that drilled through the supposed structural contact were reviewed, sampled and interpreted. Detailed structural mapping in the surroundings of the Nekézseny Thrust Fault was followed by stress field analysis and preparation of cross-sections. According to our preliminary results, at least five tectonic phases could be separated. Field work in the gently folded Senonian Nekézseny Conglomerate revealed both pre- and post-tilt low-angle thrust faults. While the pre-tilt thrust faults are clearly the results of NW-SE compression (D1), the post-tilt thrust faults can be separated into three groups that show slightly different N-S, NW-SE and E-W compression (D2). These deviations from the general NW-SE post-tilt compression only appear immediately at the Nekézseny Thrust Fault. The tilting itself is connected to NW-SE compression as well. The subsequent three deformation phases are connected to the later rotational events and extensional deformation history of the Pannonian Basin (D3: Early Miocene NNE-SSW extension, D4: Middle Miocene E-W extension, D5: Late Miocene-Pliocene NW-SE extension; Fodor et al. 2005, Budai & Fodor 2008). All this may contribute to understanding not only the deformation history of the Nekézseny Thrust Fault, but the role of the Darnó Deformation Zone during the Mesozoic structural evolution of the area.

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Three models of structure of the Carpathian Klippen Belt – variable records of nappe thrusting, backthrusting and transpression

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The Carpathian Pieniny Klippen Belt (PKB) is characterized as an orogen-scale, unusually narrow but continuous zone with intricate internal structure. It follows the boundary between the Cretaceous Central Western Carpathian (CWC; Austroalpine) stack of thick- and thin-skinned nappes and the Cenozoic accretionary wedge (Flysch Belt). The PKB involves its own special units (Pienidic or Oravic) that were derived from an independent palaeogeographic domain known as the Czorsztyn Ridge and its slopes. This represents an intra-Penninic continental sliver that was separated from the Austroalpine domain during the Middle–Late Jurassic and rifted off the foreland European plate in the Early Cretaceous, hence bounded by two respective branches of the Pennine oceans – the Piemont-Váh Ocean in the south and the Rhenodanubian-Magura Ocean in the north. Orogenic deformation progressed from the Late Cretaceous onward when the Oravic cover units were detached from their basement, which underthrust the CWC orogenic wedge, and were assembled in a shallow fold-and-thrust belt. As shortening embraced the North Penninic Biele Karpaty and Magura units, the PKB Oravic units have got caught between the developing accretionary wedge of the present Flysch Belt and the CWC rigid buttress. In this backstop position, the original PKB nappe structure was variously modified up to almost destroyed by subsequent out-of-sequence thrusting, backthrusting, transpressional and transtensional movements.
Presence of the Oravic units, the Czorsztyn succession in particular, is along with frequently disorganized block-in-matrix structure the most distinctive aspect of the PKB structure that occurs all along its ca 600 km length. However, especially the western Slovakian PKB branch incorporates also cover nappe units of the CWC provenance (Peri-Klippen zone with the Klape, Manín and Drietoma units) that were emplaced in the late Turonian and then deformed together with the Oravic units. As a result, they partially share the "klippen tectonic style" and include also the Senonian-Paleogene post-nappe strata deposited in the wedge-top Gosau-type basins (Plašienka & Soták 2015 and references therein). On the other hand, the eastern PKB branch

only includes the Oravic units, with the exception of small Haligovce unit in the Pieniny Mts.

Despite the ubiquitous presence of Oravic units all along the PKB strike, its individual segments exhibit considerable differences in the structural style, presence and extent of individual units, as well as relationships to the "non-Oravic" units and to the neighbouring zones. The three basic tectonic models presented here represent the end members of countless variabilities in the PKB structure. The original nappe structure is best preserved in the eastern PKB branch (e.g. Uhlig 1907, Birkenmajer 1986, Plašienka & Mikuš 2010, Plašienka et al. 2012). The latter authors distinguished three major units from bottom to top: (1) the Šariš unit with a rather uniform basinal Jurassic-Middle Eocene succession; (2) the Subpieniny nappe with variable ridge-derived Jurassic-Cretaceous successions (Czorsztyn, Niedzica, Czertezik); (3) the Pieniny nappe with basinal Jurassic-Cretaceous successions (Pieniny, Kysuca, Branisko). Although modified by Paleogene out-of-sequence thrusting, dextral transpression and Early Miocene backthrusting, the well-preserved nappe structure can be documented in places. The sequential latest Cretaceous-Early Eocene timing of thrusting is revealed by the age of respective synorogenic clastic deposits (e.g., Plašienka 2012).

Due to a continuous Late Cretaceous-Paleogene piggyback fore-thrusting, which incorporated also the frontal CWC units, the PKB in the Middle Váh River Valley (Púchov sector) was strongly modified by post-nappe deformation processes. The unidirectional NW–SE compression lasted from the latest Cretaceous until the Middle Eocene. Meanwhile, the Oravic units were gradually transposed from the head to the rear of the developing accretionary wedge, as the Magura units were progressively accreted to the wedge tip. As a result, the PKB units were affected by out-of-sequence thrusting, backtilting and backthrusting that largely obliterated their primary nappe edifice (Plašienka & Soták 2015). During the Eocene, shortening became slightly oblique and produced transpressional structures, followed by the Miocene sinistral transtension as the stress-field progressively rotated clockwise (e.g., Šimonová & Plašienka 2017).

Backthrusting of the PKB and adjacent zones reached its maximum in the Kysuce and Orava sectors in NW Slovakia. The extraordinarily complex structure of this PKB part can be characterized as a synclinorium with almost all beds and successions overturned and steeply N-dipping. In general, the Oravic units are mostly rimming the PKB along its northern and southern margins, while the "non-Oravic" Klape unit with associated Senonian flysch deposits (Pupov Fm.) occur mainly in the centre. Backthrusting of the whole PKB edifice into a superposition over the CWC units of the Malá Fatra Mts. attained at least 5 km (as indicated by interpretation of a local seismic profile by Pešková et al. 2012) and was accompanied by an extensive disintegration of the previous overthrust structures, whereby isolated slivers of various formations derived from different units often occur in very strange positions.

Since the three model areas described occur in diverse parts of the arcuate PKB structure but register the same changes in the stress field orientation, they record the post-nappe deformation processes in different ways. The general NW-verging nappe thrusting (NW-SE oriented compression axis during the Senonian up to Middle Eocene) was continuously followed by back-tilting and thrusting in the western PKB branch trending perpendicularly to the shortening direction. The NW–SE compression was associated with a rising dextral transpressional component in the northern and eastern branch that reached its maximum in the NW-SE oriented eastern Slovakian part strongly affected by dextral transpression (Plašienka 2012). Clockwise rotation of the maximum compression axis up to the SW-NE orientation during the Early Miocene generated sinistral transtension in the western branch (Kováč & Hók 1996) and fore- and backthrusting along the PKB boundaries in the northern and eastern branch (Plašienka et al. 2013).

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Ediacaran rift at the SW margin of the East European Craton

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During the Neoproterozoic to early Palaeozoic an extensive system of sedimentary basins developed along the western slope of the East European Craton (EEC), often collectively referred to as the Peri-Tornquist Basin System (PTBS). It is composed of (from NW to SE): the Baltic Basin (BB), the Lublin-Podlasie Basin (LPB), and the Volyn-Podillya-Moldova Basin (VPMB). A new high-quality deep seismic imaging provided by the PolandSPAN® data from southern part of the LPB allowed for precise interpretation of the top of Precambrian crystalline basement, top of Ediacaran, top of Cambrian and top of Ordovician even at a great depth of 9–18 km. The data documents presence of a large extensional half-graben developed in the Palaeoproterozoic crystalline basement, which might be filled up by a Neoproterozoic syn-rift volcano-sedimentary succession (Krzywiec et al. 2018). The graben is limited from the SE by a normal listric fault. Similar Neoproterozic extensional half-graben was revealed by seismic data from the Danish sector of the BB (Lassen et al. 2001). Both grabens indicate rift-related extensional regime at the SW slope of the ECC during Neoproterozoic time. Crustal scale normal faults in the LPB might have acted as the pathways for the Neoproterozic up-section lava migration that have given rise to the formation of the extensive flood basalts. The rift-related origin of the magmatic activity is confirmed by results of geochemical analysis (e.g. Białowolska et al. 2002, Krzemińska 2005). Precise age of the volcano-clastic complex, and therefore timing of the rift activity, were so far difficult to constrain. However, current U–Pb SHRIMP dating for several tuff and basalt samples from the entire volcano-clastic section revealed ages range ~551–567 Ma. Therefore, the syn-rift volcanic activity might be defined as latest Ediacaran. A concept of development of the latest Ediacaran rift along the entire SW margin of the EEC (i.e. PTBS) is confirmed by the results of tectonic subsidence analysis, with the subsidence pattern characteristic of rift basins evolving into post-rift thermal sag basins (Poprawa & Pacześna 2002, Poprawa 2006, Poprawa et al. 2018). The syn-rift extension phase, manifested by a rapid tectonic subsidence, took place during the latest Ediacaran, while post-rift thermal sag, characterized by a systematically decreasing rate of subsidence, governed the basin development since the Cambrian to Ordovician. A magnitude of syn-rift and post-rift tectonic subsidence increased towards the SW. This indicates that the Ediacaran rift zone was located farther west of the current EEC edge. Additionally, the facies development of the late Ediacaran and lower Cambrian succession in the LPB and VPMB is coherent with the model of transition from syn-rift to post-rift deposition. The syn-rift volcano-clastic complex passes up-section into conglomerates, which are covered by coarse- and fine-grained sandstones that eventually are replaced by mudstones and claystones (Pacześna 2006). Latest Ediacaran–Ordovician lateral expansion of the PTBS is also characteristic of post-rift thermal sag stage (Poprawa & Pacześna 2002). Development of this large extensional basin system was related to the latest stages of break-up of the Precambrian super-continent Rodinia/Pannotia and ultimately formation of the Tornquist Ocean. The Ediacaran rifting along the SW margin of the EEC was coeval with rift-related extension in the Orsha-Volyn Aulacogen (OVA), perpendicular to the PTBS. The intersection of the both systems of sedimentary basins, i.e. LPB, was a location of the Ediacaran triple junction. While the OVA became an aborted rift, the rift system related to the PTBS led to separation of the Baltica and adjacent plate, being presumably Amazonia, and formation of the Tornquist Ocean.

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Geological structure of the Veporic-Gemeric contact zone in the area between Slavošovce and Ochtiná villages (Western Carpathians, Slovakia)

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We have studied structural relationships and tectono-metamorphic development of units in the Veporic–Gemeric contact zone in the Revúcka vrchovina Highland in central Slovakia. The area includes the Veporic pre-Alpine basement complexes and Permian cover rocks, which are juxtaposed to the Gemeric Ochtiná Unit along the complex SW–NE trending Lubeník fault zone. The Veporic basement is composed of low- to medium-grade metasediments of the Hladomorná dolina complex (HDC) intruded by Variscan granitoids of the Kráľova hoľa complex in the NW part of the area. While the Early Paleozoic age of HDC was assumed by Klinec (1966, 1971), its Pennsylvanian age (Slatviná Fm.) was suggested by Vozárová and Vozár (1988 and later works) and so it is indicated also in the modern geological maps of the area. Towards the SE, the HDC is discordantly overlain by the post-Variscan Permian continental clastics (Rimava Fm.). The Gemeric Ochtiná Group of the Mississippian age (e.g., Vozárová 1996) is composed of low-grade metamorphosed fine-grained marine clastics intercalated by metacarbonates (partly transformed to magnesite) and basic metavolcanites. Farther SE, a narrow slice of the Meliatic Bôrka Unit occurs within the Hrádok fault zone that parallels the Lubeník fault and represents a boundary of the Ochtiná Unit with the main Gemeric Volovec Unit composed only of Permian clastics (Gočaltovo Fm.) in the investigated area. Furthermore, the area was affected also by contact metamorphism induced by the subsurface Rochovce granite body of Late Cretaceous age (e.g. Poller et al. 2001). The purpose of our study was to distinguish between the Alpine and pre-Alpine structural elements and metamorphic associations especially in the HDC, as well as to interpret the structural-metamorphic evolution of this complexly deformed and metamorphosed region.

Our research methods included a field-based structural analysis of deformation elements, geological mapping and collection of rock samples, partially oriented, for the following lithological, petrological and microstructural investigations of thin sections. Several samples were investigated also by the electron microanalyzer. The measured structural elements, mostly metamorphic foliation, were collected and analyzed for each unit separately.

Bedding and low- to very low-grade, bedding-parallel metamorphic schistosity is mostly moderately SE-dipping in the Veporic, Meliatic and Gemeric post-Variscan complexes. Consequently, it is interpreted as the Alpine foliation that influenced all units occurring in the area and represents their main structural element. In contrast, the HDC exhibits the S- to SW-dip of apparently higher-grade, Variscan metamorphic foliation. The Alpine overprint in HDC is confined to SW–NE trending ductile shear zones that affected also the Variscan granitoids.

During the Alpine tectonic stage, rock complexes in the area were affected by the greenschists facies (LP/LT) regional metamorphism that caused crystallization of new mineral assemblages. Higher grade metamorphic associations occur in HDC indicating metamorphism in the lower amphibolite facies (MP/MT). The Cretaceous Rochovce granite intrusion produced the LP/HT contact mineral assemblages, which are overprinting the regional metamorphic association and overgrow foliation in HDC (e.g. Korikovsky et al. 1986). Rocks of the originally HP/LT Bôrka Unit were considerably affected by the greenschist-facies retrograde metamorphism, the Early Cretaceous age of which is indicated by the CHIME dating of monazites.

Two generation of monazites occur in the chlorite-sericite phyllites of the Bôrka Unit. Gathered ages calculated by the statistical method of Montel et al. (1996) fall into two groups, likely indicating two distinct tectono-metamorphic events: (1) the older ages 139±13 Ma indicate exhumation of the Bôrka rocks postdating subduction of the Meliata Ocean; (2) the younger age 97 ± 5 Ma records collision and the main phase of nappe stacking in the southern Western Carpathian zones.

In summary, our results demonstrate that: (1) based on the structural and metamorphic criteria and in line with the earlier views of Klinec (1966, 1971), the Early Paleozoic age of HDC is favoured; (2) only Permian age of the Veporic post-Variscan cover in the investigated area is proposed; (3) the pervasive low-grade Alpine metamorphic foliation is consistently SE-dipping in all post-Variscan complexes involved, whist Variscan medium-grade metamorphic foliation of HDC is differently oriented; (4) monazite ages from the Bôrka Unit fall within the age ranges of principal tectonic events affecting the inner Carpathian zones (summarized e.g. by Plašienka et al. 2016).

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Strength anisotropy of joints and faults

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Joints and faults are the most common brittle structures, which disrupt the continuity of the rocks. This lower rock cohesion has its origin in less strength of joint or fault surfaces in comparison to unfractured rock. Joints are usually considered to be isotropic but this point of view may be used only in the first approximation, but it is very simplified in fact. We tried to testify and quantified idea of shear strength anisotropy of such real fractures and comparised with two types of manmade ideal rupture models from gypsum.

Real joint and fault we took from the Brno massif (Vranov qarry). We drilled 9–16 drill cores in minimum through one selected fracture, as samples were tested in nine – 16 different directions. We tested five fractures. To keep original orientation, samples were marked to show “zero” direction. It was chosen randomly in case of joints or corresponds to striation on faults surfaces.

Ideal rupture models we prepared like two types of manmade surface geometry of ruptures First type with bigger strias and second type with finer strias. Surface shape of it was chosen uncomplicated with parallel ridges and mirror symmetry. We made ten series of first type (160 casts) and 11 series of second type (176 casts).

Ideal models were tested in 5 different directions. Striation on model surface was selected as a “zero” direction. Thanks to mirror symmetry of surfaces it was not necessary to tests all 16 directions as on real non-symmetrical ruptures. Tests were made only in 5 directions in range 0–90° and results were copied in other directions. Black line is first type with bigger strias, grey line is second type with smaller strias (Fig 1C). All samples and models were tested at shear tensile machine Matest A129.

Strength pattern of real joints showed typically one peak of shear strength while other directions we characterized by lower strength level (see Fig. 1A). This type of strength pattern might be explained by presence of more or less noticeable steps on joint surfaces. Tested faults brought completely different picture of results. Two types of fault strength pattern were recognized. The first one was typical by the lowest values of shear strength observed in directions parallel to fault striation regardless of the sense of movement and by weak maximum strength in directions perpendicular to striation (Fig. 1B), which was preliminary expected. Faults with the second pattern indicate different strength in direction of striation due to asymmetrical structures on fault surface. Both pattern types have tendency to show some weak peaks in oblique directions, which were sometimes higher then strengths in perpendicular directions.

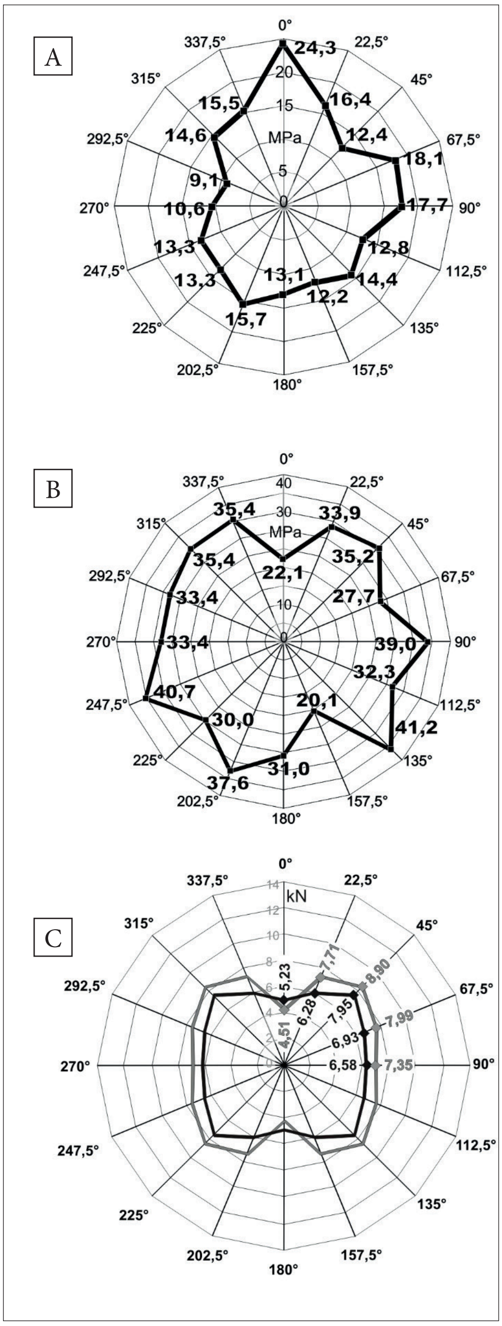

Fig. 1. *Spider diagram showing different shear strength in different direction: A) real joint; B) real fault; C) two types of ideal rupture models (grey line – smaller strias, black line – finer strias)*

At both type of ideal rupture models, we can observe the lowest values of shear strength in direction parallel to striation. This result was expected and correlated with real faults (Fig. 1C). But distribution of shear strength along model rupture shows one peak of shear strength maximum, which is in oblique angle 67,5° This result confirms results of testing of real ruptures (Proisl, 2013). Other data were lower than this oblique one, even in direction perpendicular to striation. Different were the absolute values of shear strength. In the case of finer strias were almost two times higher.

This result of testing indicates some unknown strength behavior of striated planes. It is evident, that shear strength of real and gypsum ruptures is anisotropic. Very important factor is the surface roughness. Absolute shear strength is affected by stria size (bigger strias – smaller extremes) and anisotropy of ideal rupture models and real faults works similar way.

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Infratatricum of the Inner Western Carpathians: Coupled Albian-Eocene accretionary wedge exposed in a Miocene tectonic window

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The Inner Western Carpathians (IWC) orogenic wedge formed in the course of progressive closure of the Meliata(-Hallstatt) and the Penninic oceanic basins and related subduction-collision processes (e.g., Kozur 1991, Putiš 1991, Neubauer 1994, Faryad 1995, Plašienka et al. 1997, Schmid et al. 2008). This study targets the frontal IWC Infratatric Unit termed Infratatricum (Putiš 1992), which represents integrated Albian and Eocene accretionary wedges. An older, Late Jurassic-Early Cretaceous Meliatic accretionary wedge (~150–100 Ma; Putiš et al. 2014 and references therein) of the IWC formed due to closure of the Neo-Tethys Meliata oceanic basin. This includes the exhumed blueschist- and flysch-bearing nappe slices underthrust by continental margin Gemeric and South-Veporic slices at ca. 130–100 Ma. As a response the deposition of the Albian-Cenomanian syn-orogenic flysch terminating the Jurassic-Lower Cretaceous successions occurred in the foreland North-Veporic and the Tatric areas.

The Albian-Cenomanian flysch succession is missing in the Infratatric Selec Block that is exposed in the northern part of the Považský Inovec Mts., N of the Hrádok-Zlatníky thrust-fault separating the Infratatric and Tatric units. At that time the micaschist-gneiss basement with the Upper Carboniferous to Lower Cretaceous cover Humienec Succession became a part of the Albian accretionary wedge represented by the Infratatric Inovec Nappe. This event is indicated by the white mica $^{40}Ar–^{39}Ar$ plateau age of 101.2 ± 2.9 Ma obtained from the sheared Permian meta-arkose associated with meta-rhyolites and meta-basalts. The Lower Cretaceous slates illite-phengite shows even older Albian $^{40}Ar–^{39}Ar$ plateau ages of ca. 114–106 Ma (Putiš et al. 2009). The higher anchimetamorphic conditions at ca. 250–300°C are consistent with the newly-formed Chl, Ab, Act, Ep-Czo, Phg, ±Pmp, Qz, Cal (Putiš 1986, Korikovsky et al. 1995) due to burial below the partly wedged Tatric Unit. The previous attenuation of the Infratatric basement is inferred according to the presence of the Jurassic to Lower Cretaceous members in the Humienec Succession (Putiš et al. 2006, 2008). It is characterized by the Early Jurassic rifting and passive margin formation, with post-rift deepening pelagic radiolarites and cherty shales (Middle Jurassic-Lower Cretaceous) considered by Plašienka et al. (1994) and Plašienka (2012) as being a part of the South-Penninic (~Váh) Basin.

The very low-grade Alpine metamorphism of the Inovec Nappe is related to two deformation stages: i) the Eoalpine, Early Cretaceous deformation stage AD1, with the tectonic style of NW-vergent kilometer-scale recumbent folds and overthrust structures of the crystalline complexes including the Upper Paleozoic and Mesozoic cover. This event is also registered by the white mica $^{40}Ar–^{39}Ar$ mean age of 102.3 ± 1.9 Ma from the Hrádok-Zlatníky thrust-fault zone blastomylonites, and a zircon fission track age of ca. 102 Ma from the micaschist-gneiss in the footwall of the Tatric Panská Javorina Nappe; ii) the Mesoalpine (late Maastrichtian-Eocene) deformation stage AD2 with the fold-thrust to imbricate tectonic style (Putiš 1980, 1983, 1995) in NE–SW direction, determined by a white mica re-activation $^{40}Ar–^{39}Ar$ plateau age of 48 ± 2 Ma from the Infratatric/Tatric boundary blastomylonites.

The sedimentary cycle of hemipelagic Cenomanian-Santonian Couches-Rouges type marls between the Pieniny Klippen Belt and the northern Infratatric margin continued by late Santonian to Maastrichtian Belice flysch trough sedimentation (Horné Belice Succession after Ivanička et al. 2011). Olistoliths, olistostromes and scarp breccias, especially of the micaschist-gneisses and the Permian sedimentary and volcanic rocks, derived from the Inovec Nappe (Putiš et al. 2008). The Late

Cretaceous extension and sedimentary basin opening may suggest the inferred South-Penninic oceanic crust subduction below the being exhumed Albian accretionary wedge. The white mica ^{40}Ar–^{39}Ar exhumation or unroofing plateau age from the Inovec Nappe meta-arkose of 83.4 ± 2.2 Ma (with the peak-burial age at 101.2 ± 2.9 Ma) is consistent with the time of a higher-anchimetamorphosed material supply into the foreland Upper Cretaceous Belice flysch trough. The Inovec Nappe fragments, including the Humienec Succession olistoliths, occur in the very low anchimetamorphosed (at ca. 150–200°C; Putiš et al. 2006, 2008, Putiš & Tomek 2016) Upper Cretaceous flysch sediments (Kullmanová & Gašpariková 1982) of partly rebuilt the Albian accretionary wedge. The common subvertical tectonic structures of the Inovec Nappe basement and infolded Upper Cretaceous sediments, forming the frontal Infratatric Belice slices, were investigated by the electric resistivity tomography (Pelech et al. 2017) to ca. 100 m depth. However, the NW-SE oriented reflection seismic profile 6HR revealed detachment shear zones below the Infratatric Unit, with unknown underthrust units, and the MOHO reflexes at about 30 km.

The closure of the Belice flysch trough initiated re-activation of the Albian accretionary wedge in the Eocene (46 ± 3 Ma whole-rock K–Ar age from the Belice slice basalt olistolith in flysch; Putiš et al. 2008), including the Tatric/Infratatric boundary at ca. 48 Ma. The Infratatric wedge formation in the Eocene was contemporaneous with the starting closure of the Magura Basin in the Outer Western Carpathians and the North-Penninic Ocean in the Alps. A higher low-temperature exhumation history of the Inovec Nappe was determined by a relatively broad range of zircon fission track ages of ca. 48–38 Ma from the western and relatively deeper NNE–SSW striking steeply dipping tectonic slices, documenting the cooling through the 220°C isotherm already in Paleogene. This indicates re-heating of the Inovec Nappe to at least 250°C within the Eocene accretionary wedge due to overloading by the Tatric Unit and the Mesozoic Fatric and Hronic nappes. Moreover, the temporary burial below the Paleogene sediments of the Central-Carpathian Paleogene Basin may have occurred. This slowly exhuming Eocene "core-complex" finally cooled below ca. 100°C during the Miocene orogen parallel extension from 21 to 13 Ma according to apatite FT ages (Danišík et al. 2004, Králiková et al. 2016).

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Early tectonics of the Outer Carpathian accretionary prism: a case study from the Magura Nappe

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Small-scale tectonic structures formed in poorly indurated strata are characteristic features of an accretionary prism and record the stress arrangement which occurred during the sedimentation of the host strata. In this paper, we report the results of the structural analysis of early small-scale structures in a single exposure in the Outer Carpathian accretionary prism.

The studied exposure is located at Ropica Górna in Poland, within the Siary Slice of the Magura Nappe. There, in the Sękówka river valley, Upper Eocene-Lower Oligocene flysch strata are exposed. In the section of the exposure, three rock complexes were distinguished from the bottom to the top: (1) thin- to thick bedded mudstones interbedded with thin-bedded sandstones, (2) a chaotic complex of mudstones and thin bedded sandstones deformed into sheath folds; this complex is interpreted as a slump and, (3) thick-bedded sandstone. The strata are cut by five groups of planar small-scale structures: (i) joints, (ii) clastic dykes, (iii) joints cutting dykes, (iv) deformation bands (DB) and, (v) faults.

The complexes (1) and (3) display two sets of orthogonal joints (L and T), striking approximately NW-SE and NE-SW, parallel and perpendicular to the bedding strike, respectively. In the exposure, two sets of clastic dykes (I and II) were observed. Dykes of the set (I) cut strata of the complex (1) whereas dykes of the set (II) cut the chaotic complex (2). The dykes of set (I) are oriented parallel to set L joints whereas dykes of the set (II) are parallel to the set T joints. Dykes of the set (I) are cut by a single set of joints oriented parallel to set T joints. Two conjugated sets of early non-cataclastic, disaggregation DB cut these clastic dykes with acute angles of about 70–90°. The chaotic complex (2) is cut by dextral strike-slip faults. These faults strike approximately NE-SW. One of the faults is lined by a breccia layer up to 15 centimetres thick.

The architecture of the joints fits the model of the orthogonal sets of extension joints very well (Caputto 1995). Set T joints are extensional features formed in a compressional stress field, of horizontal σ_1 oriented SW-NE, whereas set L joints were formed simultaneously during stress relaxation. The joints are early features formed when the host strata of the complex (1) were poorly indurated_as many of them are filled by clastic dykes consisting of material from this complex. Dykes of the set II are parallel to joints of set T. It follows that the set II dykes were also formed in a compressional stress field with σ_1 oriented SW-NE. The discussed DB were formed when the host dykes were poorly indurated (cf. Świerczewska & Tokarski 1998), as two conjugated shear failures in a compressional stress field with σ1 oriented SW-NE. Joints cutting dykes formed in the same stress conditions. The occurrence of the breccia layer lining one of the faults cutting the complex (2) indicates that faulting took place after the lithification of rocks in a compressional stress field with σ_1 oriented SW-NE. Summing up, we conclude that (1) all of the observed small-scale structures (i-v) formed in the same stress field and (2) most of the structures (i-iv) are early features which developed at the onset of folding when the host strata were poorly indurated. Only later, when the host strata became more indurated, the studied strata were cut by (v) strike-slip faults.

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The Western Carpathians from an Alpine and East Carpathian perspective

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The contact zone between the External Western Carpathians and the Central West Carpathians, the Pieniny Klippen Belt s.l., is of bewildering complexity compared to what is found west and east of the Western Carpathians, namely in the Alps and Eastern Carpathians of Romania. This is at least partly due to substantial modifications of the original Pieniny Klippen nappe pile, presently only preserved as steeply dipping fragments, during the east-directed lateral extrusion of ALCAPA in Miocene times. Hence, it is useful to go west and east from the Polish-Slovakian sector in order to speculate what might have been going on within this contact zone before the Miocene.

Given the complexity of the Pieniny Klippen Belt s.l. it is not surprising that the nomenclature of the tectonic units within and adjacent to this belt is of even greater complexity. Plašienka (2008) used the term "Oravic" in order to distinguish those parts of the Pieniny Klippen Belt s.l. that constituted an independent paleogeographic unit from other parts of the Pieniny Klippen Belt s.l. that are derived from dismembered parts of the Central East Carpathians (e.g. Manin, Klape, Haligovce units). The northern boundary of the "Oravic" units adjacent to the Magura flysch is equally complicated and there is a debate about the tectonic position and paleogeographic position of the Grajcarek succession, probably to be parallelized with the Saris unit of Slovakia (Birkenmajer & Gedl 2017, Jurewicz 2018), which may be taken as the structurally lowest part of the "Oravic" unit (Plašienka 2012), or, as a part of the Magura basin consisting of Mesozoic rocks thrust northwards over the mostly Cenozoic parts of what is considered the Magura unit s.s., or, as a transitional zone (Jurewicz 2018).

Viewed from the Alps it is clear that tectonic units derived from the Briançonnais microcontinent disappear east of the Engadine Window. There are no signs of a ribbon continent between the derivatives of the former Valais Ocean (Lower Penninic nappes) and the former Piemont-Liguria Ocean (Upper Penninic nappes) in Austria (Schmid et al. 2004). This implies that the Valais Ocean that opened in Lower Cretaceous times must have opened within a pre-existing Piemont-Liguria Ocean open since Mid-Jurassic times. Remnants of both oceans are present in Austria (Rheno-Danubian flysch and Glockner nappe representing the Valais Ocean; Yppsitz Klippen in Niederösterreich and Rechnitz Window representing the Piemont-Liguria Ocean). In the Western Carpathians, however, a kind of Briançonnais appears again in the form of the "Oravic" units; particularly the Czorsztyn unit shows amazing facies similarities (Trümpy 1988). Therefore, one expects derivatives of the Valais Ocean north of, and/or below the Czorsztyn unit, i.e. in the Graicarek unit of Poland and the Saris Unit of Slovakia. If correct, these two units would not represent parts of the "Oravic" (=Briançonnais) paleogeographical domain but rather Jurassic-Cretaceous parts of the Magura basin, later thrusted onto the Cenozoic of the Magura Unit s.s. South of the "Oravic" (=Briançonnais) Zone Units one expects relics of a Piemont-Liguria Ocean since the parallelization of the Central Carpathian nappe pile with the Austroalpine nappes of the Alps is beyond any doubt. Logically this suture would have to looked for between the "Oravic" parts of the Klippen Belt (Pieniny s.s. and Branisko/Kysuca) and the inner "Periklippen" units (Manin, Klape, Haligovce); yet they have not been found yet, presumably due to intense Miocene displacements and reworking associated with the lateral extrusion of ALCAPA taking place within the Pieniny Klippen Belt s.l. The only known remnants of a Piemont-Liguria Ocean are found in the Belice Unit of the Považský Inovec Mts. and in the Inacovce-Krichevo Unit known from bore holes in eastern Slovakia (Plašienka et al. 2012), both occurrences being located in tectonic windows below Central Carpathian thrust sheets and south of the Klippen Belt s.l.

The two-ocean hypothesis proposed for the Western Carpathians finds support viewed from the Eastern Carpathians of Romania and adjacent Ukraine (Schmid et al. 2008). The Ceahlau-Severin unit contains relics of an ocean that opened in Mid-Jurassic times, contemporaneous with the opening of the Piemont-Liguria Ocean, and hence can be considered the easternmost extension of the Piemont-Liguria Ocean along which the Tisza and Dacia Mega-Units of European origin separated from the European foreland. This demands a link between Piemont-Liguria and Ceahlau-Severin oceans across the future Western Carpathians. While the Ceahlau-Severin unit was closed and accreted to the Dacia Meg-Unit already in Early Cretaceous times another oceanic to semi-oceanic domain, the Carpathian embayment, remained open much longer, i.e. until the Miocene roll-back of the European slab allowing for the invasion of the embayment by the Tisza and Dacia Mega-Units. It is proposed that this second oceanic domain was connected to the Valais-Magura Ocean that opened in Early Cretaceous times.

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Variscan structures in the Khasagt Mountains (SW Mongolia) and their relations to evolution of south-western margin of the Zavkhan terrane (Central Asian Orogenic Belt)

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The Khasagt Mountains massif is located NW from Altai City in SW Mongolia. Its basement represent SW part of the Zavkhan terrane of the Central Asian Orogenic Belt (CAOB). Geological structures in that area trends WNW-ESE, paralelly to the Main Mongolian Lineament which is located to SW and S. Our research concerns the western part of the massif. In the study area from South to North, increasingly younger rocks sequences (from Mesoproterozoic to Devonian; Énhbaár et al. 2005, Wójcik et al. 2015) are exposed. Tectonic structures in the southern part of study area were identified as related to Proterozoic (Baikalian orogeny) and Middle Cambrian (Early Caledonian orogeny) tectonic events (Sikora et al. 2016, Sikora & Wójcik 2017) which are linked with early stages of accretion of the CAOB. In northern part of study area, we documented tectonic structures linked with Variscan orogeny. Especially we present structural data about compressional deformations in brittle regime, which occured after placemet of the Lower Devonian (Late Ordovician-Silurian? vide Bold et al. 2016) Numrug complex granitoids. Evidence for post Middle Devonian tectonic event are the overthrusts of Lower Cambrian carbonate rocks (Salaany Gol Fm.) and Lower Devonian granitoids on Middle Devonian clastic sediments (Tsagaan Shoroot Fm.). In many outcrops of the Tsagaan Shoroot Fm. reverse faults and thrust duplexes are observed. It should be noted that Variscan structures have simillar orientation like the oldest structures from southern part of the Khasagt Mountains, but their range is smaller. In our opinion post-Middle Devonian structures documented tectonic event on periphery of main Variscan tectonic zone, which was located on southern part of the Main Mongolian Lineament. Nevertheless, presented data are important for analysis of tectonic evolution of the Zavkhan terrane and understanding complicated terranes accretion in this part of the CAOB.

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Numerical simulations of the structure evolution in three-layer evaporite systems and its application to tectonic structures from the Kłodawa Salt Structure (Poland)

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Evaporites are usually composed of rocks containing different constituents: halite, K-Mg salts, sulphates and siliciclastics. Most of the salt rocks and potash are characterized by low density and viscosity as compared to other rocks and their physical and mechanical properties may significantly vary. Mixed mineral composition of single layers as well as impurities and intercalations of other rocks in the sequence, e.g. clay rocks, further influences rheological heterogeneity within the evaporite series. This heterogeneity may lead to development of complex tectonic structures during deformation, which is especially pronounced in diapiric salt bodies. The Kłodawa Salt Structure (KSS), central Poland, is an example of a diapiric wall, where the mechanical stratification played an important role in the evolution of its internal geometry. This study presents results of analysis of spectacular folds that developed within evaporites of the Younger Potash K3 (potash complex of the third Zechstein cycle), where intercalating layers of kieserite-halite-carnallite form finger-shaped folds.

The evolution of the gravitationally instable three-layer model using numerical simulations was investigated. It was assumed that the layers are linear viscous with low-amplitude red-noise perturbation imposed on the interfaces. A range of simulations with different sets of geometries and rheological properties, and the role of: 1) effective viscosity ratios, 2) relative layer thickness and 3) density differences between the layers was studied. For numerical simulations, own codes implemented in MATLAB environment, based on MILAMIN and MUTILS numerical packages were utilized.

The structures developed in the simulation were compared with documented examples of the fold structures from the KSS. Variable resemblance to the natural examples was achieved. Depending on the applied parameters, different sets of tectonic structures developed. Such an analysis of the models shows that rheological properties of natural evaporite rocks during deformation can, to a degree, be estimated based on the numerical simulations.

Cambro-Ordovician anatexis of the Cadomian crust: geochemical and geochronological constrains from the Kouřim Unit (Kutná Hora Crystalline Complex, Bohemian Massif)

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The Kouřim Unit (KU) forms a large pre-Variscan metaigneous complex involved into the tectonic collage of the Kutná Hora Crystalline Complex (Synek & Oliveriová 1993), at the northern margin of the Moldanubicum in the Bohemian Massif. Despite the long-term research on the region, the nature and age of the KU and/or provenance of the Kutná Hora Crystalline Complex are not well understood. The study of such an ancient magmatism could provide a unique insight into the pre-collisional history of intensively reworked high-grade complexes of the Variscan orogenic belt. The LA-ICP-MS zircon ages and geochemical characteristics of metaigneous rocks from the KU, together with detrital zircon age data from their host metasedimentary rocks, allow us to determine the timing and nature of magmatic activity within this part of the Bohemian Massif and thus to decipher its pre-Variscan evolution.

The KU is composed of high-grade metaigneous rocks, dominated mainly by various types of migmatites and orthogneisses. The newly obtained U–Pb zircon ages of five orthogneisses ranging between 492 ± 3 Ma and 484 ± 2 Ma are interpreted as time of the magma crystallization. Frequent older ages (c. 600–530 Ma) most likely represent zircons inherited from the source, whereas somewhat younger ages (c. 450–410 Ma) probably reflect a variable lead loss triggered by the Variscan metamorphism. Detrital zircon age populations of the two host metasedimentary rocks show a dominant Neoproterozoic age group at c. 700–530 Ma, a minor peak at c. 750 Ma and broad Palaeoproterozoic peaks at c. 2.2–1.8 Ga and c. 3.0–2.7 Ga. Several youngest ages at c. 450–360 Ma could be again related to the metamorphic resetting. This age pattern is nearly the same as those from the Teplá–Barrandian Unit and Moldanubicum (Košler et al. 2014 for review).

The orthogneisses are acid (SiO_2 = 68.6–76.4 wt.%), exclusively subaluminous and seem to form a single calc-alkaline trend. The chondrite-normalized REE patterns show LREE enrichment (La_N/Yb_N = 1.5–8.9) and deep negative Eu anomalies (Eu/Eu* = 0.42–0.32); the NMORB-normalized spiderplots feature LILE/HFSE enrichment with deep negative Nb-Ta-Ti anomalies. The Sr-Nd isotopic composition of orthogneisses clearly indicates geochemically rather evolved sources of the magmas ($^{87}Sr/^{86}Sr_{485}$ = 0.7053 to 0.7153; ε_{Nd}^{485} = –4.3 to –6.3). The magmas of the KU were thus mainly derived from a homogeneous crustal source, most probably fertile metasedimentary rocks with a relatively long crustal residence (T^{Nd}_{DM}.2stg = 1.50–1.66 Ga).

Ages of inherited zircons detected in orthogneisses of the KU correspond well to the dominant age peaks of the detrital zircon spectra of their host rocks. The magmatic arc-like geochemical signature of the orthogneisses is interpreted as inherited from the source, represented most likely by recycled immature arc-related material (metagraywackes). The isotopic compositions of the orthogneisses fall into the range of those reported from the (meta-)sedimentary rocks of Teplá-Barrandian Unit and Moldanubicum (Drost et al. 2007 for review). This view, together with similarities in detrital zircon age populations, implies that the magmas of the KU were generated by partial melting of Cadomian metasedimentary middle crust of the Kutná Hora Crystalline Complex, as equivalent of the Teplá-Barrandian Unit and Moldanubicum.

Documented c. 485 Ma anatectic event and S-type protolith of the KU orthogneiss can be correlated with contemporaneous extension-related igneous complexes in the Bohemian Massif (Žák et al. 2013 for review). Similar occurrences of intraplate magmatism and metamorphic and sedimentary record documented throughout the basement of the European Variscan Belt (Crowley et al. 2000), indicate an important period of lithospheric thinning often considered as associated with opening of the Rheic Ocean (Nance et al. 2010). Nevertheless, pre-collisional configuration and origin of continental segments involved in the Variscan Orogen remains partly enigmatic, yet more recent studies point to their overall Late Cambrian-Early Ordovician rift-related tectonic history.

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New stress inversion method based on 3D fault movements

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This contribution presents new technique for determining contemporary stress states from three-dimensional displacement of active tectonic faults situated near the ground surface. The development of the method was motivated by availability of the precise measurements of displacement between fault planes in all three orthogonal directions. These measurements are made using a range of instruments spanning from traditional three-dimensional crackmeters such as the moiré extensometer TM 71 (Košťák 1991) to new technologies such as those based on magnetoresistance (Rinaldi-Montes et al. 2017).

Input data fundamental for presented method are orientation of the fault surface represented by the down directed fault normal $\mathbf{n} = [n_x, n_y, n_z]^T$ and the vector of displacement between the particular fault blocks $\mathbf{P} = [P_x, P_y, P_z]^T$. Character of input data – 3D total vector of displacement from open faults situated near the ground surface – enables to propose three major assumptions, which lead to the numerical calculation of reduced stress tensor $[\mathbf{T'}_\sigma]$, i.e. the orientation and relative magnitudes of principal stresses (Angelier 1994).

The first assumption is generalization of Wallace–Bott (Wallace 1951, Bott 1959) hypothesis and it states that movement of fault blocks (**P**) occurs in the direction of stress vector (**S**) acting on fault surface. The second assumptions states that isotropic stress at the surface or at shallow crustal depths is negligible. Third assumption is based on Anderson's theory (Anderson 1951) and it states that one of the principal stresses close to the ground surface must be vertical. Based on these assumptions it has been possible to develop a relatively simple numerical approach for determining contemporary stress states using displacement data recorded across a single fault. The outlined method therefore does not require a set of fault slip data, as needed in order to use classical inversion techniques.

Developed method has been tested on fault displacement monitoring data which have been recorded at seven sites in in the Eastern Alps since 2013. An example of presented stress inversion is demonstrated using displacement data which evidence a single fault reactivation event on 7 November 2014 in Obir Cave. The outlined method is thought to have a considerable number of future applications in the many fields which use stress analysis, e.g., earthquake monitoring, landslide monitoring, and active-tectonic research.

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Late Cretaceous evolution of NE Poland – new insight based on regional seismic data

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The main objective of this study was to recognize gross depositional architecture of the Upper Cretaceous succession in the NE Poland formed in response to regional uplift of various segments of the European crust. The study area is located in the western part of the Mazury-Podlasie Monocline and Płock Trough, in vicinity of Kościerzyna, Grudziądz and Sierpc towns (Fig. 1). In Mesozoic it belonged to the NE flank of the Mid-Polish Trough – the most subsiding axial part of the Polish Basin. During the Late Cretaceous-early Paleogene the Mid-Polish Trough was inverted and transformed into the Mid-Polish Swell (MPS). Most of the Upper Cretaceous cover is now absent in the axial part of the MPS due to the widespread erosion. It is only preserved along both flanks of the Mid-Polish Swell. The Upper Cretaceous succession consists of mostly fine-grained siliciclastics and carbonates (Leszczyński 2012).

Regional depositional architecture of the Upper Cretaceous succession was studied using high-end regional seismic data of the PolandSPAN survey. Three deep research wells Kościerzyna IG-1, Grudziądz IG-1 and Polik IG-1 were used to calibrate seismic data. The most striking feature visible for the thick (up to 1000 m) Upper Cretaceous succession are sigmoidal and oblique seismic reflections, and regional unconformities and numerous local discontinuity surfaces highlighted by downlap, onlap and toplap seismic terminations. Some of those local features have been described using well data from the Płock Trough (Leszczyński 2017). All these features are strongly suggesting regional Late Cretaceous progradation directed from the North towards the South. Hitherto unknown progradational pattern indicates regional Late Cretaceous uplift of the area located in the North, i.e. of the present-day Baltic Sea and/or the South Swedish Dome (Japsen et al. 2016). Development of the syn-tectonic Upper Cretaceous succession can be explained using a model similar to that proposed for the Bornholm-Darłowo Fault Zone (Krzywiec et al. 2003) and SE Poland (Krzywiec et al. 2009, Krzywiec et al. 2018).

This study that was supported by NCN grant No 2015/17/B/ST10/03411. ION Geophysical is thanked for providing seismic data, and IHS for providing seismic interpretation software.

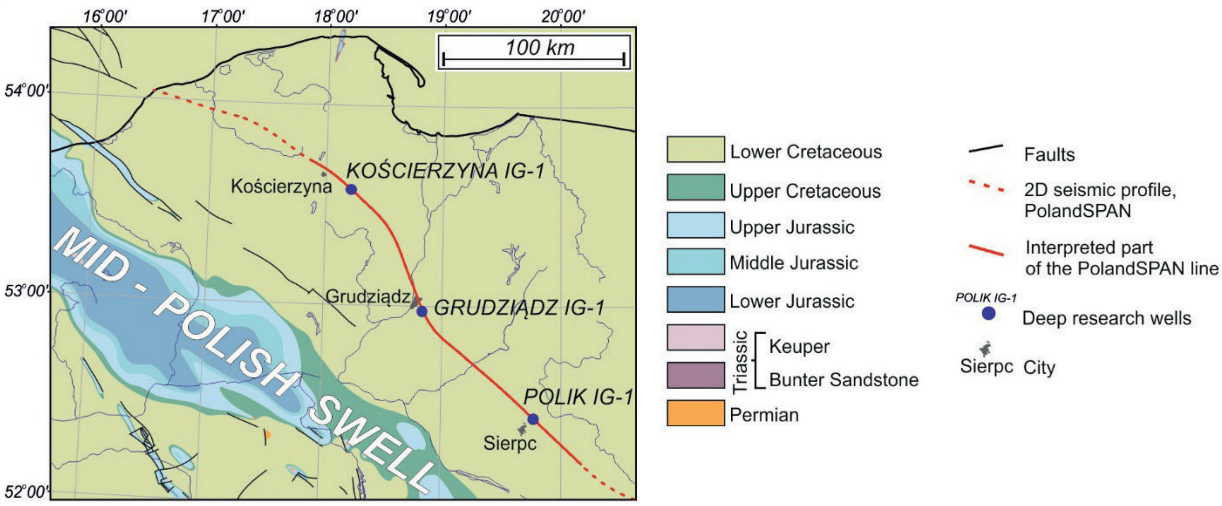

Fig. 1. *Geological map of NE Poland without Cenozoic (simplified after Dadlez et al. 2000)*

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Structural evolution of the eastern part of the Silesian Nappe recorded in deformation bands, Polish segment of the Outer Carpathians

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Deformation bands (DB) are microstructures that keep a record of burial conditions at the time of their formation hence they are very good as a tool for the reconstruction of structural history. DB are known to develop in porous sandstones and they often accompany fault zones (Fossen et al. 2007). However, DB are rarely reported within the Outer Carpathians (Tokarski et al. 2006). This paper presents a record of DB in flysch strata of the eastern part of the Silesian Nappe between the Dwernik and Solinka rivers. In this segment of the Outer Carpathians, the southern part of the Nappe is subdivided into the Central Carpathian Synclinorium and Fore-Dukla Subunit. In the studied section of the Central Carpathian Synclinorium, the Lower Krosno beds (Oligocene to early Miocene in age) are folded into regional-scale NW-SE trending folds. The studied section is bordered and cut by several fold-parallel regional-scale thrust faults (Ślączka 1980, Malata et al. 2014). DB are distributed unevenly along the studied section and their appearance is restricted to thick-bedded sandstones. They are arranged into cluster zones with a strike parallel or sub-parallel to the strike of the host strata. Phyllosilicate, solution and cataclastic DB with a shear component were distinguished. The majority of DB are represented by the shear cataclastic type with a thickness of below 0.5 mm and a displacement of up to few millimeters. Cathodoluminescence studies reveal feldspar cataclasis within DB, and the presence of at least three types of carbonate generation in the host rock, where 2 of them postdate the formation of the DB. Structural analysis suggests that the DB mainly formed at the present position of the strata. The DB record represents a NE-SW oriented compressive stress field state. Most DB were found within zones relatively close to the regional-scale faults but they also occur in zones where these faults are not found. In most cases, DB were found in strata tilted at a moderate angle. Furthermore, the orientation and kinematics of the DB fit the Riedel shear structures model. It seems that locally, along thick-bedded sandstones, shear zones originated in which DB were formed. In the studied section, the DB record predominantly represents post-folding compression.

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Synconvergent exhumation of volcano-sedimentary succession from the Kamieniec Metamorphic Belt (Central Sudetes, Bohemian Massif)

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A volcano-sedimentary succession with preserved three deformation fabrics is exposed in the Kamieniec Metamorphic Belt (KMB) in the Central Sudetes. The Belt represents the easternmost part of the Variscan

Belt of Europe and is interpreted as an allochtonous portion of the Saxothuringian Domain that was formed owing to Variscan collision between Saxothuringian and Brunovistulian domains representing Central and East Sudetes, respectively. The KMB comprises mica schists with intercalations of quartzo-feldspatic schists and subordinate marbles, amphibolites and eclogites. These rocks bear a strong imprint of Variscan tectono-metamorphic reworking.
Petrological study and pseudosection modelling have been used to establish the PT history of these rocks. Thermodynamic modelling suggests that mineral assemblages record peak-pressure conditions of 20–25 kbar at ca. 520°C (M1) which is inferred from fengitic micas and chloritoid blasts preserved in garnet porphroblasts. The M1 stage was related to formation of S1 sub-vertical fabric preserved in the investigated area. Quartz deformation microstructures associated with this event are characterized mainly by single c-axis girdle pointing to top-to-NNE-N non-coaxial shearing and quartz aggregate typical for transition between GBM and SGR mechanisms. The M1 stage was followed by decompression to 6–7 kbar and subsequent metamorphism with record of temperature progression from 500°C to 600°C at 10 kbar (M2). This part of the PT path was calculated based on garnet composition utilising isopleth geotermobarometry. The M2 event was related to various stages of F2 folding and was responsible for passive rotation of S1 fabric. F2 folding led to formation of flat S2 fabric and quartz textures associated with this event are characterized by I-type crossed c-axis girdles pointing to coaxial plain-strain deformation during this event. Quartz aggregate related to S2 fabric display microstructures typical for GBM recrystallization mechanism. Final retrogression to 3 kbar and 550°C (M3) is inferred from occurrence of staurolite and andalusite porphyroblasts. The M3 stage was associated with non-coaxial shearing with top-to-SW-W kinematics. The later conclusion is based on quartz textures resembling single c-axes maxima as well as several kinematic indicators like S-C type structures, asymmetric pressure shadows developed around garnet porphyroblasts or sigmoidal inclusion trails preserved in garnet and plagioclase grains. Development of deformation microstructures during this stage was related to reactivation of older S2 sub-horizontal fabric. Quartz microstructures related to new complex S2+3 fabric are typical for SGR recrystallization mechanism.
A combined petrological and microstructural study based on metamorphic assemblages associated with described deformation fabrics and quartz textures and microstructures allowed characterisation of the observed deformation structures as related to syn-convergent exhumation of the volcano-sedimentary succession exposed in the Kamieniec Metamorphic Belt. The whole process underwent in front of a rigid buttress represented by the Brunovistulian terrane.

The study was financed by the NCN research grant UMO-2015/17/B/ST10/02212.

Presentation of complex geological structures in the PGI-NRI 3D model viewer "Geo3D"

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The PGI-NRI is developing in-house web viewer allowing to manipulate, query, slice and virtually drill a 3D representation of geology (3D geological model). Current beta version supports display of solid models, cross-sections, horizontal section maps and virtual boreholes. Layers can be switched on and off or "exploded" – that is uplifted with mouse to see next layer's top (Fig. 1). This viewer is being constantly upgraded and we hope to also visualize parametric grids in the relatively near future. Furthermore, we are researching ways of visualizing model uncertainty in this viewer. Capabilities of current release version of the viewer can be explored at:
http://webcad.pgi.gov.pl/geo3d/pl/projekty.

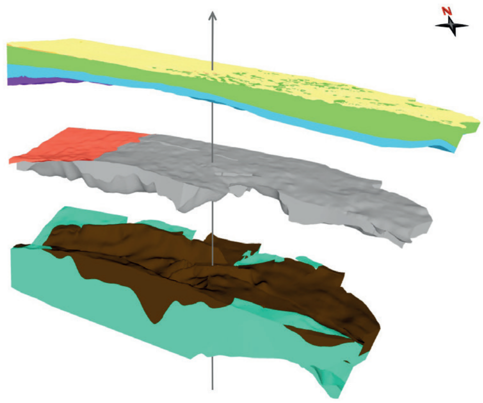

Fig. 1. *Visualization of a 3D model of Lublin basin, in "explode objects" mode of WebGeo3D viewer*

Zircon U–Pb dating of lower crustal rocks from the Góry Sowie Massif (Central Sudetes, SW Poland): new insights on the sedimentary origin and the tectono-thermal evolution

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Devonian HP-UHP lithotectonic associations represent pivotal element of Paleozoic evolution of European Variscan belt across the continent from Portugal to Poland. The Góry Sowie Massif (GSM), located in the Central Sudetes, represents one of the best preserved outcrops of lower crustal rocks that experienced protracted Devonian tectono-metamorphic history at the easternmost extremity of the belt. The area is surrounded by Devonian ophiolite remnants (c. 400 Ma; Kryza & Pin 2010) and by Devonian and Silurian to Carboniferous sedimentary basins in the northern and southern part, respectively. The GSM is mainly composed of paragneisses and subordinate orthogneisses, metabasites and granulite. The dominantly sedimentary association and the overall geotectonic setting contrast with other kilometer-scale granulite complexes in the Bohemian Massif that are dominated by felsic granulites and Late Cambrian orthogneisses that experienced 340 Ma HP metamorphism. Weak Carboniferous overprint makes the GSM a key locality to better understand Devonian stages of formation of HP granulites and provenance of the whole pre-Devonian lithological association. New U–Pb analyses were carried out on zircons from four migmatitic paragneisses, three felsic biotite-poor granulites and two biotite-rich granulites in the northern part of the GSM, in order to constrain source provenance and tectono-thermal history of the area.

The paragneisses are dominated by stromatic migmatite, comprising medium-grained leucosomes alternating with melanosomes. The main mineral association is biotite, plagioclase, K-feldspar, quartz, garnet and locally sillimanite and/or kyanite. Accessory minerals include zircon, apatite, monazite, rutile, opaque and minor tourmaline. Zircons from the paragneisses are mostly prismatic to sub-rounded grains with oscillatory cores (Th/U > 0.1) overgrown by dark homogenous metamorphic rims (Th/U < 0.1). The cores record a main age population between 492–545 Ma (40–50% of concordant analyses) and few Neoarchean to Proterozoic clusters, whereas the metamorphic rims yield younger ages (25–40%) between 381–396 Ma. Felsic granulites occur as hundred m-scale bodies associated with metric lenses of amphibolites, mafic and ultramafic rocks in the northern part of the massif. The felsic granulite is mainly composed by plagioclase, quartz, garnet, kyanite and with biotite and K-feldspar. In biotite-poor granulites there is minor biotite, whereas the biotite-rich granulite is characterized by abundant biotite, and sillimanite replacing kyanite. Zircon, monazite, apatite, rutile and opaque minerals are present as accessory phases. Zircons from biotite-poor granulites are mostly sub-rounded and "soccer-ball" grains, while zircons from biotite-rich granulites are mainly idiomorphic prisms. Under CL, zircons show similar patterns of those from paragneisses: cores surrounded by rims. Zircons from biotite-poor granulites show a main Devonian peak (25–40%) with ages between ca. 391–402 Ma obtained on rims and entire "soccer-ball" grains. Cores record abundant Cambro-Ordovician population and few Neoproterozoic ages. In contrast, zircons from biotite-rich granulites provide a main peak (25–34%) at ca. 499–531 Ma with a small younger cluster at ca. 396–425 Ma and minor older population at Neoarchean to Proterozoic. The well preserved Cambro–Ordovician population in the biotite-rich granulites correlates with less preserved population of the biotite-poor granulite, suggesting more pronounced metamorphic (re)crystallization of zircon in biotite-poor granulite.

The new data reveal that source provenance of the paragneisses as well as granulitic rocks was dominated by Cambro-Ordovician sources. The Cambrian sedimentary and possibly also felsic and mafic volcanic rock association was subsequently metamorphosed by Middle Devonian HP tectono-thermal event coeval with the emplacement of the Devonian ophiolitic rocks surrounding the area. Therefore, the Devonian HP event is possibly related to large scale oceanic/continental subduction.

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Polyphase structural evolution of the supracrustal series of the Orlica-Śnieżnik Dome (Sudetes, Poland): modelling based on new data from amphibolites and mica schists

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The supracrustal succession of the Orlica-Śnieżnik Dome (OSD; Sudetes, Poland, NE Bohemian Massif), composed of metasediments and metavolcanic rocks, experienced one progressive or number of single tectono-metamorphic events during the Variscan orogeny. Because of very complex deformation history recorded in the supracrustal rocks and discrepant structural observations, there is still no consensus on the number of deformation phases, shear/folding regimes and strain directions (for review see Żelaźniewicz et al. 2014). New data obtained from the meta-igneous amphibolites and neighboring mica schists revealed that only the mica schists recorded the full sequence of deformations. The D1 stage involved W-E or NW-SE contractional thrusting that caused development of isoclinal to tight F1 microfolds with subhorizontal N-S-oriented axes, V-shaped foliation S1 oriented axially to the F1 folds or mimetically to the protolithic bedding (S0) and intersection lineation L1i because of crossing S0 and S1 planes. This stage is poorly preserved in the amphibolites but some relictic S1 planes are findable within the plagioclase porphyroblasts formed afterwards. The next D2 stage was linked with maximal burial, when well-preserved steeply to moderately-plunging E- or NE-oriented schistosity (S2 planes) with intertectonic garnet and plagioclase σ-clasts in the mica schists and penetrative foliation/bedding in the amphibolites were formed. Tight asymmetric intrafolial micro- or meso-folds with axial foliation S2 and subhoritontal axes are abundant in NE part of the OSD (where the schistosity is vertical), whereas S-C structures in mica schists were found in the western part. On the S2 planes there are mineral/elongation lineation (L2). Crossing S1 and S2 planes form intersection lineation L2i. In the amphibolites, both types of the F2 folds are oriented similarly. After the D2 stage, because of the onset of exhumation, the tectonic regime rotated from thrusting into transform motion which is documented by folding of the S1+S2 subvertical planes and formation of dextral tight asymmetric "Z"-shaped mesofolds (F3) with subvertical N-, NE or E-oriented steeply-plunging axes. Moreover, during this stage, there are shear bands formed along the reactivated S1+S2 surfaces. Directly thereafter, still under transform regime, there was a change of shear stress direction from dextral into sinistral, which is documented by formation of new S-C structures, crenulation cleavage (with intersection lineation L3i and mineral lineation L3min) and "S"-shaped asymmetric folds that coaxially overprinted the earlier F3 folds to finally form "S on Z" superimposed second structures *sensu* Ramsay (1962). In the NE part of the OSD, such change in the regime was not observed in the NE part of the OSD. In the amphibolites, both kinds of S-C' structures, plagioclase-calcite σ-clasts (L3min) and anastomosing cleavage with crenulation lineation are oriented similarly to those of the mica schists. Finally, a set of large-scale F4 folds with subhorizontal or gently-plunging S- or SW-dipping axes and variously-oriented shear bands was generated merely in the mica schists.

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Morphotectonic control of the Poprad valley development within the Outer Carpathian units, Sądecki Beskid, Kraków-Prešov fault zone, Poland and Slovakia. The preliminary studies' results

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Kraków-Prešov fault zone might be the most important regional tectonic structure to influence the geological architecture of the study area. It is an extension of the subsequent mutual strike-slip displacements of the two blocks along the Kraków-Lubliniec Fault Zone (Golonka et al. 2009, 2011). Both faults distinguish the border zone between the East European Craton (represented by the Małopolska Block) and the Brunovistulicum Terrain (represented by the Upper Silesia Block; Żaba 1995, Buła et al. 2008). Their impact on the morphology of the area is restricted by the fact that they belong to the deep, Sub-Carpathian, Paleozoic complex overlaid by the younger Mesozoic complex as well as the Carpathian nappes (Buła et al. 1997, Żaba 1999, Buła 2000). However, some features within those young formations exhibit the signs of possible activity of the Kraków-Prešov dislocation.

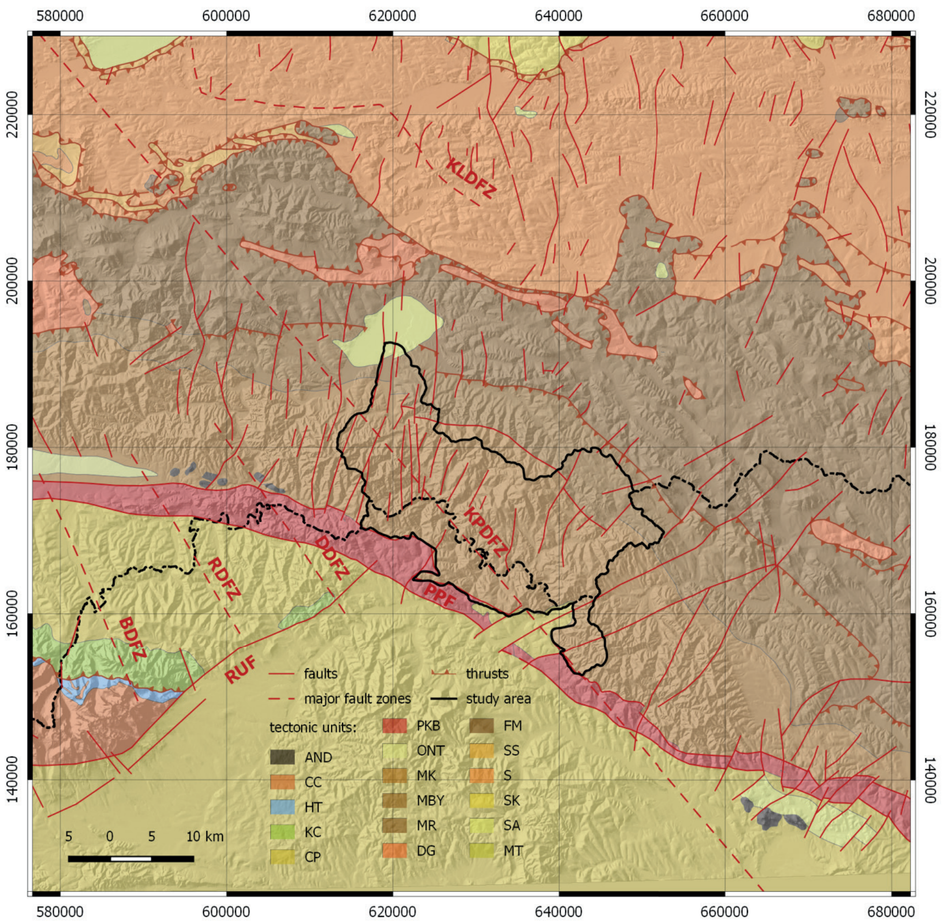

Fig. 1. *Tectonic sketch map (compiled from various authors, e.g.: Zuchiewicz 1981, Jurewicz 2005, Buła et al. (eds.) 2008, Żelaźniewicz et al. 2011, Mastella et al, 2012): BDFZ – Białka Deep Fault Zone; RDFZ – Rijeka Deep Fault Zone; DDFZ – Dunajec Deep Fault Zone; KPDFZ – Kraków-Prešov Deep Fault Zone; KLDFZ – Kraków-Lubliniec Deep Fault Zone; PPF – Peri-Pieniny Fault; RUF – Ružbachy Fault; AND – andesites; CC – Crystaline Massif of the Tatra Mts.; HT – High Tatra units; KC – Krížna and Choĉ nappes; CP – Central Carpathian Paleogene sediments; PKB – Pieniny Klippen Belt; ONT – Orava-Nowy Targ Basin; Magura Nappe: MK – Krynica Unit; MBY – Bystrica Unit; MR – Raca and Siary units; DG – Dukla and Grybów units; FM – Foremagura Nappe; SS – Sub-Silesian Nappe; S – Silesian Nappe; SK – Skole Unit; SA – Cenozoic cover of the Outer Carpathians basement; MPC – Mesozoic cover of the Outer Carpathians Basement; PPC – Paleozoic cover of the Outer Carpathians basement; NPC – Neoproterozoic rocks below the Paleozoic cover; CB – Outer Carpathians basement*

The DEM based morphometric studies and remote sensing analysis performed within the Dunajec catchment area proved that the deep-seated NW-SE oriented fault zones play a vital role in the geological architecture and morphology of the Central Carpathians. The development of the secondary fault structures was strictly determined by those dislocations. The manifestation of their activity can be observed as the deformations of some other tectonic structures along the main fault zones, especially the folds' axes. Also, the geometric and morphometric features of the drainage system were influenced by the activity of those deep structures. The concavity analysis of streams as well as isolongs analysis and the hypsometric integral calculation suggest the Kraków-Prešov zone as the area of high relative tectonic activity.

The base-level surfaces indicate the general tendencies in relative vertical movements within the analyzed area.

The zones along the major dislocations exhibit the features characteristic for the active areas including high concentration of the base-levels isolines (isobases), as well as, their curvy shape.
The preliminary structural observations and measurements made within the Poprad drainage basin support the thesis that the Kraków-Prešov fault plays a vital role in the development of the geological architecture and morphology of the study area. The development of the secondary fault structures was strictly determined by those dislocations. The manifestation of their activity can be observed as the deformations of some other tectonic structures along the main fault zones, especially the folds' axes. Also, the geometric and morphometric features of the drainage system were influenced by the activity of those deep structures.

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Comprehensive analysis of geological, geochemical and geophysical data during the exploration campaign of ORLEN Upstream in the Outer Carpathians

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Carpathian exploration assets were purchased by ORLEN Upstream in 2015/2016. The area consists of the 435 concession block, parts of 434 and 433, and the Skołyszyn concession block. From that time, a detailed analysis of archival geological data – including available wells and seismic survey (Pola – Pasterniki 3D – total area 190 km^2), as well as surface geological mapping were performed.
A very intense exploration activity on ORLEN's Carpathian assets is currently carried out. In 2016–2017 a comprehensive analysis of petroleum, reservoir and source rocks collected from field outcrops was made. Moreover, in order to characterise a petroleum system of the analysed area, as well as to achieve the subsurface saturation image, a regional geochemical analysis was carried out. Currently it is one of the widest surface geochemical surveys made in the Polish Outer Carpathians (almost 80 km^2). The surveys were carried out on hydrocarbon samples collected form soil air and shallow wells. Finally, biogenic, thermogenic and mixed gas was identified.
As a result of the integrated data analysis, ORLEN Upstream team have found a number of potential exploration objects, which are located in Iwonicz – Gorlice fold and Harklowa Depression. In 2016–2018 three exploration wells have been drilled. During drilling and well tests, geochemical analysis of mud gases, desorbed gases and production gases was made. The full spectre of geophysical measurements was made as well.
In 2017 seismic survey of Korzenna 2D and geological cartography on 475 km^2 was held. Currently, an

acquisition of 3D seismic data in Biecz and Jasło region (total surface source area ca. 200 km^2) as well as complementary cartographic surveys are carried out.
The results of the tests confirmed high complexity of this region and showed out the differences between the seismic survey and results of wireline logging. Considering the technical progress and new research and analytical methods, it seems that only multidisciplinary approach to assessment of hydrocarbon potential in fold and thrust areas, such as the Carpathians, enables a rational carrying out exploration works in the future.

A testimony to the fall of Rodinia and rise of Pangea: Neoproterozoic through Paleozoic orogenic events in Poland

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When Rodina started to break-up ~750 Ma ago, Poland was partitioned into two parts. One part stayed on the SW margin of Baltica while the other was lost (now in Amazonia?) as it was separated by rifting and drifted away. Baltica was left with the attenuated, somewhat embayed margin with a Neoproterozoic passive succession growing upon. Few continental ribbons presumably remained close to the Baltica mainland. The thinned margin, rheologically weaker, was the very feature that controlled later evolution of the Trans-European Suture Zone, TESZ, a wide junction between the East European Platform (EEP, ~Baltica) and the West European Platform (WEP) that possessed extensive Neoproterozoic/Cadomian basement of Gondwana descent. A process of building the new supercontinent, Pangea, commenced with the Cadomian accretions, now fragmentarily encountered subsurface in southern Poland, in the Małopolska block, MB, and the Upper Silesia block, USB. The USB was part of the composite Neoproterozoic terrane of Brunovistulia. In both blocks, Cadomian foreland deposits developed with detrital deliveries both from the orogen and from Baltica. In Baltica, Małopolska and Brunovistulia formed a promontory, so that the continental Poland expanded a bit to the SW.
Some further expansion took place when the Gondwana-born East Avalonia accreted to Baltica in the Late Ordovician, which gave rise to the so-called Balonia. With the new gains, though small, Poland acquired a wide embayment in the Rheic/T-T Ocean. The embayment resulted in various geodynamic, paleogeographical and paleobiostratigraphical consequences. East Avalonia established a barrier from Laurentia. In the Late Silurian, the collision between Laurentia and Balonia, brought about the Caledonian orogen, the Avalonian foreland of which was topped with an external fold-thrust belt. In NE Poland, the belt embraced parautochthonous/autochthonous units of Ordovician-Silurian succession of mixed provenance as proved by the detrital zircon spectra. In SE Poland, the HCM do not meet criteria for the orogen. It developed in a specific position within the TESZ which in the very sector embraced the attenuated passive margin of Baltica in the lower crust and the Cadomian foreland units in the upper crust. In the southern HCM, the dextral wrenching on the NE margin of the TESZ gave rise to the S-verging folds in Lower Paleozoic succession (<40% N-S shortening). This sucession did receive detrital input from both Baltica and the westerly located Cadomides. On the SW edge of the TESZ (USB-MB border), sinistral strike-slip regime was generated and controlled deformation in the vicinity of the Kraków-Lubliniec Fault Zone. Afterwards the then Poland was covered with Devonian-Carboniferous platform. Since Mid-Devonian times, the embayment in Laurussia started to accommodate an archipelago of mutually colliding terranes that slightly outpaced the Gondwana mainland. In the Late Carboniferous, the space between Laurussia and Gondwana was tightly sealed with the Variscan belt. Tectonic stresses generated by the continental collision were transmitted far into the foreland and caused folding and some localized thrusting/reverse faulting, especially within the TESZ close to or over the buttressing EEP slope. Those events brought final gains to Poland on the southwest and eventually completed the modern Polish territory within the reborn supercontinent known as Pangea.

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