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Obsah – Content

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COVER: Klippe of red nodular limestones of the Czorsztyn Formation (Middle–Upper Jurassic) of the Litmanová group of klippens near the Litmanová ski resort. This klippen group represents olistoliths occurring within bodies of the Milpoš Breccia of the Proč Formation (Paleocene–Lower Eocene) of the Šariš Unit. Locality is presented in article by Plašienka et al. in this issue. Photo D. Plašienka. The backgroud of the cover visualizes the grey calcitic marble in the alochthonous body of Meliaticum in the North-Gemeric zone cropping out in the quarry on Kurtová skala hill at Jaklovce village. The deformation-recrystallization characteristics of the rocks of Kurtova skala hill are presented in article by Németh et al. Photo Z. Németh.

OBÁLKA: Bradlo červených hľuznatých vápencov czorsztynského súvrstvia (stredná – vrchná jura) skupiny litmanovských bradiel pri lyžiarskom stredisku Litmanová. Litmanovské bradlá reprezentujú olistolity vystupujúce v telesách milpošských brekcií paleocénno-spodnoeocénneho pročského súvrstvia šarišskej jednotky. Daná lokalita je prezentovaná v článku Plašienka et al. v tomto čísle. Foto D. Plašienka. Pozadie obálky reprezentuje sivý kalcitický mramor alochtónneho telesa meliatika v severogemerickej zóne v kameňolome na Kurtovej skale v oblasti Jakloviec. Deformačno-rekryštalizačné charakteristiky hornín na Kurtovej skale sú prezentované v článku autorov Németh et al. Foto Z. Németh.

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Early stages of structural evolution of the Carpathian Klippen Belt (Slovakian Pieniny sector)

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Abstract

The Pieniny Klippen Belt (PKB) is a distinctive, suture-like tectonic zone that separates the External Carpathian Tertiary accretionary wedge (Flysch Belt) and the Cretaceous thrust stack of the Central Western Carpathians. Whereas the lithostratigraphy of various PKB units is fairly well-known, its tectonic evolution and development of the peculiar "klippen tectonic style" is a subject of very different opinions. We present structural data from the Pieniny sector of the PKB in NE Slovakia, which indicate that: 1) distinction should be made between the "blocky" klippen and the "ribbon" klippen, since locally considerable reorientation of the original attitudes of structural elements is presumed for the former ones; 2) bedding poles of the "ribbon" klippen (Jurassic to Neocomian limestones and radiolarites) plot in a girdle in NWN–SES to N–S direction, while those of the klippen matrix (mid-Cretaceous to Lower Eocene marlstones, shales and sandstones) are shifted clockwise; 3) occasionally, the bedding-perpendicular cleavage and buckle folds record an early layer-parallel shortening, which are clearly older than brittle transpression-related faults and fractures – therefore they are interpreted as initial detachment and thrusting deformation elements that are likely related to the nappe-forming processes in the PKB; 4) fold axes, β-intersections of mesoscopic fold limb pairs, as well as a part of the bedding/cleavage intersections are all oriented in the SW–NE direction (mean 55°), i.e. oblique to both the mean bedding strikes (85°) and the PKB boundaries (trending ESE ca 120°); 5) the dextral transpression model of an originally SW–NE trending fold-and-thrust belt is favoured to explain these relationships; 6) in addition, there are indications of another deformation event recorded by NW–SE trending cleavage traces and minute fold axes in places.

Key words: Pieniny Klippen Belt, structural analysis, bedding, cleavage, folds, Western Carpathians,

Introduction

The Western Carpathians evolved as a collisional orogen for ca 150 Ma from the Late Jurassic until the Late Neogene. The complex convergent movements involved crustal shortening, basement-involved and cover nappe thrusting, as well as elimination of some intervening oceanic domains. There are two zones considered as oceanic sutures and/or fossil plate boundaries present in the Western Carpathian structure (e.g. Froitzheim et al., 2008 and references therein). The first suture relates to the Middle/Late Jurassic closure of the Neotethyan (Meliata-Hallstatt) Ocean and its elements are to be found in the Internal Western Carpathian and Eastern Alpine zones. The second suture follows the inner/outer Carpathian boundary and separates the Cretaceous Central Carpathian basement/cover thrust stack from the Tertiary External Carpathian accretionary wedge. The main element of the latter is the Pieniny Klippen Belt, a very narrow and partly discontinuous, but in its special composition and structure coherent zone that extends for hundreds of kilometres. Even though no ophiolite rocks in primary position are present there, the zone is commonly believed to be somehow related to closure of the Penninic oceanic domains.

Although the Pieniny Klippen Belt (PKB) is regarded as a basically tectonic phenomenon by most authors, the detailed structural works that would attempt at qualification and quantification of its deformation features, as well as at explanation of the peculiar inner PKB structure, are rather sparse. Traditionally, the general tectonic ideas were based on some macroscopic structures indicated by field mapping, and on the mutual relationships of rock units with known lithology and stratigraphic age (e.g. Andrusov, 1938, 1968; Birkenmajer, 1977). Their grouping into lithostratigraphic and tectonic units then served as a basis for all interpretations of the PKB structure and evolution. However, this approach has its limits and many pitfalls. It is strongly dependent on the actual knowledge about the age and position of the key formations, such as conglomerates and synorogenic flysch deposits. For example, Andrusov based his assumptions about the age of thrusting events in the PKB first on regional discordances (Pieniny Phase, later renamed to Manín Phase, Upper Aptian – Andrusov, 1938),

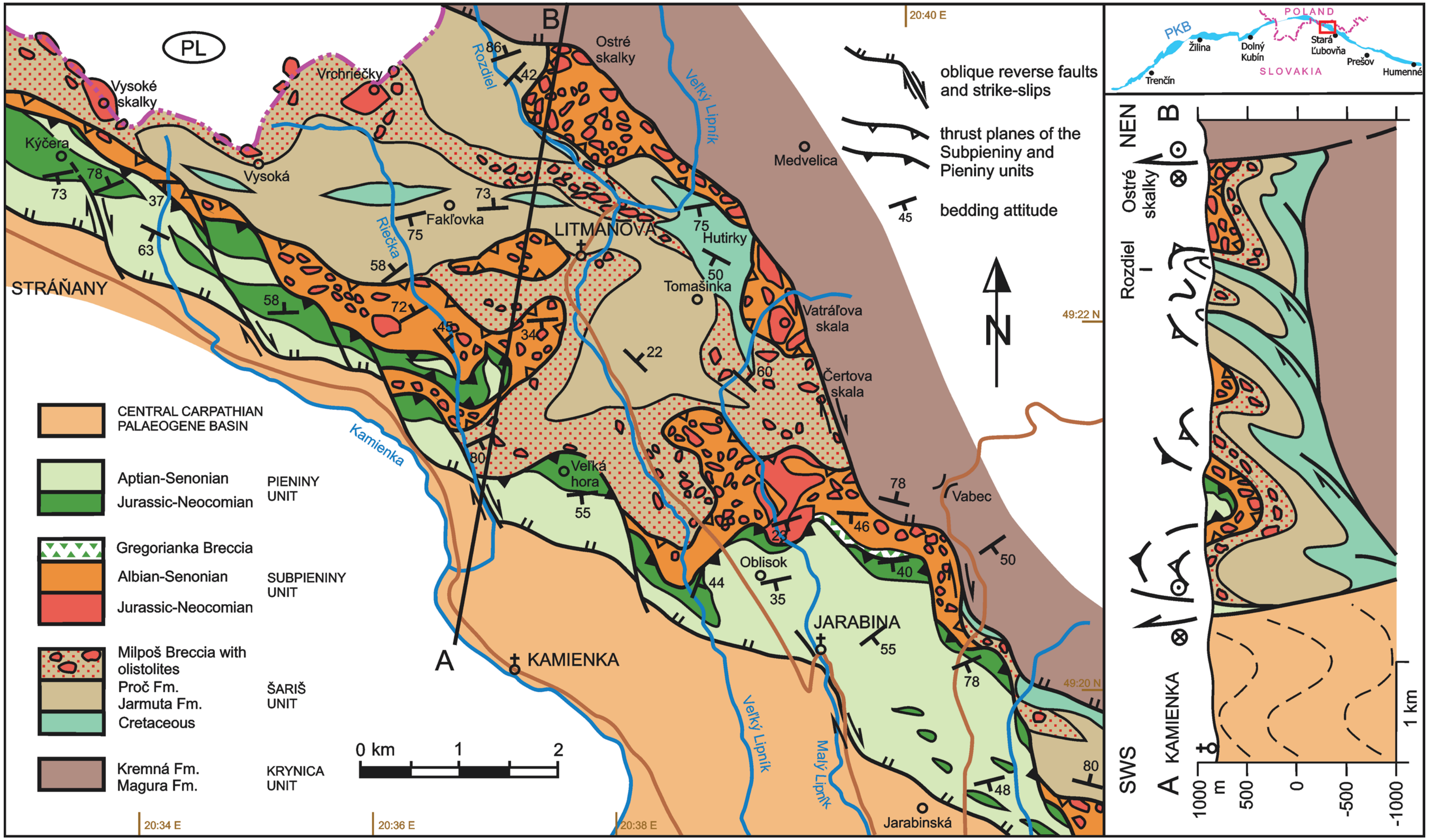

Fig. 1. Simplified geological map and cross-section of the Slovakian part of the Pieniny sector of the Klippen Belt between Stráňany, Litmanová and Jarabina villages (for its eastward continuation up to the Údol village see Plašienka and Mikuš, 2010; their Fig. 2).

later he relied on the supposed transgressive position of the Senonian Upohlav conglomerates (Subhercynian Phase – Andrusov, 1968) and, finally, he accepted the intra-formational character of these conglomerates as members of continuous Cretaceous PKB successions and stated the Laramian Phase as the main nappe-forming stage in the PKB (Andrusov, 1974). Even today, when the age of most of the formations is relatively well established, there are quite opposite views on some local, but also large-scale structures. For instance, the Upper Cretaceous clastic formations of the "Periklippen Zone" (sensu Maheľ, 1980) in Western Slovakia are either regarded as members of continuous sedimentary successions of the Manín and Klape units (e.g. Marschalko, 1986; Salaj, 1994), or they should represent an independent, "post-nappe" transgressive cycle (Gosau Group – Plašienka, 1995a; Salaj, 2006), or even a separate tectonic unit in a lower structural position (Podháj Unit – Rakús & Hók, 2005; Rakús in Mello ed., 2011). Consequently, it appears inevitable to utilize also some other, independent methods, which would bring new arguments in favour of the either opinion. Field-based structural analysis and its following laboratory applications could be one possibility. Nevertheless, these have some limits and shortcomings as well.

First of all, the entire deformation evolution of the PKB units virtually occurred under very low temperatures at diagenetic conditions, i.e. it is dominated by brittle structures – faults, joints, syntectonic veins etc., partially preceded or accompanied by diffusion mass transfer mechanisms like pressure solution and precipitation. The fault structures of known kinematics are usually elaborated by various, computer-aided methods of palaeostress analysis. In addition to the methodological problems of this technique in polyphase deformed regions, the Western Carpathians deal with the special problem of rotations. This concerns both the Tertiary clockwise stress field rotation, as well as the counterclockwise block rotation of the entire Western Carpathian part of the ALCAPA megaunit (see e.g. Marko et al., 1995). The PKB, with its exposed tectonic position at the backstop of the accretionary prism, was particularly influenced by these complex movements. The dominant transpressional mode of deformation reported by several authors (Ratschbacher et al., 1993; Nemčok and Nemčok, 1994; Kováč and Hók, 1996) may have caused additional minor block rotations within the PKB wrench zone. As a result, the reconciliation of the polyphase tectonic movements recorded by brittle deformation structures faces important problems not only in their absolute, but in the relative dating as well. Some authors even regarded the PKB structure as resulted from a single, Oligocene to Lower Miocene deformation phase (Srnánek and Salaj, 1965; Sikora, 1974; Książkiewicz, 1977; Ratschbacher et al., 1993).

The purpose of this contribution is to communicate several conclusions based on structural investigation of a rather small, but important segment of the PKB. It is located in the Slovak part of the Pieniny sector between the Stráňany and Údol villages near the town of Stará Ľubovňa. From this area, we describe the principal mesoscopic structural elements, such as bedding, cleavages and folds, as well as their mutual relationships in various rock media, attitudes and overprint criteria with the aim at recognition of the earliest deformation stages recorded in various PKB units. We do not explore the superimposed brittle structures, such as faults with slickensides or joints, in detail here. The reader is recommended to the above mentioned papers (especially Ratschbacher et al., 1993 and Nemčok and Nemčok, 1994). New investigations of brittle structures (Mikuš, 2010) will be published separately. The present paper follows the publication of Plašienka and Mikuš (2010) and brings structural arguments in favour of a conceptual model of the PKB structure and evolution outlined in that article.

Methods

The paper presents results of a classical, field-based structural analysis. The structural mapping was performed simultaneously with normal geological mapping in the scale 1 : 10 000, lithological-biostratigraphical observations and sampling. By this way, a distinction could be made between individual tectonic units which are participating at the structure of the investigated PKB segment (see Plašienka and Mikuš, 2010). This approach also enabled to categorize the structural input data accordingly.

Structural data used for the orientation and kinematic analyses were gathered during several field seasons (2004–2010) from more than 200 localities spread over the whole area (Fig. 1 in the present paper and Fig. 2 in Plašienka and Mikuš, 2010). Around 700 individual measurements have been evaluated and the majority of them are presented in this paper. The oriented data were handled and are represented using the software Stereo32 (http://www.ruhr-uni-bochum.de/hardrock/downloads.html).

Structure of the PKB between the Stráňany and Údol villages

The investigated segment of the PKB belongs, according to the classical division of Scheibner (1967), to the Slovak part of the Pieniny sector. All principal units of the PKB were described from this area (e.g. Matějka, 1963; Srnánek and Salaj, 1965), however, they have never been depicted cartographically as regional tectonic entities. The existing geological maps in the scale 1 : 50 000 (Nemčok, 1990; Janočko, ed., 2000) show only klippen of various compositions as rigid inclusions surrounded by a poorly defined klippen "mantle". In this area, Ján Nemčok (1980; Nemčok et al., 1989) even came to the conclusion about the sedimentary origin of the PKB, i.e. the klippen are merely olistoliths resting in the Palaeogene, coarse-grained deposits (Gregorianka Breccia) of the Jarmuta-Proč Formation.

Recently, three principal tectonic units of the PKB have been distinguished in this area by Plašienka and Mikuš (2010). From bottom to top, these are the Šariš, Subpieniny and Pieniny thrust sheets. They are ranged to the tectonic unit of higher order – the Oravic Superunit that represents the PKB "sensu stricto", i.e. units derived from an independent palaeogeographic realm surrounding the Czorsztyn Ridge. This ridge is interpreted as a continental fragment – a splinter of the North European Platform in the Middle Penninic position, which was separated by Middle Jurassic – Lower Cretaceous rifting processes (Plašienka, 2003; Froitzheim et al., 2008). For a more detailed description of lithostratigraphy successions of these three units see Plašienka and Mikuš (2010) and Plašienka et al. (this issue). Here we present only a brief summary.

Šariš Unit

The Šariš Unit occurs in the lowermost structural position and includes a basinal, Jurassic to Lower Eocene succession. In the area investigated, its oldest recognized member is represented by the Lower Cretaceous thin-bedded, pelagic, often spotted limestones similar to the Pieniny Fm. (Fig. 2E). These are followed by various mid-Cretaceous hemipelagic sediments, including bioturbated marlstones of the "Fleckenmergel" facies, variegated, weakly calcareous shales and the so-called "black flysch" deposits – black shales and siliciclastic sandstones rich in mica flakes (cf. Oszczypko et al., 2004). The Upper Cretaceous sequence again involves variegated, mostly red shales (Malinowa Fm.) with thin intercalations of distal turbiditic sandstones. Starting from the latest Cretaceous and up to Lower Eocene, a calciclastic sequence of coarsening-upward, synorogenic flysch to "wildflysch" deposited (Jarmuta and/or Proč Fms). This includes hundreds of metres thick calcareous sandstone-dominated complex with bodies of coarse-grained mass-flow deposits, including huge slide blocks – olistoliths (Milpoš Breccia – Plašienka and Mikuš, 2010). The breccias and olistoliths are commonly composed of material derived from the overriding Subpieniny and Pieniny nappes. The tectonic style of the Šariš unit is controlled by the competent complex of Palaeogene sandstones, which either form gentle monoclines, or broad synclines divided by anticlinal cusps of older incompetent strata (Fig. 1).

Subpieniny Unit

The Subpieniny Unit is commonly designated as the Czorsztyn Unit in the Pieniny area (e.g. Birkenmajer, 1986). However, according to our investigations, this unit as a tectonic entity includes not only klippen of the typical Czorsztyn Succession, but also the Niedzica and Czertezik "transitional" successions. Therefore we find better to return to the original Uhlig´s term (Uhlig, 1907). Unifying of all these successions or partial units into one principal tectonic unit closely corresponds to the views of Sikora (1971) and Książkiewicz (1977) who, however, retained the name Czorsztyn for it. The Jurassic – Lower Cretaceous rocks form the stiff klippen of tectonic origin in the Subpieniny Unit and may be assigned, according to sometimes subtle differences in lithostratigraphic composition, to several successions named above (Birkenmajer, 1977; Wierzbowski et al., 2004). These klippen rest in the Albian to Maastrichtian matrix of various composition, including e.g. also the mid-Cretaceous "Fleckenmergel" facies and "black flysch", but dominated by the Senonian red pelagic marlstones of the "Púchov facies". The Subpieniny successions are terminated by a coarsening-upward sequence of calcareous turbiditic sandstones (Jarmuta Fm.) and carbonate tectono-sedimentary breccias of the Maastrichtian, possibly up to early Palaeocene age, which are known as the Gregorianka Breccia (Nemčok et al., 1989; Plašienka and Mikuš, 2010). This breccia is composed of material derived from the overlying Pieniny thrust sheet, typically Lower Cretaceous Pieniny limestones and cherts, Upper Cretaceous marlstones and sometimes also Jurassic radiolarites.

Structurally, the Subpieniny Unit was subdivided into two partial subunits (Plašienka and Mikuš, 2010). The Jarabina Subunit represents areally limited occurrences of thick imbrications of typical Czorsztyn Succession forming antiformal thust stacks in the rear part of the Subpieniny Unit (area around the Jarabina gorge and quarry – see Plašienka et al., this volume). The second, Maslienka Subunit, is tightly imbricated with isolated, decametre-sized blocky klippen of the Czorsztyn, as well as "transitional" Jurassic – Lower Cretaceous formations embedded in a strongly sheared matrix of Upper Cretaceous shales, marls and sandstones, hence forming a typical block-in-matrix structure of tectonic origin (broken formations or tectonosomes). This subdivision closely matches that of Książkiewicz (1977) who also distinguished the "Czorsztyn imbricated unit" (our Jarabina Subunit) and the "Czorsztyn blocky unit" (our Maslienka Subunit) with nearly identical characteristics. The inner structure of the Subpieniny Unit is controlled by the presence of a variously thick layer of mostly massive, competent Middle to Upper Jurassic sandy-crinoidal and nodular limestones, which are inserted between incompetent shally and marly Lower Jurassic and Upper Cretaceous strata. In the course of thrusting-shearing deformation, the competent layer was either dismembered into numerous small imbricates and boudins floating in incompetent matrix, or, in the case the competent layer was very thick (more than 50 metres), it forms a stack of thick imbricates that are laterally continuous for several hundred metres (see Fig. 3 in Plašienka et al., this issue). At the same time, these differences may have resulted also from the rugged, synsedimentary fault-controlled morphology of the Czorsztyn Ridge that was truncated by the basal detachment of the Subpieniny Nappe at various levels, sometimes may be even not reaching deep enough to attack the Jurassic rocks. This can be also the cause of a lateral discontinuity of the unit, which cannot be ascribed to the tectonic reasons only.

Pieniny Unit

The Pieniny Nappe involves basinal Jurassic – Cretaceous successions with small local variations in their lithostratigraphic content used for distinguishing of several lithostratigraphic successions (Pieniny s.s., Kysuca, Branisko; for the detailed lithostratigraphy see e.g. Birkenmajer, 1977). However, all these are united in a single, laterally continuous thrust sheet in the uppermost structural position within the Oravic Superunit of the PKB (see also Książkiewicz, 1977). The Pieniny successions are composed of well-bedded pelagic radiolarites, limestones and marlstones, hence forming a multilayer prone to folding. Consequently, also the overall structural style of the Pieniny Unit is different from the other two. The klippen of Jurassic – Lower Cretaceous formations are more elongated, lensoid or lozenge-shaped, extending for tens to hundreds of metres, but often they form stripes prolonged to a few kilometres. In this case they represent limbs or cores of large-scale upright folds, i.e. cuestas in the geomorphological sense. These types of klippen will be called "ribbons" in the following text.

Structural elements

In the PKB segment under question, we distinguish three types of rock media differing by their rheological properties and mechanical behaviour during the deformation processes. These are the "blocky klippen", the "ribbon klippen" and the "klippen matrix". The blocky klippen are nearly isometric, rectangular, spherical or ellipsoidal pieces, a few metres to hectometres in diameter, composed of competent rocks, mostly thick-bedded or massive limestones. They form the typical "block-in-matrix" klippen structure – rigid inclusions embedded in a soft shale-marl-sandy matrix. They rest either as olistoliths in the Milpoš Breccia of the Jarmuta--Proč Fm. of the Šariš Unit, or as tectonic fragments in the Upper Cretaceous variegated marlstones of the Maslienka Subunit of the Subpieniny Nappe. In the former case they can be considered as "extraclasts", because they were transported by sedimentary processes far from their place of origin into a younger foreland flysch basin. The latter are analogous to "intraclasts", i.e. they were derived from the same sedimentary succession as their matrix, but were emplaced by tectonic processes. Nevertheless, both types of the blocky klippen are structurally independent from surrounding matrix complexes and both participate on the typical humpy relief of the PKB.

The ribbon klippen are characterized by closer structural relationships to their soft matrix formations, even continuous successions are sometimes present. They can be subdivided into two subtypes again – the first are thick, but areally limited imbrications built by the massive or thick-bedded limestones of the Czorsztyn Succession (Jarabina Subunit of the Subpieniny Nappe) that usually form antiformal stacks with the matrix sediments inserted between individual scales (see section C in Fig. 2 by Plašienka et al., this issue). The second subtype is represented by elongated stripes, lozenges or lenses of well-bedded Jurassic – Lower Cretaceous strata of the Pieniny or Kysuca (Branisko) Succession accompanied by less competent younger Cretaceous formations. In this case, the competence contrast between klippen and matrix is less pronounced and structural and stratigraphic continuity occurs in places. However, there are also places where the Pieniny ribbon klippen are separated from their matrix by distinct faults indicated by sharp angular relationships of the inner bedding of klippen with respect to the klippen boundaries and surrounding strata (see below).

The klippen matrix (also variously named as the klippen "mantle" or "envelope" in the literature) consists of lithologically variable deposits that are generally less competent compared to the enclosed klippen. For that reason they experienced stronger deformation than the klippen, recorded e.g. by scaly structure, cleavages and folds. Moreover, shales and marls of the klippen matrix often exhibit penetrative shear deformation which postdated the primary structures described in this article, consequently these were strongly modified up to obliterated. Only more competent portions of the klippen matrix, like the thick--bedded or massive Jarmuta-type sandstones and breccias can form morphologically positive forms, which were designated as "pseudoklippen" (Stache, 1871 ex Andrusov, 1938).

The main structural elements, which will be treated in this contribution, are bedding, cleavages and minor folds. They represent the initial structures predating development of brittle fractures, faults and shear zones, which are so frequent in the PKB and which imprinted its final structural pattern. However, the faults and joint will not be treated in this paper, since the extensive dataset needs a large space to be evaluated thoroughly and will be presented in another publication. Some data concerning the kinematic and palaeostress analyses of the fault and joint structures of the region concerned and/or adjoining areas have already been presented by Birkenmajer (1970, 1983), Mastella (1975), Ratschbacher et al. (1993), Jurewicz (1994, 1997), Nemčok and Nemčok (1994), Jacko and Janočko (2000), Vojtko et al. (2010), Ludwiniak (2010) and Mikuš (2010).

Several lines of evidence indicate that the planar anisotropies and their fold distortions described here developed at very low temperatures. Despite macroscopically pervasive deformation, whereby even hand specimens are rich in veinlets, solution seams or fractures, the undistorted portions preserve the original microstructures perfectly, much better than e.g. the corresponding carbonates of the Central Carpathian units (e.g. Andrusov, 1974). The PKB carbonates generally lack the low-temperature authigenic minerals, such as albite or quartz, which are otherwise common in the Carpathian Mesozoic successions (Mišík, 1966, 1994, 1995; Mišík and Reháková, 2009). The temperature estimates in the PKB come from rather scarce data about the clay mineralogy, vitrinite reflectance, fluid inclusions, apatite fission-tracks and calcite strains.

According to temperature-dependent smectite to illite transformation data by Świerczewska (2005), the PKB experienced a lower imprint than the adjacent Magura Unit. The Grajcarek Unit (partly corresponding to the Šariš Unit of our area) exhibits temperatures between 110 and 135 °C, up to 165 °C in places. The rock complexes in the Maruszyna deep drilling record the temperature increase from ca 130 °C at 500 m depth to more than 160 °C at 4,500 m. However, some illite "crystallinity" and vitrinite reflectance data from mid-Cretaceous black shales of the Pieniny Unit indicated temperatures locally exceeding 200 °C, i.e. reaching the anchimetamorphic conditions (Wójcik-Tabol, 2003). Few fluid inclusion data were published directly from the PKB rock formations, Jurewicz

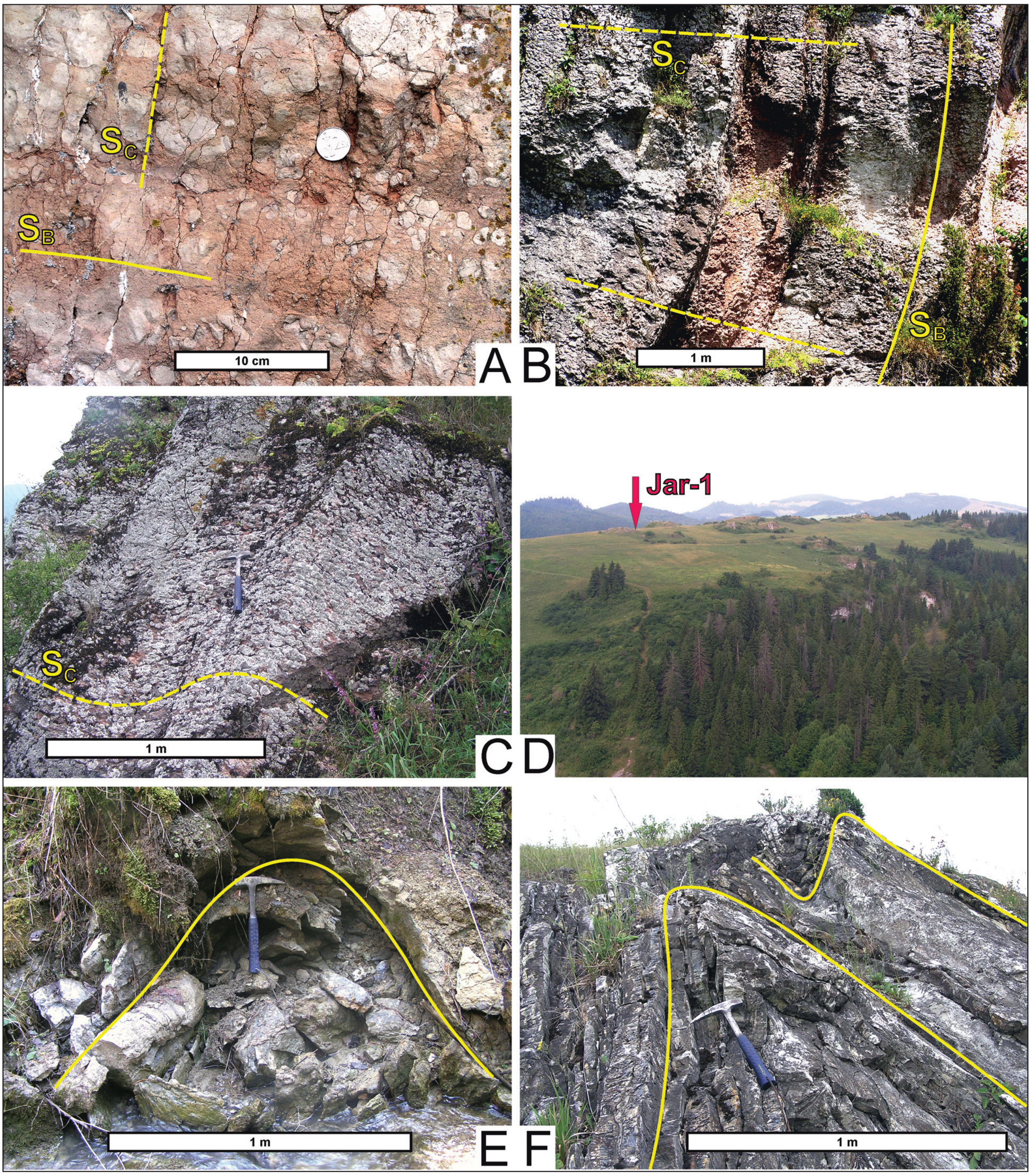

Fig. 2. Field photographs: **A** – bedding (subhorizontal) vs. cleavage (subvertical) relationship in the Czorsztyn nodular limestone (Malý Lipník Valley north of Jarabina); **B** – axial plane cleavage S_C in red nodular limestone, bedding vertical, cleavage horizontal (stumped blocky klippe, Rozdiel Valley northwest of Litmanová); **C** – buckled cleavage traces (intersection lineation of S_B and S_C) on the "en face" bedding surfaces (Czorsztyn limestone, Veľký Lipník Valley northwest of Jarabina); **D** – typical relief of small blocky klippen embedded in a marly matrix with the Jar-1 borehole site indicated (Maslienka Subunit, a view from the Lysá skala klippe above the Jarabina quarry to the NW on a flat ridge between Jarabina and Litmanová villages; forested valley in the foreground is the Jarabina gorge incised in the Jarabina Subunit); **E** – small anticline in the Lower Cretaceous dark marly limestones of the Šariš Unit (Malý Lipník Brook below the Vatráľova skala klippe); **F** – chevron-type folds in radiolarian limestones and radiolarites (Pieniny Unit, Podsadok village near Stará Ľubovňa).

(1994) mentioned widely scattered measurements from the vein calcite of various units between 40–60 and 160–180 °C (analyzed by Kozlowski). The data of vein quartz crystals from Palaeogene complexes of the adjacent Magura Unit and Central Carpathian Basin (e.g. Hurai et al., 2002, 2006) are not relevant for the basically pre-Eocene structural history described here. The same applies for the very rare fission-track analyses of apatites from clastic PKB formations, as the published datings between 36 and 16 Ma (Anczkiewicz and Świerczewska, 2008) again refer to the Oligocene – Early Miocene exhumation history.

Calcite monocrystals, e.g. blocky calcite from early diagenetic veins or crinoid ossicles in Jurassic limestones, are often twinned. Twinning is a low-grade, crystal-plastic deformation mechanism dominating in coarse-grained, calcite-rich rocks. The width and spacing of twin lamellae provide useful information about the temperature conditions of deformation. The PKB samples usually show a dense network of hair-thin twin lamellae indicating temperatures below 170 °C (Ferrill et al., 2004).

Primary structures – bedding and synsedimentary slump folds

The bedding (stratification) is a ubiquitous primary planar structure in the PKB sedimentary formations, therefore the superimposed cleavages and folds will be analysed in relation to it. The bedding character and morphology depend on its origin – it is well developed and regularly spaced in eupelagic sediments (radiolarites, biancone--type limestones) and in thin-bedded distal turbidites; less distinct, but pervasive in clay-rich hemipelagites, up to unrecognizable in massive shallow-marine carbonates and mass-flow deposits as olistostromes or fluxoturbidites. The bed spacing and lithology are the main controlling factors of deformation mechanisms during layer-parallel shortening at low temperatures. The well stratified formations are prone to buckle folding, while the more massive ones tend to be shortened by some mass-transfer or brittle deformation modes.

The primary stratification is often amplified by early post-sedimentary, penecontemporaneous processes such as compaction due to vertical sediment loading producing bedding-parallel solution seams. These may be typical wriggling stylolites in pure pelagic, biancone-type limestones, up to laminae enriched in clay minerals in more marly deposits. The bedding-normal compaction structures are a cumulative product of sediment dewatering, pressure solution of the soluble phase (predominantly calcite), and accumulation of an insoluble material composed mostly of phyllosilicates that were progressively rotated into the bedding-parallel foliation planes. Bedding-normal shortening is also indicated e.g. by flattened bioturbation spots in the "Fleckenmergel" facies marlstones, or by early diagenetic, discontinuous calcite veinlets subnormal to the bedding-parallel foliation, but confined to individual beds. A specific type of the bedding-parallel foliation enhanced by pressure solution developed in the Jurassic nodular limestones (Czorsztyn Fm.). It is very irregular especially when the nodules are large and it can be easily confused with the bedding-perpendicular cleavage (see below) in the case of no other stratification markers are present. Both the primary sedimentary stratification and the early diagenetic, compaction-related bedding-parallel foliation are given the provisional symbol S_B ($S_{BEDDING}$) in the following text and structural diagrams.

In several places (e.g. in the valley north of Chmeľnica village), decimetric synsedimentary slump folds were observed in the Lower Cretaceous, biancone-type cherty limestones (Pieniny Fm.) of the Pieniny Nappe. Folds are intrafolial, tight to isoclinal of the similar type. Often only isolated fold cores occur, while their axes are scattered. They are bound to several metres thick lens-shaped packets surrounded by undisturbed strata. In thin sections, both the cores and limbs of these folds do not show any features of a solid-state ductile strain, therefore their origin by soft-sediment deformation process, such as slumping, is suggested.

Regional pattern of the bedding-parallel foliation S_B is presented in the stereographic projection diagrams (Fig. 3). The united plot of all poles to bedding from the whole region (Fig. 3A) shows a modest preferred orientation with the poles scattered along a wide girdle in N–S direction, with most of strata dipping moderately to the south. We tried to refine this pattern by extracting the data coming from blocky klippen occurring in the Šariš Unit and in the Maslienka Subunit of the Subpieniny Nappe. As mentioned above, the klippen of the Šariš Unit are olistoliths, therefore orientation of their stratification might have no relevance for the regional tectonic assumptions. Likewise the Maslienka small blocky klippen, although tectonic by origin, were omitted due to their presumed "free" movement within the incompetent shale matrix. This might have caused significant reorientation of original bedding attitudes by rotation about variously oriented axes not only in the course of the earliest phases of deformation, but also later during multiphase structural evolution of the PKB. Moreover, since these blocky klippen represent isolated rigid inclusions in a soft matrix, they were often liberated and affected by the subrecent down-slope gravitational movements like landsliding, creeping, or even free rolling downwards. The diagram of bedding attitudes from the blocky klippen is shown in Fig. 3B and indicates that strata flatly are inclined in various directions.

The rest of data are considered to represent strata attitudes *in situ*. These were subdivided into two groups – the first is represented by the ribbon-type klippen themselves, i.e. by the Middle Jurassic to Lower Cretaceous competent limestones and radiolarites of the Jarabina Subunit of the Subpieniny Unit and, predominantly, those of the Pieniny Nappe (Fig. 3D). The second group includes measurements from the klippen matrix or "mantle", i.e. mostly incompetent shales, marls and flysch sediments of the Lower Jurassic, but chiefly mid-Cretaceous to Lower Eocene age (Fig. 3E). The aim was to find out the possible differences between the bedding orientations patterns in the klippen and in their matrix, which would provide certain information about the continuity or discontinuity between them.

After extraction of widely scattered data from blocky klippen, the resulting patterns of bedding positions are quite well organized both in the ribbon-like klippen and in their soft surrounding sediments. In the former, the bedding poles spread along a narrow girdle in the NWN–SES direction (Fig. 3D) with a maximum around 355/45, which indicates dominancy of moderately SES to S inclined strata. In general, the strata are tilted about approximately ENE–E trending axis (π1 pole at 265°), which is most probably parallel to the trend of large-scale folds or imbricates. At the same time, a majority of bedding strikes is clearly oblique to the general PKB trend in this area (ca 120°) with a deviation of ca 30°. Virtually identical data were published by Jurewicz (1994) from the adjacent Polish part of the PKB (Małe Pieniny Mts). Ratschbacher et al. (1993) and Nemčok and Nemčok (1994) came to similar results as well. It means this is a regionally important phenomenon that needs some explanation.

A somewhat different depiction is offered by the klippen matrix data. The bedding poles are concentrated along two girdles which are crosscutting near the centre of the diagram (Fig. 3E). The first, weaker girdle closely matches orientation of bedding in the klippen ribbons (π1 pole at 85°). The second, stronger girdle is positioned clockwise in

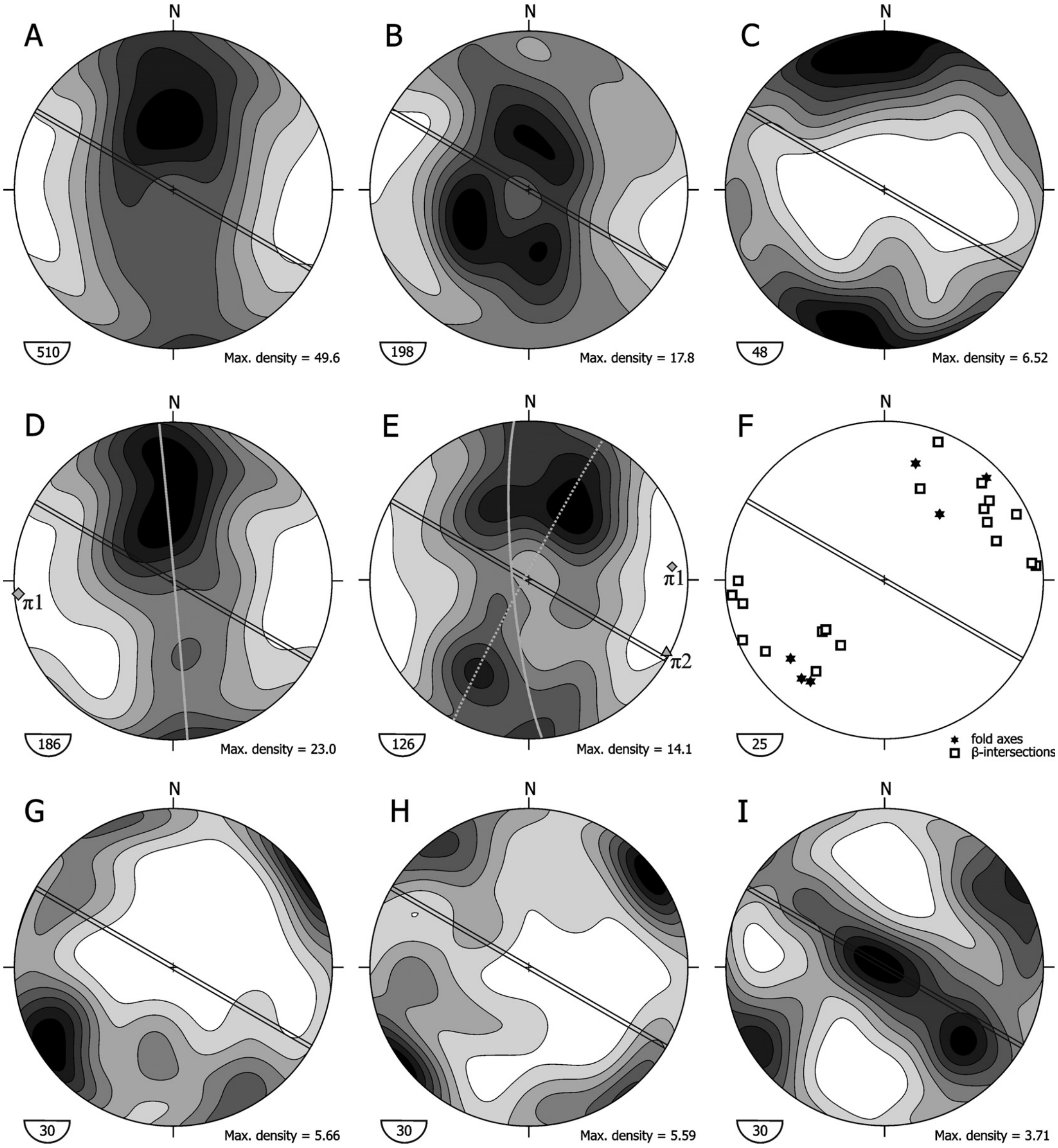

Fig. 3. Structural diagrams showing attitudes of strata and cleavages in the studied area (equal area projection, lower hemisphere): **A** – unsorted poles to bedding from the whole region; **B** – poles to bedding from the blocky klippen; **C** – tilt-corrected poles to S_C cleavage from blocky klippen (respective S_B planes were rotated to horizontal); **D** – poles to bedding from the ribbon-type klippen; **E** – poles to bedding from the klippen matrix, note the two girdles and their π-poles discussed in the text; **F** – axes (stars) and β-intersections of fold limbs (squares) of the F_1 fold population; **G** – poles to cleavages from the ribbon klippen; **H** – tilt-corrected poles to cleavages from the ribbon klippen (bedding/cleavage couples rotated to horizontal bedding position); **I** – intersections of bedding with cleavage. The oblique double-line indicates the general trend of the PKB in Eastern Slovakia. The data were elaborated by the computer program Stereo32.

some 30° with the maximum in the NE sector of the diagram (the attitude of the mean pole to cleavage is approximately 35/45, i.e. strata are moderately SW-dipping). Accordingly, the average bedding strikes of the latter girdle (π2 pole at 118°) would be exactly parallel to the 120° PKB trend.

Cleavage

Cleavage is an early stage planar structure that is developed at high angles to the pre-existing bedding-parallel foliation S_B (Fig. 2A, B). It was mostly observed in marly carbonates, especially in the Jurassic "ammonitico rosso" nodular limestones and Upper Cretaceous "couches rouges" variegated marlstones. Similarly as the bedding-parallel foliation S_B, it was formed during the late diagenetic stage in not fully lithified sediments, as revealed by analogous deformation mechanisms – pressure solution and concentration of the insoluble clayey material along the new foliation surfaces, which are given the symbol S_C ($S_{CLEAVAGE}$) in the following. At very low-grade temperature conditions, the clay minerals transformations, such as smectite to illite, produced additional aqueous fluids necessary for pressure solution processes. What had principally changed, however, was orientation of the shortening direction. Instead of vertical compaction and flattening resulting from the sedimentary load, it was the subhorizontally operating maximum tectonic stress axis, i.e. the PKB sedimentary rock complexes suffered bedding-parallel shortening during this deformation stage. Because of SC cleavage is usually normal to, or at high angles to bedding, it is inferred that it developed contemporaneously with macroscopic folding.

The spacing of S_C foliation is variable, though it is sometimes macroscopically penetrative, particularly in the red nodular limestones. Having measured the axes of strained ammonite moulds in the Czorsztyn Fm., Krokowski and Tarkowski (1984) estimated about 40 % of layer-parallel shortening related to the cleavage development (i.e. flattened within the bedding planes and elongated in the cleavage direction). However, this is probably the maximum value that cannot be directly adopted for the whole PKB, as the cleavage is usually only weakly developed, or often missing completely. In the massive limestones poor in the clay content, the SC cleavage is feebly developed or not present at all. Also the radiolarites and flysch sandstones are devoid of macroscopic cleavage.

The cleavage planes are mostly subparallel and straight. Occasionally, their refraction was observed in marly, thick-bedded types of red nodular limestones. There the cleavage is less distinct and perpendicular to stratification in central parts of the beds, while it is sigmoidally curved to lower angles with respect to the nearby bedding plane in the marginal, clay-rich parts of strata. In a few instances, obvious buckling of closely spaced S_C foliation traces on bedding surfaces was observed (Fig. 2C). The kinematic meaning of this post-cleavage folding is unclear, owing to it was found only in two blocky klippen. Nevertheless, this phenomenon indicates shortening parallel to both the cleavage and bedding trends, which would require a special position of these planar anisotropies relative to the operating stress field.

The attitudes of S_C cleavage were plotted in three diagrams (Fig. 3C, G and H). The selection was based, similarly as for the bedding, on the types of klippen they occur in. In the blocky klippen, it means in olistoliths and Maslienka-type tectonic lumps, each couple of bedding and the corresponding cleavage value was rotated about the bedding strike axis to the horizontal position of bedding. The results (Fig. 3C) show that cleavage is on the whole steeply inclined to the bedding planes, while the weak preferred orientation of the cleavage poles indicates its predominating W–E strike. The other two plots (Fig. 3G, H) present the S_C orientation within ribbon klippen in the original position and tilt-corrected (for horizontal bedding), respectively. However, also these cannot be considered as maintaining the original position with full certainty, as well the data are quite scarce. Presence of two clusters will be discussed below.

Folds

In general, the mesoscopic folds are less frequent as one would expect in such a highly deformed zone as the PKB is. Despite poor outcrop conditions, folds are surprisingly very rare in the thin-bedded flysch or marly formations. Only the highly tilted strata and the map pattern infer the presence of large-scale, usually upright macrofolds with steep axial planes and undulating, flatly to in places steeply plunging axes (mostly periclines).

Small-scale folds are sometimes present in well-bedded pelagic limestones (Pieniny Fm.) and radiolarites (Czajakowa Fm.) of the Pieniny Nappe. The best example is the prominent outcrop near the Gypsy settlement of the Podsadok village (Fig. 2F), east of the Ľubovňa Castle hill. There, the pale siliceous limestones or calcareous radiolarites are pervasively folded to metric, chevron-type, open to closed, upright folds with straight limbs and angular hinges. Their axial planes are steeply south-dipping in general; the folds are symmetric to slightly asymmetric with northern vergency. Fold axial planes are often truncated by steeply south-dipping faults with oblique-slip dextral shear sense indicators, mainly calcite slickenfibres. From the local tectonic circumstances it follows that this fold track occurs in the core of a tight, decametre-sized anticline. The fold axes are gently to moderately plunging either towards the NE, or to the SW (Fig. 3F). The same applies for the β-intersections constructed from the fold limb pairs (Fig. 3F) that were measured in the whole area.

Interpretation of oriented data

Bedding vs. cleavage and mesoscopic fold attitudes

The bedding, cleavage and fold attitudes summarized in Fig. 3A–I allow for formulation of the following tentative assumptions:

1) The bedding attitudes plot of the small blocky klippen reveals that in the majority of cases bedding is gently dipping in various directions, while the corresponding cleavage

is dipping steeply (Fig. 3B, C). This position supports our field observations that most of small platy klippen are resting parallel by their two long axes and bedding with the underlying gentle slopes. This is typical for domains built by the Šariš or Maslienka complexes, even the maxima in Fig. 3B correspond to the prevailing slope orientation of the area with ridges trending NW–SE. This fact calls for cautious handling with oriented structural data (e.g. cleavage treated here, or younger slickensides) from these klippen, since obviously not only the sedimentary and tectonic processed, but also the subrecent gravitational slope movements may have affected their final orientation. In the case of steeply dipping blocky klippen, these are usually resting parallel with the surrounding stratification and/or tectonic boundaries and may indicate the general inclination of strata in that area, but again a caution is necessary, particularly concerning the isometric, thick--bedded or massive klippen.

2) As follows from comparison of the bedding attitudes of the ribbon-type klippen and the klippen matrix included in the D and E diagrams (Fig. 3), respectively, they show certain differences. The bedding poles of the ribbon-type klippen are plotted in a distinct single N–S girdle with a maximum in the northern sector and submaximum in the southern one. This distribution would indicate generally W–E (mean 85°) bedding strikes, prevailing moderate to steep southern dips and presence of asymmetric macrofolds with northern vergency. In contrast, the bedding poles of the klippen matrix are arranged in two girdles. The first is indicated by a less pronounced cluster corresponding to that of the ribbon klippen ($\pi1$ poles of both plot at 85 or 265°), while the second girdle with two maxima and corresponding $\pi2$ pole are shifted by some 30 degrees clockwise with respect to that of the ribbon klippen. It means that bedding strikes of the klippen matrix have either been progressively rotated into parallelism with the PKB margins, or the SWS–NEN oriented girdle with two opposite maxima resulted from a distinct folding event with shortening in this direction, which is, on the other hand, very weakly recorded in the ribbon klippen. Taking into account the structural evolution of the area, both possibilities are viable, though the separated maxima would rather indicate the latter case. If so, angular macrofolds with WNW–ESE trending axes should govern the klippen matrix structure.

3) Fold axes, β-intersections of mesoscopic fold limb pairs (Fig. 3F), as well as a part of the bedding/cleavage intersections (Fig. 3G and H) are all oriented in the SW–NE direction (mean 55°), hence indicating contractional shortening in the NW–SE direction. This orientation is highly oblique to both the bedding strikes (mean 85° in the ribbon klippen) and the PKB boundaries (trending ESE ca 120°). The angular relationships between fold axes, bedding and cleavage strikes, and the overall trend of the PKB in the investigated area described above, would fit perfectly the dextral transpression model of Ratschbacher et al. (1993), provided that all these elements are regarded as developed in a genetically related sequence, i.e. if a progressive reorientation of incremental folds and bedding strikes into subparallelism with the PKB boundaries occurred.

How many folding phases?

In addition to the above described complexities, there are indications of another deformation event occasionally recorded by generally NW–SE trending cleavage traces and minute fold axes (Fig. 3G, H, I). Cleavage poles from the ribbon klippen concentrate in two discrete clusters indicating two cleavage sets perpendicular to each other (Fig. 3G). This relationship would indicate two separate deformation stages. Their relative succession is unclear, since overprinting criteria were rarely observed, moreover only in the blocky klippen.

The first, but less pronounced cluster in Fig. 3G relates to the cleavage set with a general SW–NE strike. Subhorizontal pole cluster maximum indicates that the cleavage is subvertical. This pattern is little changed after the bedding tilt correction (Fig. 3H) with poles showing slight tendency to a girdle arrangement. It would imply the cleavage is neither pre-folding, nor post-folding, but syn-folding and forms indistinct (probably late-stage) convergent/divergent cleavage fans (see also Ratschbacher et al., 2003).

This cleavage array parallels the mesoscopic fold axes and β-intersections of Fig. 3F, as well as bedding/cleavage intersections depicted by a cluster in the SW–NE sectors of Fig. 3I. Owing to these geometric, and presumably also genetic relationships, as well as their regional extent and clear relationships to the thrust structures, we regard these elements as a record of most likely the first deformation stage D_1; hence the cleavage of this orientation would be indexed as S_{C1} and folds as F_1. The D_1 linear elements are scattered within the SW and NE sectors of the diagram Fig. 3F with some of them being subparallel to the $\pi1$ poles to great circles of bedding pole girdles in Fig. 3D and E. Considering the dextral transpressional regime within the PKB (Ratschbacher et al., 2003), this would indicate slight clockwise rotation of the principal shortening axis from NW–SE to almost N–S direction. Simultaneously, the fold amplitudes increased from mesoscale (decimetric to metric) to macroscale (deca- to kilometric). By this, the mean 55° trending mesofolds and 85° trending macrofolds would represent the end members of the same deformation process characterized by the gradual rotation of the developing compressional structures with respect to the operating stress field.

The second, stronger cluster of cleavage poles indicates that this cleavage set is nearly vertical with the NW–SE strike. The same applies to the cleavage/bedding intersections well ordered in a distinct NW–SE trending girdle (Fig. 3I). Obviously, this set is orthogonal to the mesoscopic folds described above, and at the same time it is clearly oblique to the PKB trend and related macrofolds. The kinematic meaning and tectonic significance of this cleavage set cannot be resolved from the studied area, due to its scarcity and unclear overprint criteria. However, the NW–SE to N–S striking cleavages and minor fold axes, i.e. perpendicular or highly oblique to the PKB trend, were occasionally observed all along the PKB from the westernmost Myjava area up to easternmost Slovakia. Mesoscopic folds with NWN plunging axes are especially frequent in the steeply N-dipping, overturned Lower Cretaceous cherty limestones (Pieniny Fm.) of the Kysuca Succession north of Žilina. They were described by Beidinger et al. (2011) and interpreted as being related to the post-tilting W–E compression and superimposed sinistral strike-slipping in this W–E trending PKB sector. We preliminarily consider this event as superimposed on the D_1 deformation stage and thus designate it as the D_2 stage, and the related folds and cleavage as the F_2 and S_{C2}, respectively.

As revealed by the $\pi 2$ girdle in Fig. 3E, the third folding event should be considered, too. This affected preferably the klippen matrix complexes, probably because of ribbon klippen had been already individualized and verticalized due to the preceding transpressional disbanding, hence they were not prone to further internal shortening by folding. Furthermore, the shortening subnormal to the PKB boundaries has affected not only Cretaceous – Lower Eocene, but the Middle Eocene to Oligocene, and possibly also the Lower Miocene formations as well (cf. Oszczypko et al., 2005; Plašienka and Mikuš, 2010). Consequently, it would represent a distinctly younger deformation phase designated as D_4 here.

Broad-scale structure of the PKB in the investigated area

Regionally, two segments differing in structure are discerned within the described part of the PKB. The western segment, depicted in Fig. 1, is characterized by a complex, broad antiform cored by the Šariš Unit and flanked by the Subpieniny and Pieniny Units. Eastwards, the Ľubovňa – Údol segment (see the detailed map in Plašienka and Mikuš, 2010), has a comparatively simple structure with a well-preserved original, moderately SW- to S-dipping superposition of all three nappe units. In the area between Jarabina and Litmanová, several W–E trending broader partial synclines and tighter anticlines may be discerned (compare the map and cross-section A–B in Fig. 1). The broad synclines are cored with nappe outliers of the Maslienka and Pieniny units, while the tight, slightly asymmetric, N-vergent anticlines are indicated by narrow lenses or strips of the oldest – Cretaceous members of the underlying Šariš Unit. The most distinct is the anticlinal belt that can be followed from the southern slopes of the Mt. Vysoká in the east, through the Mt. Fakľovka up to Litmanová village and the Hutirky Valley east of it (see

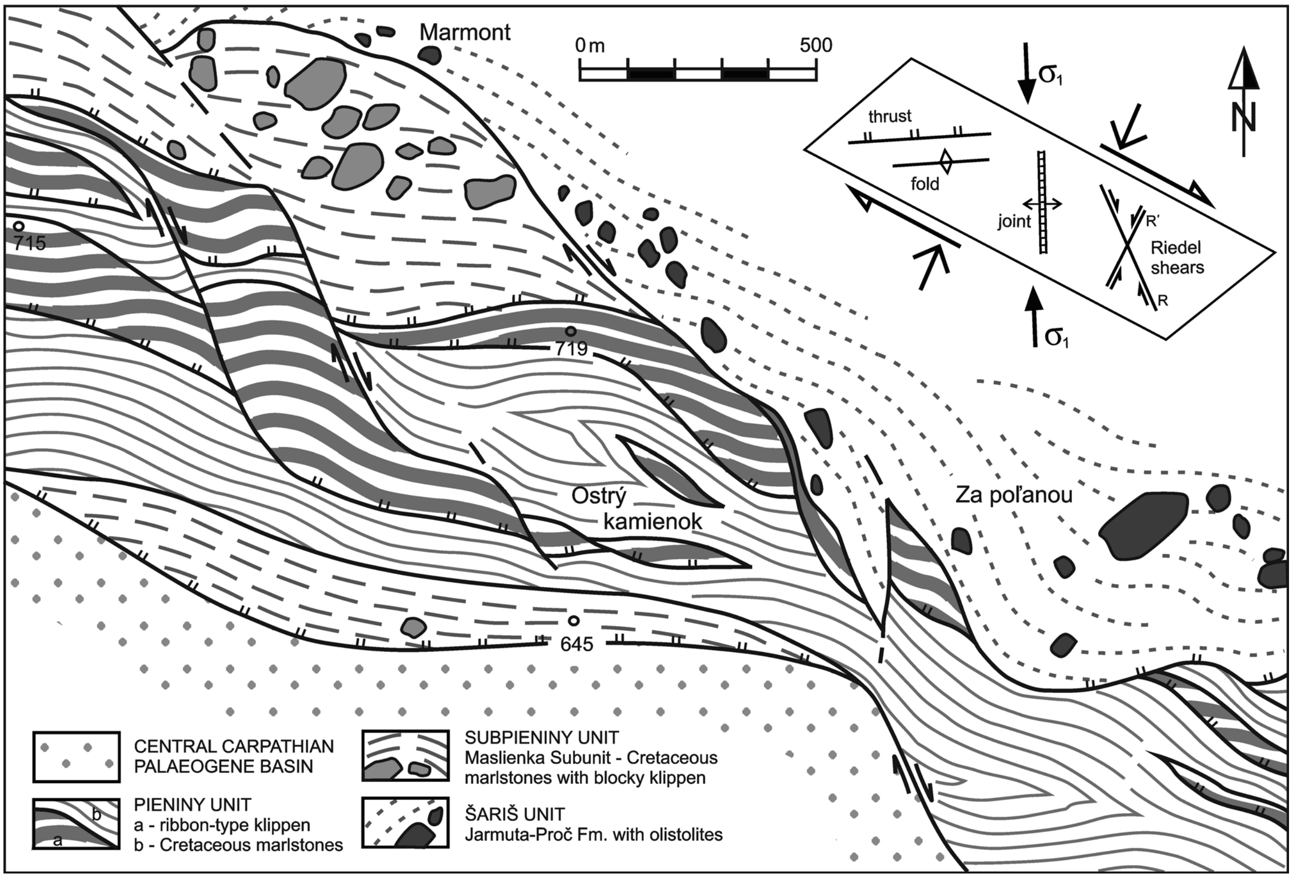

Fig. 4. A sketch map of southern marginal part of the PKB between Chmeľnica and Hajtovka villages showing relationships of bedding strikes to the fault boundaries of rectangular lenses or ribbons of the Pieniny Limestone Formation. The striped hachure outlines the measured or inferred bedding trends. The inset scheme shows theoretical structures of a dextral transpression zone for comparison with real structures.

also cross-sections in Fig. 11 in Plašienka et al., this issue). The system of W–E trending macrofolds F_1 is obliquely cut by the dextral strike slip (the Vabec Fault) offsetting the northern boundary fault of the PKB (the Rozdiel Fault – cf. Plašienka and Mikuš, 2010). The southern, marginal Podhale Fault is truncated by similar dextral strike-slips, but these are showing much less offset.

Field examples of complex structural relationships

As it was stated above, the folds are comparatively rare in the studied area. However, everybody who rafted down the Dunajec River (few km westward from the examined area) through the Pieniny Canyon has probably noticed that surrounding white cliffs, which are built by the Pieniny limestones, are pervasively folded into metric to decametric folds, appearing very irregular in variously oriented sections. Closer examination indicates that this is due to interference of two fold sets of a comparable morphology, one of them being W–E, and the other roughly N–S oriented. Taking into account previous assumptions, the former fold set would correspond to F_1, the latter to F_2. Unfortunately, the detailed structural analysis of complex relationships of these two fold tracks has not been performed yet.

In a hilly area between the Ľubovňa Castle and Hajtovka village, one can observe interesting relationships between the ribbon-type klippen and surrounding matrix of the Pieniny Unit (Fig. 4). Sometimes the narrow, NW–SE trending ridges – klippen – formed by Lower Cretaceous limestones of the Pieniny Fm. exhibit angular, even perpendicular relations of their internal bedding attitude with respect to the ridge/klippe boundaries. Obviously the boundaries of ribbon- or lozenge-shaped klippen are cut by faults running obliquely to the dominant bedding strike, which generally corresponds to that shown by diagram D in Fig. 3. The bedding/fault pattern in Fig. 4 illustrates the dextral offset along these faults, which geometrically correspond to the synthetic Riedel shears R. Antithetic shears R´ are seldom present as well (e.g. “Za poľanou” area in Fig. 4). The overall fault pattern is then in line with the dextral wrench model of the PKB in Eastern Slovakia (see inset in Fig. 4).

Discussion

Dating of deformation events

In the near-surface structural levels, the dating of ancient deformation events is difficult. In polydeformed regions, such as the PKB, even the relative timing is obliterated by complex relationships and often unclear overprint criteria of diverse brittle structures unevenly recorded in rheologically varying rock media. The most common method to resolve this puzzle is the step-by-step removal of the latest structures recorded in the youngest rocks down to the oldest ones, which should be the only affected by the earliest event. This structural approach has been quite successfully applied to the Late Tertiary tectonic history of the Western Carpathians, which is characterized by rotations of both the palaeostress field (clockwise), as well as the block rotation of entire Western Carpathian domain (anticlockwise) – e.g. Marko et al. (1995), Márton and Fodor (1995), Kováč and Márton (1998), Nemčok et al. (1998), Kováč (2000), Vojtko et al. (2010) and references therein. This scheme elaborated for the whole mountain belt can be then interpolated to the PKB, where rocks younger than Eocene are usually missing (e.g. Pešková et al., 2009; Bučová et al., 2010; Mikuš, 2010; Šimonová and Plašienka, 2011).

On the other hand, the pre-Eocene deformation appears to be equally important and multistage in the PKB, therefore some other dating techniques should be used as well. One of them is the stratigraphic approach by biostratigraphic dating of the key sedimentary formations or successions. In fact, this is a classic timing method of tectonic events utilized already by Uhlig (1903, 1907), Andrusov (1938, 1968), Birkenmajer (1970, 1986) and many others. However, the results are very much dependent on the actual knowledge about the age of these key formations, and on the actual interpretation of their origin (see e.g. the transgressive vs. wildflysch origin of the Upohlav or Jarmuta conglomerates). Therefore the age determinations of the principal tectonic stages are varying from author to author and no general agreement in this topic has been achieved in the PKB yet. Many authors used, and some of them are still using, the odd Stillean terminology (Stille, 1924) of the global tectonic phases like Austrian, Subhercynian, Laramian, Illyrian, Savian etc. Usage of this preconceptional template inevitably leads to an oversimplification in the better, or incorrect predetermined conclusions in the worse case.

Ratschbacher et al. (1993), applying the structural approach, assumed the Oligocene age of the PKB internal thrusting and strike-slip faulting. Several other authors (Srnánek and Salaj, 1965; Sikora, 1974; Książkiewicz, 1977) were relying on the stratigraphic approach and still supposed that the main, even the only deformation phase of the PKB in the Pieniny sector occurred during the Early Miocene. This timing is highly improbable, since the principal klippen structures are sealed by the Middle Eocene – Oligocene, fairly deep-water sediments of the Údol (Ujak, Richvald) Succession (Leško, 1960; Nemčok et al., 1990; Oszczypko et al., 2005; Plašienka and Mikuš, 2010), e.g. in the Plaveč “graben” crosscutting the PKB between the Pieniny and Šariš sectors. This has lead to the concept of the Middle Eocene, “Illyrian” (or early Pyrenean) tectonic phase (Leško, 1960; Stráník, 1965; Nemčok, 1971). According to Plašienka and Mikuš (2010), this tectonic event was related to an extensional collapse of the rear part of a growing accretionary wedge, thus it obviously postdates development of the principal PKB structures in Eastern Slovakia. In addition, as it was shown by Plašienka et al. (1998), the post-Oligocene deformation of the Šambron-Kamenica antiformal zone located just south-west of the PKB was governed by nearly orthogonal SW–NE compression with only weak features of a slight dextral transpression. Furthermore, the palaeomagnetic hints of Lower Miocene counterclockwise rotation indicate that the Western Carpathians rotated nearly as a unity by some 70–80° in the inner and 50–60° in the outer Carpathian zones (Márton et al., 1999, 2009a, b), which would imply only a slight dextral offset along the PKB and adjacent zones, as well. Therefore in our view the latest Cretaceous – Palaeocene – Early Eocene nappe thrusting was subsequently followed by a dextral dispersal of the primary fold-and-thrust belt. This event created the leading structural features of the PKB, and was superimposed by extension related to the foundation of the Central Carpathian Palaeogene Basin, including the Údol Succession that seals the early PKB structures (Plašienka and Mikuš, 2010). Later on, during the Early – Middle Miocene, the compressional regime returned to trigger additional, more-or-less orthogonal shortening the PKB and adjacent Šambron-Kamenica antiform zone. Possibly during this event, out-of-sequence thrusting that brought the PKB units into superposition above the Lower Miocene sediments of the Kremná Formation may have operated, too (see Oszczypko et al., 2010; Oszczypko and Oszczypko-Clowes, 2010).

Dating of thrusting events in the studied PKB segment could be based on the presumed stratigraphic age and composition of the synorogenic, coarse-grained sediments that terminate the thickening- and coarsening upward "wildflysch" sequences of the units involved. By this approach, Plašienka and Mikuš (2010) estimated the latest Cretaceous/earliest Palaeocene age of the Pieniny Nappe overthrusting, while the Subpieniny Nappe with the piggy-back Pieniny Unit was finally emplaced during the Early Eocene. Accordingly, the whole thrusting process may have lasted for about 15 Ma.

Structural evolution

As reconstructed by Plašienka and Mikuš (2010), stacking of the PKB nappe units progressed from the Uppermost Cretaceous (Pieniny Unit over the Subpieniny), through Palaeocene – Lower Eocene (Subpieniny + Pieniny over Šariš) and terminated by the Lower Miocene piggy-back thrusting of the Šariš Unit and the overlying nappe and overstepping complexes above the Magura Superunit. This tectonic scenario is corroborated also by the mesoscopic structural record described herein. However, the succession of deformation stages stated by Plašienka and Mikuš (2010) has to be slightly modified.

Following some soft-sediment, gravitationally induced syn-sedimentary deformation (D_0 stage), the inventory of the oldest compressional deformation stage D_1 is represented by the pressure solution cleavage oriented at high angles to bedding in competent limestones of the Subpieniny Unit. The S_{C1} cleavage shows genetic relationships to the mesoscopic F_1 folds. As it was shown by Jurewicz (1994), sedimentary successions with complex lithological-rheological stratification exhibit various kinds of structural response to compressional shortening – predominantly cleavage is developed in thick-bedded to massive, marly limestones (e.g. the nodular Czorsztyn Limestone), but buckle folding characterizes the well-bedded limestones or cherts. This incipient mechanical decoupling within sedimentary successions might have been amplified later in the thrusting process and finally could lead to a complete dismembering of original successions into separate blocks floating within an incompetent marly matrix. This is particularly typical for the "transitional" successions (Niedzica and/or Czertezik), which also form the substantial part of the blocky klippen in the Maslienka Subunit. During the superficial thrusting process, the tectonically individualized blocky klippen were occasionally deliberated from their matrix and transported as olistostromes (Milpoš Breccia) and olistoliths into the frontal, trench-type Jarmuta-Proč Basin of the later Šariš Unit.

The D_1 structures are related to incipient detachment of PKB successions from their subducted substratum and subsequent thrust stacking, including both the foreland-propagating and out-of-sequence thrusting recognized by geological mapping. Assuming the stacking succession of the three PKB units, the D_1 stage was not coeval in all of them, but progressed in a piggy-back manner from higher to lower thrust sheets. Thus the late F_1 macroscopic folds, subsequent and slightly oblique to the mesoscopic F_1 folds, are related to out-of-sequence thrusting in the rear of the developing thrust wedge (especially in the Pieniny Unit) during the same D_1 thrusting event (and not in a separate stage D_2 as proposed by Plašienka and Mikuš, 2010). At the same time, we now include also the dextral transpressional dispersal of the original PKB fold-and-thrust belt in the principal D_1 stage. It means that the three principal steps in the structural evolution of the PKB – i.e. (1) SW–NE mesofolds, (2) W–E macrofolds and related out-of-sequence thrusting, and (3) dextral transpression represent three substages, partially overlapping, of one major deformation stage D_1.

The poorly constrained D_2 event as discerned in this work represents a kind of "cross folding", which was otherwise recognized all around the Central Western Carpathians (e.g. Plašienka, 1995b). The relative dating allows for its correlation between these two domains. However, the kinematic significance of D_2 stage is uncertain, possible relations to the Western Carpathian arc formation might be inferred.

The D_3 deformation stage is registered by extensional ductile to brittle shear zones oriented mostly at low angles to bedding. Plašienka and Mikuš (2010) related this event to the extensional collapse of the overthickened thrust wedge accompanied by subsidence and deposition of the overstepping, Middle Eocene to Oligocene Údol Succession.

During the final D_4 stage the PKB attained its present linear form, bounded by steep fault boundaries from both sides – the Rozdiel Fault from the NE and the Podhale Fault from the SW. These faults are clearly post-Oligocene, possibly post-Eggenburgian in age. They correspond to oblique-slip, reverse-dextral backthrusts. Their post-Oligocene age means that they should not be genetically related to the pre-Middle Eocene transpression as described above. Consequently, the boundaries of the dextral wrench zone shown e.g. in the inset of Fig. 4 may have not directly coincided with the present bounding faults of the PKB. On the other hand, it is quite possible that the Rozdiel and Podhale marginal faults are simply reactivating older fault boundaries of this pre-existing transpression belt.

However, the Podhale Fault is also systematically truncated by obliquely NWN–SES trending strike-slips with dextral offsets (see Fig. 1), which obviously coincide with the synthetic Riedel shears of the principal pre-Oligocene dextral wrenching event (compare with inset in Fig. 4). Further eastward, the innermost Krynica Subunit of the Magura Belt is thrust back over the PKB that even causes its disappearing from the surface for a short section NW of Prešov. This late SW–NE shortening event affected also the inner structure of the PKB (F_4 folds), as well as the adjacent part of the Central Carpathians Palaeogene Basin (Šambron-Kamenica anticlinal zone – Plašienka et al., 1998). Accordingly, we interpret these small offsets as reactivated Riedel slips acting as transfer faults that accommodated the eastward increasing amplitude of backthrusting of the Magura Unit. Oblique dextral steps of the northern, Rozdiel maginal fault of the PKB (the Vabec, Olšavec, Olejníkov, and Drienica faults – cf. Plašienka and Mikuš, 2010, their Fig. 4), exhibit even much larger offsets and bring about the progressive eastward narrowing of the PKB up to its diminishing near the Drienica village.

Conclusions

The primary and deformation structural elements of various units of the Pieniny Klippen Belt exhibit complex mutual relationships, which together with complicated lithostratigraphy and sedimentology of the tectonic units involved result in an intricate, if not chaotic structural pattern depicted in the published geological maps of the investigated area. After a clear separation and definition of the tectonic units (Plašienka and Mikuš, 2010), we have tried to show in this paper that also the inner deformation fabric of the PKB is far from chaotic; but ruled by the leading structures that developed sequentionally in response to the overall tectonic evolution of the entire Western Carpathian orogenic system and operating palaeostresses. In spite of numerous features remain unexplained, the general evolutionary tectonic model of the PKB gradually attains its assured contours. Regardless of its special composition and peculiar structural features, the PKB is a normal, though a bit strange component of the Carpathian orogen. Tectonic studies in the PKB have the advantages in a wide stratigraphic range and lithological rock types involved, which by far surpass the disadvantages of complicated structure and composition, as well as usually poor outcrop conditions. The material and structural record of palaeotectonic evolution is extraordinarily rich in the PKB and its reconciliation is not an easy task, but its results appear to be important not only for the evolution of the PKB itself, but for the entire Western Carpathians as well.

We have presented structural data from the Pieniny sector of the PKB in NE Slovakia, which generally indicate that:

1) distinction should be made between the "blocky" klippen and the "ribbon" klippen, since locally considerable reorientation of the original attitudes of the structural elements is presumed for the former ones;

2) bedding poles of the ribbon-type klippen plot in a girdle in NWN–SES to N–S direction, while those of the klippen matrix (mid-Cretaceous to Lower Eocene marlstones, shales and sandstones) are shifted clockwise – this feature is explained as a result of two distinct folding phases;

3) occasionally, the bedding-perpendicular cleavage and buckle folds record an early layer-parallel shortening, which are clearly older than the brittle transpression-related faults and fractures – therefore they are interpreted as initial detachment and layer-parallel shortening deformation elements that are likely related to the nappe-forming processes in the PKB;

4) fold axes, β-intersections of mesoscopic fold limb pairs, as well as a part of the bedding/cleavage intersections are all oriented in the SW–NE direction (mean 55°), i.e. oblique to both the mean bedding strikes (85°) and the PKB boundaries (trending ESE ca 120°); thus the dextral transpression model of an originally SW–NE trending fold-and-thrust belt is favoured to explain these relationships;

5) in addition, there are indications of another deformation event recorded occasionally by NW–SE trending cleavage traces and minute fold axes, the kinematic meaning of which remains unresolved for the time being.

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Structure and evolution of the Pieniny Klippen Belt demonstrated along a section between Jarabina and Litmanová villages in Eastern Slovakia

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Abstract

Basic features of the Pieniny Klippen Belt (PKB) structure and evolution are presented on example of a small area between Jarabina and Litmanová villages in Eastern Slovakia. T he area exhibits a rich sedimentary and structural record of the Late Cretaceous – Early Paleogene thrusting processes which generated the three main units of the PKB edifice in this region – the Šariš Unit, the Subpieniny nappe and the Pieniny nappe from bottom to top. The following essential phenomena are demonstrated at eight key localities, including field exposures and two borehole profiles: lithology and stratigraphy of the Czorsztyn-type klippen, deep-marine hemipelagic deposits and oceanic red beds of the Šariš Unit, synorogenic coarsening-upward flysch formations with bodies of tectonosedimentary breccias that register the principal thrusting events, and various structural types of superficial thrust sheets dependent on the mechanical stratigraphy and pre-thrusting morphology of the sedimentary successions involved.

Key words: Pieniny Klippen Belt, Pieniny sector, lithostratigraphy, structure, boreholes, representative localities, Western Carpathians

Introduction

The Pieniny Klippen Belt (PKB) is probably the most conspicuous structural zone of the entire Carpathian arc. Picturesque landscape and abundance of especially Jurassic fossils have been drawing the geologists' and paleontologists' attention for more than 150 years (e.g. Stur, 1860; Neumayr, 1871; Uhlig, 1890, 1903, 1904, 1907; Andrusov, 1931, 1938, 1945 etc; Birkenmajer, 1970, 1977, 1986 etc; Sikora, 1971, 1974; Mišík, 1978, 1994, 1997 etc; and many others). Looking at the general geological maps of the Western Carpathians, the PKB comes out as a backbone of the orogen, which unifies its outer and inner zones. It is positioned at the backstop of the Tertiary accretionary wedge (External Carpathian Flysch Belt), and in front of the Cretaceous nappe stack (Central Western Carpathians – CWC). The PKB involves units of two types and paleogeographic provenances – the first are nappes of the specific Oravic Superunit that are present only in the PKB (such as the Czorsztyn, Kysuca or Pieniny Unit), the second are nowadays interpreted as frontal elements of the Central Carpathian Fatric Superunit occurring mostly in Western Slovakia (Manín, Drietoma and Klape nappes; the Haligovce Unit in the Pieniny Mts – Plašienka in Froitzheim et al., 2008). In a broader sense, the PKB and the neighbouring Magura Unit represent elements of the Penninic tectonic system, while the CWC units continue to the Eastern Alpine (Austroalpine) thrust stack (e.g. Schmid et al., 2008; Froitzheim et al., 2008). From the paleogeographic point of view, the Oravic units were derived from a neighbourhood of a continental splinter, known as the Czorsztyn Ridge (e.g. Birkenmajer, 1986; Mišík, 1994), which was positioned between two branches the Jurassic – Cretaceous Penninic oceans – the South Penninic Ligurian-Piemont-Tauern-Rechnitz-Vahic and the North Penninic Valais-Rhenodanubian-Magura Ocean. Accordingly, the Czorsztyn Ridge (or Oravic ribbon continent – Plašienka, 2003) was analogous in position to the Middle Penninic continental fragments, such as the Briançonnais Ridge of the Western Alps (e.g. Trümpy, 1988).

All along its length of up to 600 km, the as narrow as merely several km PKB retains the specific features of its composition and structure. The PKB involves predominantly Jurassic, Cretaceous and Paleogene sediments with exceptionally variable lithology and intricate internal structure. During more than a century of intense research, these have been subdivided into numerous lithostratigraphic and tectonic units of distant provenances, hence witnessing excessive shortening and dispersal within this restricted zone. In general, two types of rock complexes are distinguished in the PKB. The "klippen" are formed by the rigid, nearly isometric, lenticular or lozenge--shaped blocks of Jurassic – Lower Cretaceous limestones that are ranged to several stratigraphic successions differing in lithology. The klippen are embedded in an incompetent

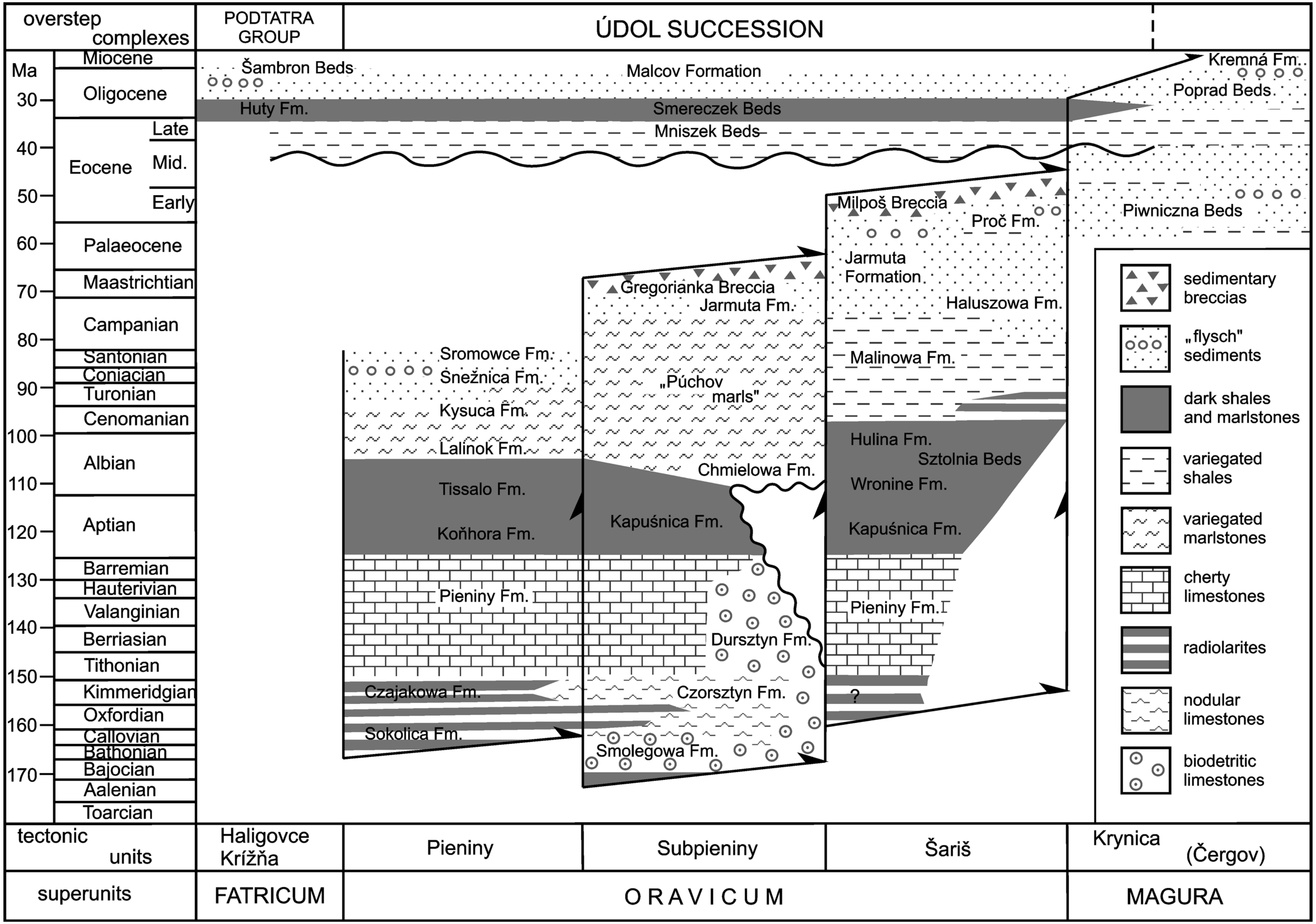

Fig. 1. Generalized lithostratigraphy of the PKB and adjacent units in the described area (after Plašienka and Mikuš, 2010, slightly modified).

matrix, the “klippen mantle”, composed of various Upper Cretaceous to Paleogene marlstones, shales and flysch sediments. Owing to this, the PKB has often been characterized as a tectonic megabreccia, mélange, or even it was speculated to represent a huge chaotic sedimentary body – an olistostrome (Nemčok, 1980). This idea was partly confirmed recently by Plašienka and Mikuš (2010) who consider a part of blocky klippen of the newly-defined Šariš Unit as olistoliths. However, the peculiar “block-in--matrix” structure of substantial parts of the PKB appears to be result of dominantly tectonic processes, governed by thrusting and subsequent along-strike wrench movements. The latter obliterated, in places completely, former thrusting--related structures. Consequently, the mutual structural relationships of various PKB units and the neighbouring tectonic zones remains a matter of controversy and no general agreement has been achieved even in some fundamental questions until now.

The present paper aims at presentation of the most characteristic attributes of the PKB lithostratigraphy and tectonic structure in a rather small area, which, however, provides numerous examples of the most unusual aspects of the PKB edifice. The satellite paper (Plašienka, this issue) provides more detailed information about the character of structural elements that control the overall tectonic edifice of the PKB segment under question.

General structure and lithostratigraphy

The Polish and adjacent Slovakian Pieniny Mountains is a classic area of the PKB geology with intense research going back to 19th century. Currently, the most widely accepted model of Birkenmajer (1970, 1977, 1986) considers the presence of several “Klippen Successions” differing by their lithostratigraphic contents, but originally deposited in the united “Pieniny Klippen Basin”. Three main sedimentary zones are distinguished within this basin: (1) the Czorsztyn Ridge and its slopes in the northern position; (2) the central furrow; (3) the southern Exotic (Andrusov) Ridge and its slopes. At the same time, the Klippen Successions represent individual tectonic nappe units. From the bottom to top, these are the ridge-type Czorsztyn Unit, the Niedzica and Czertezik Units representing the southern slope of the Czorsztyn Ridge, the basinal Branisko and Pieniny Units (partly deposited on an oceanic crust formed already in the Late Triassic), and the Haligovce Unit that originated at the southern margin of the Pieniny oceanic basin in the vicinity of the Andrusov Ridge, an enigmatic structure that should have fed the PKB Cretaceous basins with coarse exotic material and that completely disappeared later. Besides these, the special Grajcarek Unit is considered to be derived from the northern slope of the Czorsztyn Ridge facing the Magura Ocean to the north, which was thrust back over the Laramian structure of the PKB during the earliest Paleogene and then incorporated into the PKB structure. Further on, the Laramian nappe structure was partially sealed by the Maastrichtian, post--thrusting, molasse-type transgressive cover – the Jarmuta Fm. However, the Jarmuta Fm. should pass northwards into synorogenic flysch sediments of the Magura Basin (Grajcarek Unit) extending to the Paleocene (Birkenmajer et al., 1987). Certain aspects of this conception were questioned e.g. by Jurewicz (1997, 2005), who presumes the lowermost structural position of the Grajcarek Unit within the PKB edifice, i.e. the Laramian thrusting or sliding of the Czorsztyn Unit over the synorogenic Jarmuta Fm. Recently, Oszczypko et al. (2010) and Oszczypko and Oszczypko-Clowes (2010) have found that also the “Autochthonous Paleogene”, considered by Birkenmajer (1986) as transgressive and preserved in synforms within the PKB, appears in tectonic windows together with rocks of the Grajcarek Unit and ranges stratigraphically up to the Lower Miocene. These new findings partly recall the older views of Sikora (1962, 1970). Accordingly, most of the PKB rocks younger than Lower Paleocene are considered to form the lowermost structural element of the PKB connected to the southernmost parts of the Magura Unit. This, however, does not apply for Paleogene sediments with a clear transgressive position above the highest and southernmost Haligovce Unit (Súľov-type conglomerates and biogenic sediments akin to the Myjava-Hričov Group of Western Slovakia – cf. Janočko, ed., 2000). Another point of these new views is that the principal PKB units are in a completely allochthonous position above the Magura elements, i.e. they override the rear parts of the EWC accretionary wedge. Owing to this high structural position, the PKB rocks have never been buried to considerable depths, which is in line with observations about the very low thermal reworking of the PKB rock complexes.

The Eastern Slovakian part of the PKB is characterized by a noticeably small width (5 km at maximum), by presence of the Oravic units only (with exception of the small Haligovce Unit), sharp fault boundaries, widespread incorporation of Paleogene rocks and by some 50 km long sector where the stiff klippen are missing completely (Nemčok, 1990). It is an area, where the Paleogene sediments (generally known as the Proč Fm.) were long time regarded as transgressive above the deformed klippen successions and closely related to the Magura flysch complexes (e.g. Matějka, 1963; Stráník, 1965). Only Leško (1960; Leško and Samuel, 1968) postulated a structural independence of the PKB from the Magura Unit. Later on Nemčok (1980; Nemčok et al., 1989, 1990) formulated a quite different opinion, according to which all the klippen are in fact olistoliths resting within chaotic breccias horizons (Gregorianka Breccia) composed mostly of the same material as the klippen themselves. In Nemčok’s view, the breccias are members of the Maastrichtian – Lower Eocene Jarmuta-Proč Fm., which composes the matrix of the PKB megaolistostrome placed between the deposits of the Central Carpathian Paleogene Basin (CCPB), known also as the Podhale Basin in Poland, and the overriding backthrust Magura complexes.

Just in recent times, Plašienka and Mikuš (2010) presented a view fairly distinct from all previous opinions – the Jarmuta and Proč Fms. do not represent the klippen “mantle”, but are constituents of an independent, newly defined Šariš Unit in the lowermost structural position

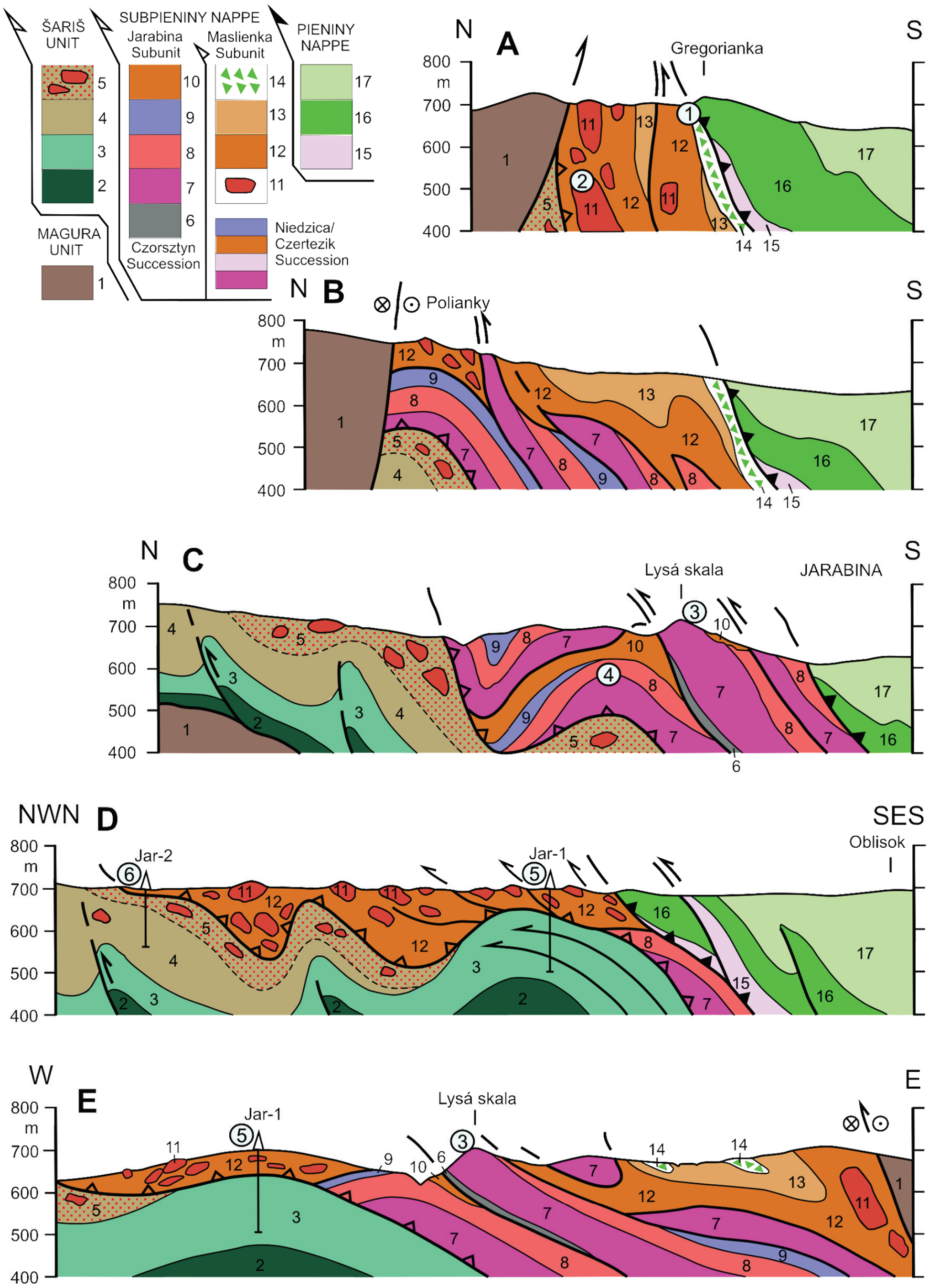

Fig. 2. Geological cross-sections **A** to **E** of the area north of Jarabina. For their approximate position see Fig. 4. 1 – Palaeogene to Lower Miocene (?) formations of the Magura (Krynica) Unit; 2–5 Šariš Unit: 2 – Lower Cretaceous marly limestones (Pieniny Fm.); 3 – various shaly, marly and distal flysch formations of Albian to Campanian age; 4 – Maastrichtian? to Lower Eocene calcareous "flysch" sandstones and shales (Jarmuta and/or Proč Fm.); 5 – the same with bodies of olistostromes and olistolites (Milpoš Breccia); 6–10 Subpieniny nappe, Jarabina Subunit: 6 – Aalenian to Lower Bajocian black spherosideritic shales (Skrzypny Shale Fm.); 7 – Bajocian sandy-crinoidal limestones (Smolegowa and Krupianka Fms); 8 – Bathonian to Lower Tithonian red nodular limestones (Czorsztyn Fm.); 9 – Upper Tithonian to Berriasian pale biomicritic limestones (Dursztyn Fm.); 10 – Albian to Campanian variegated, dominantly red marlstones ("Púchov marls", Chmielowa and Jaworki Fms); 11–14 Subpieniny nappe, Maslienka Subunit: 11 – blocky klippen of Jurassic to Lower Cretaceous formations of the Czorsztyn and Czertezik/Niedzica Successions; 12 – various marly, shaly and distal flysch formations, Albian – Campanian (Kapuśnica and Jaworki Fms); 13 – Upper Campanian – Maastrichtian calcareous sandstones, proximal flysch (Jarmuta Fm.); 14 – the same with bodies of carbonate olistostromes (Gregorianka Breccia); larger thrust imbricates with continuous, but mostly overturned "transitional" Niedzica/Czertezik Succession are shown in the area north of Litmanová (see Fig. 11); 15–17 Pieniny nappe: 15 – Callovian to Lower Tithonian radiolarite cherts (Czajakowa Fm.); 16 – Tithonian to Barremian pelagic cherty limestones (Pieniny Fm.); 17 – Aptian to Campanian variegated shales, marls and flysch deposits with bodies of exotic conglomerates in places. Numbers in circles indicate approximate positions of the respective localities.

within the PKB nappe edifice (Figs. 1, 2 and 11). The sedimentary succession of the Šariš Unit ends with Paleocene – Lower Eocene Milpoš Breccia bodies (part of the Nemčok's Gregorianka Breccia), which are composed of material dominated by clasts derived from the overriding units, including numerous sedimentary klippen – olistoliths. The overlying Subpieniny nappe (term by Uhlig, 1907) is strongly disintegrated internally, formed by numerous klippen of tectonic origin composed predominantly of the ridge-type Czorsztyn Succession, but involving also the slope-type Czertezik and/or Niedzica successions. The matrix consists of variegated Upper Cretaceous pelagic marls, the youngest member is represented by the Maastrichtian coarsening-and-thickening upward synorogenic flysch sequence (Jarmuta Fm.) with breccia bodies (Gregorianka Breccia at the type locality of Nemčok et al., 1989). These breccias are composed exlusively of material coming from the overriding Pieniny nappe. The latter thrust sheet is represented by Middle Jurassic – Upper Cretaceous, deep-water basinal succession with a comparatively simple fold-thrust structure and occurs as the southernmost structural stripe of the PKB in Eastern Slovakia. In places, the PKB tectonic units are covered by the Middle Eocene – Oligocene sediments (termed as the Údol Succession by Plašienka and Mikuš, 2010, but known also as the Ujak Facies, Ombron Group or Richvald Series), which provide a link to the CCPB sediments and coeval EWC strata of the Krosno facies. They include variegated claystones, *Globigerina* marls, menilite shales and turbiditic sandstones and shales of the Oligocene Malcov Fm. The Údol Succession partly seals the nappe structure of the Oravic units which originated by sequential stacking during the latest Cretaceous – Early Eocene, but is largely incorporated into younger, Lower Miocene deformation.

Based on these considerations, Plašienka and Mikuš (2010) and Plašienka (this issue) reconstructed the tectonic evolution of the eastern part of the PKB as follows. The outward younging synorogenic clastic formations of the three superposed Oravic units clearly record their latest Cretaceous to Early Eocene stacking progression: first the Pieniny nappe overrode the Jarmuta Basin of the Subpieniny area in the latest Cretaceous, then the Subpieniny nappe with piggy-back Pieniny Unit slid over the Proč Basin during the Late Paleocene to Lower Eocene. The post-stacking period was first governed by dextral transpression followed by extensional collapse and deposition of the overstepping, Middle Eocene – Oligocene Údol Succession, which is closely related to sediments of the CCPB. Subsequently, the PKB attained its final tectonic form by the post-Oligocene SW–NE shortening accompanied by slight dextral wrenching. This overall tectonic evolution is partially recorded also by the small-scale deformation elements developed during several deformation stages, as described in detail by Plašienka in this conference volume.

The regional structure of the area is rather complex and difficult to be recognized in places with poor outcrop conditions. Nevertheless, after a rigorous structural assessment and detailed mapping the main points become quite clear. First of all, the primary fold-and-thrust structures are fairly well preserved. In general, the area is characterized by a broad, internally complicated antiform (see Plašienka, this issue). The thrusting process progressed from foreland-propagating overthrusting of thin nappe sheets, followed by piggy-back, out-of-sequence thrusting and dextral wrenching that largely modified the original thrust structures.

Based on spatial relationships of units embracing different lithostratigraphic successions (Fig. 1), three superposed principal PKB units have been discerned in this area (Plašienka and Mikuš, 2010). The **Šariš Unit** is in the lowermost structural position, on the surface it is built mostly of hundreds metres thick calcareous flysch deposits of the Jarmuta and/or Proč Fm. of the Maastrichtian to Lower Eocene age (localities 6 and 8), including the terminating coarsening-upward sequence with bodies of the olistolith-bearing Milpoš Breccia Member (locality No. 8). Older Cretaceous members, which begin with well-bedded, marly limestones akin to the Pieniny Fm., occur in several partial anticlinal zones near Litmanová. They are followed by variegated shaly and marly formations of Albian to Campanian age, including the "black flysch" and "Fleckenmergel" deposits, weakly calcareous oceanic red beds and distal hemiturbidites (Malinowa Fm.), in part deposited below the CCD (localities No. 5 and 7). In the Polish Małe Pieniny Mts, the Šariš Unit would correspond to the Grajcarek Unit (Birkenmajer, 1970, 1986), but in the lower structural position with respect to the other PKB units, as interpreted also by Jurewicz (1997) and Oszczypko et al. (2010). Likewise the Hulina Unit and possibly also the Złatne Unit defined by Sikora (1971, 1974) appear to be analogues of the Šariš Unit.

The **Subpieniny nappe** includes, according to our investigations, not only klippen of the typical Czorsztyn Succession (locality No. 2), but also the Niedzica and Czertezik "transitional" successions (Fig. 1). The Jurassic – Lower Cretaceous rocks form the stiff klippen of tectonic origin that rest in the Albian to Maastrichtian matrix of various composition dominated by the Senonian red pelagic marlstones of the "Púchov facies". The Subpieniny successions are terminated by calcareous turbiditic sandstones (Jarmuta Fm.) and carbonate tectono-sedimentary breccias of the Maastrichtian, possibly up to early Paleocene age, which are known as the Gregorianka Breccia (Nemčok et al., 1989; Plašienka and Mikuš, 2010) – locality No. 1.

The inner structure of the Subpieniny Unit is controlled by the presence of a variously thick layer of mostly massive, competent Middle to Upper Jurassic sandy-crinoidal and nodular limestones, which are inserted between incompetent shaly and marly Lower Jurassic and Upper Cretaceous strata. In the course of thrusting-shearing deformation, this competent layer was either dismembered into numerous small imbricates and boudins floating in incompetent matrix, or, in the case the competent layer was very thick (more than 50 metres), it forms a stack of thick imbricates that are laterally continuous for several hundred metres. At the same time, these differences may have resulted also from the rugged, synsedimentary fault--controlled morphology of the Czorsztyn Ridge that was truncated by the basal detachment of the Subpieniny nappe at various levels (Fig. 3), sometimes even not reaching deep enough to attack the Jurassic rocks. This can be also the cause of a lateral discontinuity of the unit, which cannot be ascribed to the tectonic reasons only. Due to differences in the mechanical stratigraphy, the Subpieniny Unit is differentiated to two partial subunits (Plašienka and Mikuš, 2010; Plašienka, this issue). The **Jarabina Subunit** consists of thick imbrications of the typical Czorsztyn Succession forming antiformal thust stacks or duplexes in the rear part of the Subpieniny Unit (area around the Jarabina Gorge and quarry – localities No. 3 and 4, see Fig. 2). The other, **Maslienka Subunit,** is tightly imbricated with isolated, decametre-sized blocky klippen of the Czorsztyn, as well as "transitional" Jurassic – Lower Cretaceous formations embedded in a strongly sheared, scaly matrix of Upper Cretaceous shales, marls and sandstones, hence forming a typical block-in-matrix structure of tectonic origin (Fig. 2, localities 5 and 6). The peculiarity of the inner structural style of the Maslienka Subunit is that the strata succession of individual imbricates is usually overturned, which applies not only to the klippen themselves, but to the klippen matrix formations as well (see the Jar-1 borehole log at locality No. 5; Fig. 9).

The overriding **Pieniny nappe** involves basinal Jurassic – Cretaceous successions (Fig. 1) with small local variations in their lithostratigraphic content used for distinguishing of several lithostratigraphic successions (Pieniny s.s., Kysuca, Branisko; for the detailed lithostratigraphy see e.g. Birkenmajer, 1977). The Pieniny successions are composed of well-bedded pelagic radiolarites, limestones and marlstones, hence forming a multilayer prone to folding. Consequently, also the overall structural style of the Pieniny Unit is different from the other two. It obviously occurs in the uppermost structural position within the PKB edifice (Fig. 2) and forms the southernmost, internally imbricated and folded zone along the southern PKB margin.

Description of localities

The lithostratigraphic and tectonic phenomena outlined above may be examined in detail at several localities between Jarabina and Litmanová villages (Fig. 4). These localities are chosen in a way they can be passed during a one-day walking trip (6–8 hours).

<u>Locality 1</u> – Hlboký potok valley (Gregorianka Breccia)

Type locality of the Gregorianka Breccia, east of Jarabina (D. Plašienka, J. Madzin, Š. Józsa)

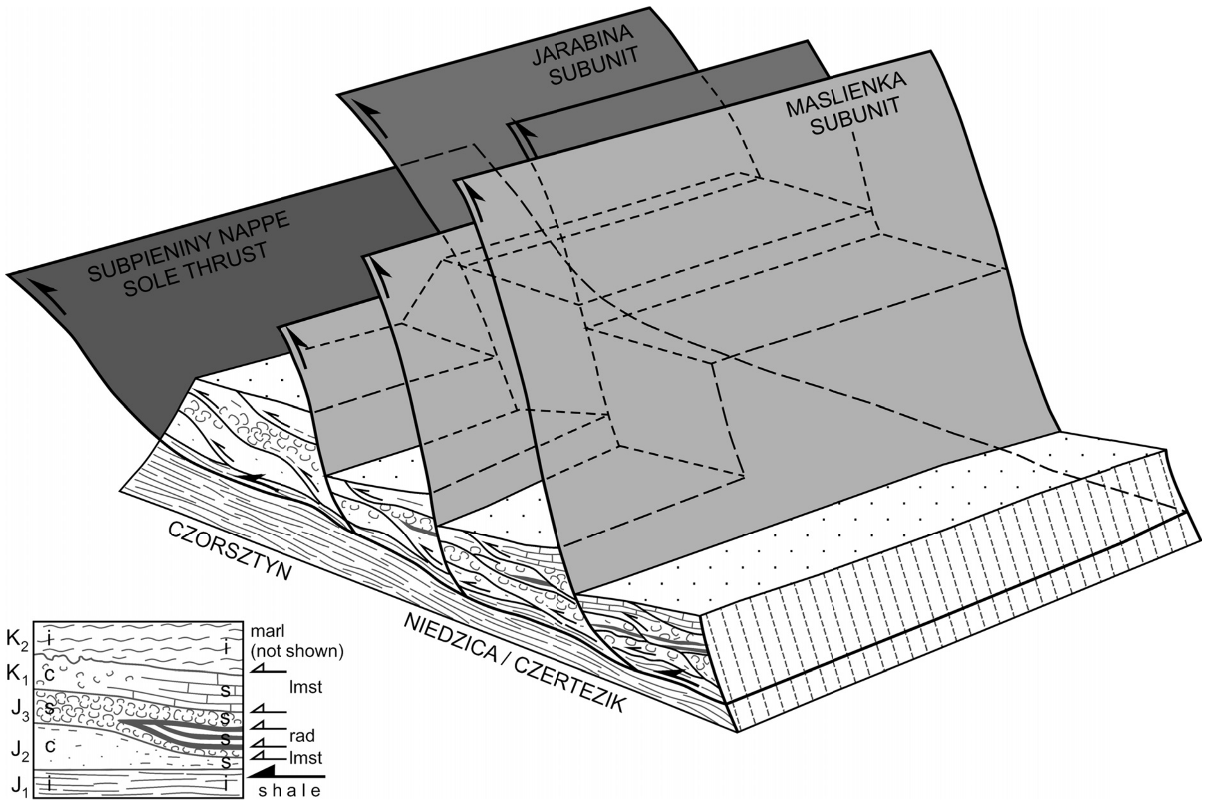

Fig. 3. Blockdiagram showing dependence of the basal detachment of the Subpieniny nappe and its partial imbricates on the pre-existing block structure and mechanical stratigraphy of the Czorsztyn-type successions. The inset indicates lithology and mechanical properties of the main formations: i – incompetent shales and marls; s – semi-competent, well-bedded limestones and radiolarites; c – competent massive or thick-bedded limestones.

Just a few tens of metres east of the last houses of the upper, NE end of Jarabina village, there is the type locality of the "Gregorian Breccia" as described by Nemčok et al. (1989). According to the current maps, the local name is "Pod Gregorankou", the original Gregorianka is the hill with the spot height 721 m some 450 metres towards the east. Outcrops of Gregorianka Breccia occur down in the valley of Hlboký potok (Deep brook – GPS N 49°20'35.8", E 20˚39'48.3"; altitude 630 m).

At their type locality, Nemčok et al. (1989) characterized the Gregorianka breccias as monomict, composed of angular, up to 60 cm large clasts of grey Calpionella limestones, grey-green radiolarites, and less radiolarian and saccocomid limestones. The breccia bodies are intercalated by up to 2 metres thick layers of red marlstones containing hedbergellas, thalmanninellas, globotruncanas, globorotalias? and globigerinas?. Based on these, they supposed their Maastrichtian, and possibly also Paleogene age. However, Nemčok mentioned these breccias also earlier (e.g. Nemčok, 1978, 1980) and based on them his conception of the sedimentary origin of not only some klippen occurring within the Proč-Jarmuta flysch deposits, but of the entire PKB as a huge megabreccia body inserted between the Paleogene flysch formations of the Magura nappe and the CCPB. This idea, whatever erroneous in general, has its positive aspects. First of all, Nemčok drew attention to the breccia bodies that occur within the flysch or "wildflych" Jarmuta and/or Proč formations as sliding masses or olistostromes and discarded the opinion about their transgressive and cliff origin. At the same time, Nemčok noticed that numerous klippen are in fact olistoliths resting within these breccia bodies. These observations were crucial, but overlooked for the next decades.

Recently, Plašienka and Mikuš (2010) studied the composition and position of these breccias and subdivided them into two separate members – the Gregorianka Breccia "sensu stricto" from this and several other localities and the Milpoš Breccia of the Šariš Unit (see locality No. 8). The former breccias appear to represent terminal deposits of the Subpieniny nappe successions, which are most likely latest Cretaceous to earliest Paleogene? in age. Their composition reveals derivation from the overriding Pieniny nappe, thus they are interpreted as tectonosedimentary breccias that originated from debris released from the tectonized front of the overriding thrust sheet. Subsequently the breccias were deposited in the frontal trench-like basin, and finally they were superposed by their original source unit. Unlike the Milpoš Breccia, the areal extent of the Gregorianka Breccia is restricted to several localities only, as well as large olistoliths are less frequent (but present in places, e.g. near the village Demjata north of Prešov).

According to our observations and the present state of the outcrop, the breccia bodies (at least two separate in the section) occur within a strongly imbricated zone

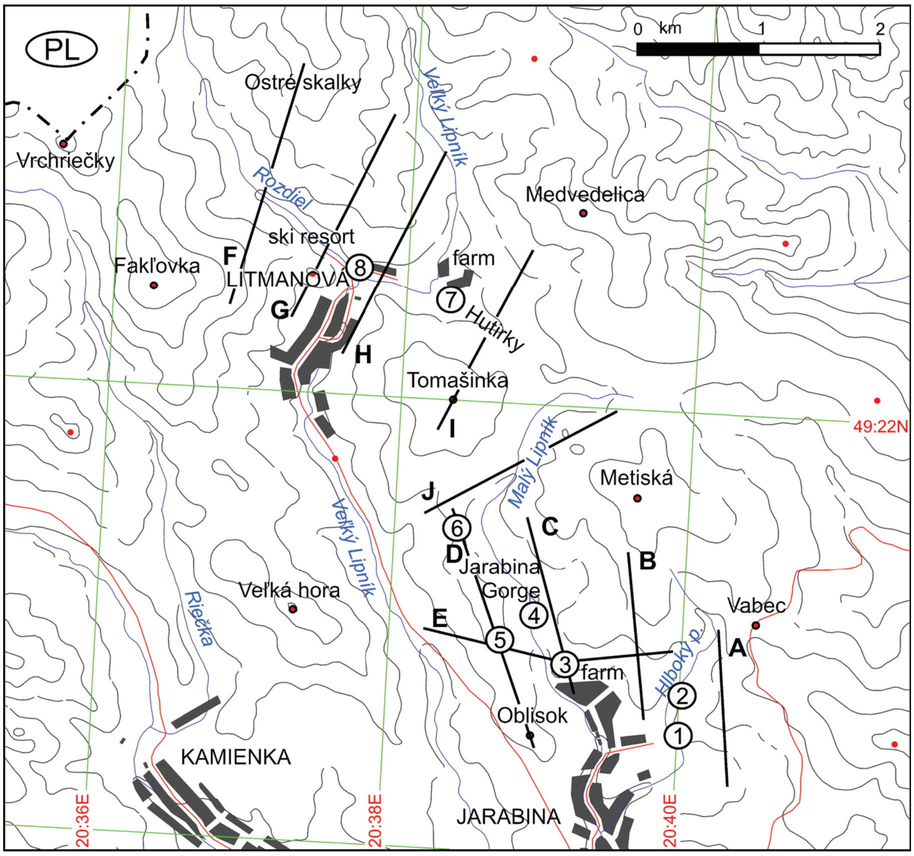

Fig. 4. Topographic map of the area with position of the representative localities described in the text and cross-sections shown in Figs. 2 and 11. Compare to the geological map depicted in the article by Plašienka (this issue).

sandwiched between the overlying Pieniny and underlying Subpieniny Unit. From south to north, the discontinuous section (Fig. 5) exposes sheared limestones of the Pieniny Fm., a sequence of variegated (grey-green, red and black) marls, then again a slice of Pieniny limestone, dark marls with limestone fragments (Upper Albian foraminifers), then, after an interruption (covered by a scree of reddish marls), the first body of breccias about 3 metres thick underlain by dark shales with thin sandstone beds (Turonian to Lower Cenomanian foraminifers). The section follows with another a few metres thick breccia body, ca 5 m thick sequence of turbiditic sandstones and marly shales underlain by 10 m of brick-red and green marlstones (planktonic foraminifers of Campanian – Lower Maastrichtian age) and grey spotted marlstones (Upper Albian – Lower Cenomanian). After a tectonic contact, the variegated marls are underlain by a thick calcareous flysch sequence of Campanian – Lower Maastrichtian age (pelagic and agglutinated foraminifers); the sequence is overturned (Helminthoid-type ichnofossils occur on upper surfaces).

According to our investigation, the clast-supported Gregorianka Breccia has a monotonous lithological composition and contains material evidently derived from the structurally higher Pieniny Unit. Grain size varies from fine (few mm) to boulder size. Most common are clasts of radiolarian limestones, wackestone to packstone texture, with abundant radiolarian skeletons. Clasts of calpionellid limestones – wackestones with Calpionella alpina Lorenz – are also frequent. Occasional non-carbonatic rock fragments are represented by siltstones and rarely metamorphic rocks (schistose quartzite). Siliciclastic imput of detrital subangular to angular quartz and feldspar grains is present as well. The voids between individual clasts are filled mainly with carbonate cement, in some cases also with silty to fine-grained sandy matrix with fine quartz and feldspar grains.

<u>Locality 2</u> – Hlboký potok valley (Czorsztyn-type klippe)

Litho-biostratigraphic profile of the Czorsztyn Succession (M. Jamrichová, D. Plašienka)

The locality is situated NE to the Jarabina village (GPS coordinates N 49°20'44.3'', E 20°39'52.7''; altitude 652 m) in a small gorge of the Hlboký potok stream crossing a klippe composed of Jurassic limestones of the shallow--water Czorsztyn Succession. The klippe is surrounded by variegated Cretaceous marlstones and is ranged to the Maslienka Subunit of the Subpieniny nappe (Plašienka and Mikuš, 2010). The following lithostratigraphic units can be recognized in this klippe (Fig. 6):

Alternating pink and grey-green crinoidal limestones of the thickness 4.9 m occur here instead of superposed white and red varieties of the Smolegowa and Krupianka Limestone Fms, respectively. Limestones represent crinoidal biosparites (grainstones) consisting of crinoidal ossciles, numerous clasts of micritic carbonates (mostly dolomites and dedolomites) and less numerous fragments of bivalves (in places only ghosts) and brachiopods, echinoid spines, agglutinated, lenticulinid and nubecularid foraminifers. Dispersed sandy quartz admixture is also frequent. The grainstones are evidence of a dynamic sedimentary environment where the mud was winnowed from the interstices. The crinoid ossicles are usually overgrown by clear syntaxial calcitic rims. The sediment was strongly affected by compaction, as indicated by frequent pressure-solution seams among the skeletal detritus, up to stylolites forming wavy to anastomozing, bedding-parallel foliation. This foliation formed during the latest diagenetic stage as it cuts the fully developed syntaxial rims on echinoderm particles.

Krupianka Limestone Formation is formed by bedded to massive, reddish crinoidal grainstone to packstone still containing abundant clastic admixture, mainly represented

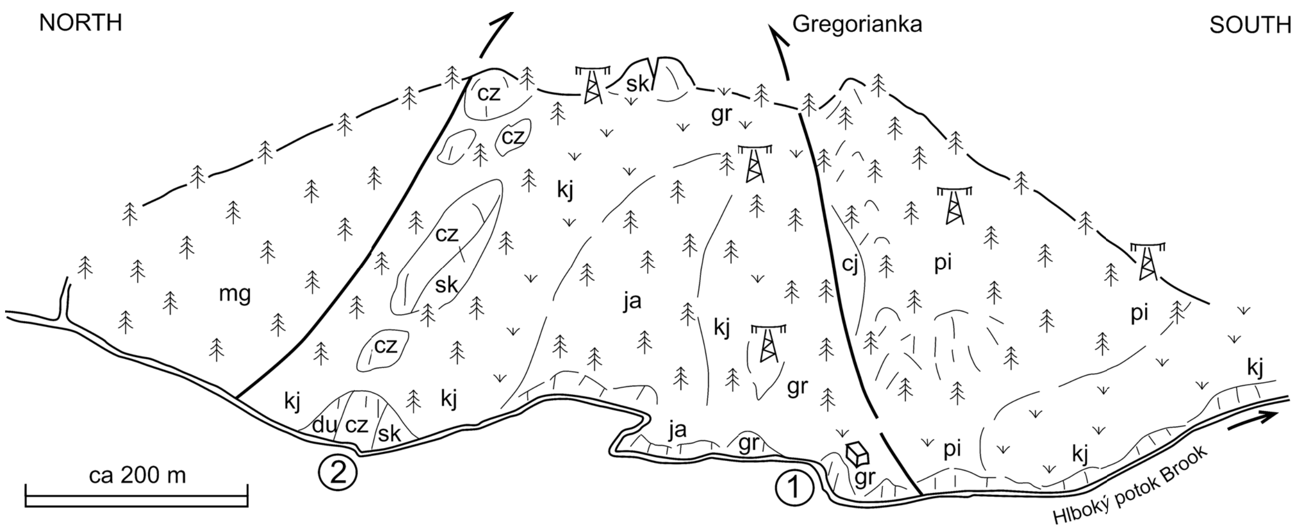

Fig. 5. Schematic view of eastern slopes of the Hlboký potok Valley (Gregorianka section, positions of localities 1 and 2 are shown). Abbreviations: mg – Magura Unit; kj – Cretaceous shales and marls (Kapuśnica and Jaworki Fms.); du – Dursztyn Fm.; cz – Czorsztyn Fm.; sk – Smolegowa and Krupianka Fms.; ja – Jarmuta Fm.; gr – Gregorianka Breccia; cj – Czajakowa Fm.; pi – Pieniny Fm.

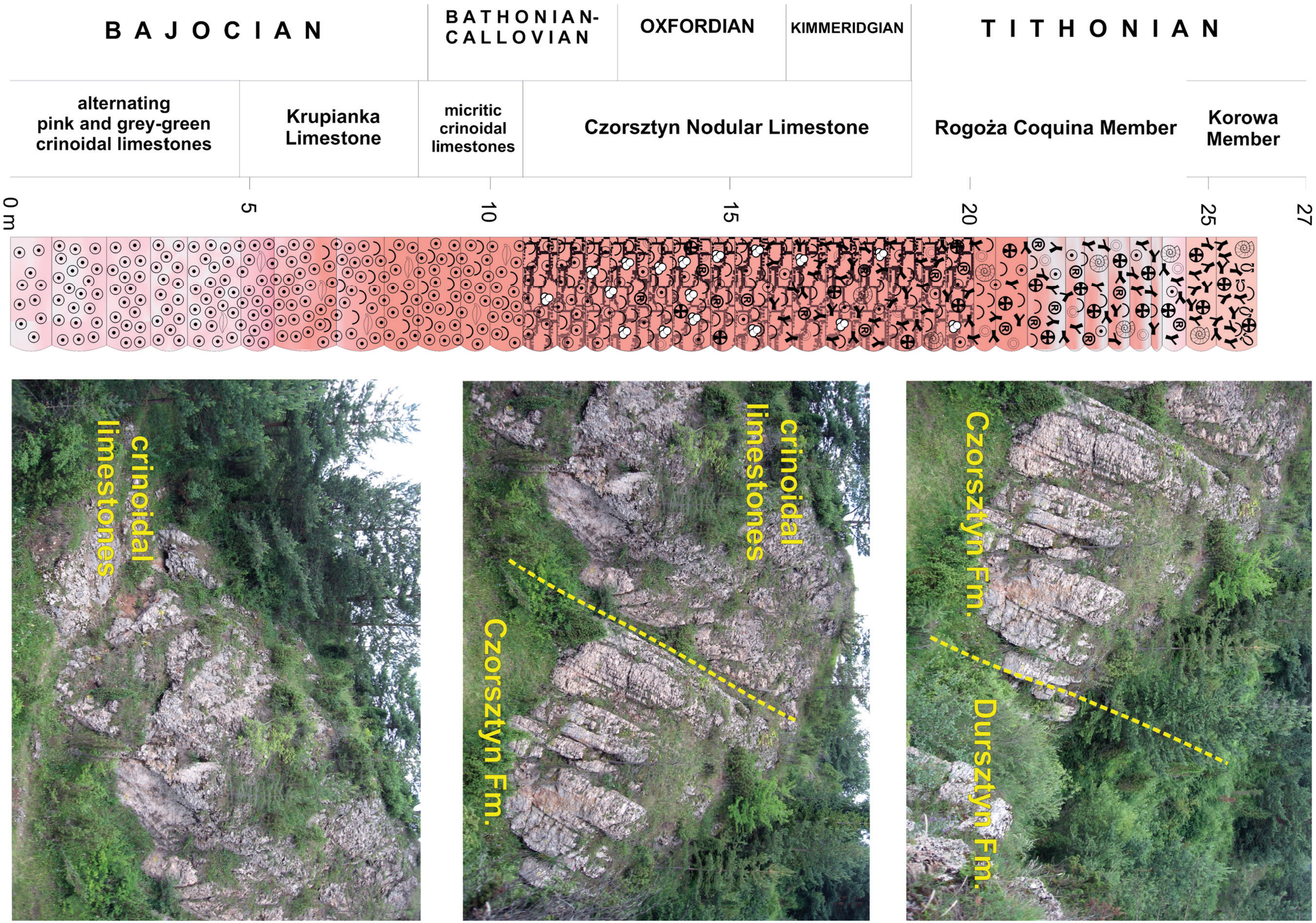

Fig. 6. Lithostratigraphic profile of the Hlboký potok klippe. The inset photos show contacts of the lithostratigraphic units described. Note subhorizontal cleavage cutting the vertical strata of the Czorsztyn nodular limestones.

by quartz grains and dolomites. The echinoderm (mostly crinoids) – filamentous (thin shelled bivalves) packstones with marly matrix are present as well. They reach thickness of around 3.4 m. The age of the alternating pink and grey-green crinoidal limestones and the Krupianka Fm. is Middle/Upper Bajocian – Bathonian (e.g. Birkenmajer, 1977). The Krupianka limestones gradually pass into the **red bedded micritic crinoidal limestones** – biomicrites (packstones) with crinoid-filamentous microfacies. In this formation, a condensed sedimentation was registred, which is indicated by the Fe-Mn crusts, marking the hiatus between the crinoidal and red micritic limestones. Their thickness reaches almost 2 m.

Czorsztyn Limestone Formation – after the sedimentary break, the Czorsztyn Nodular Limestone with filamentous microfacies sedimented. The deposits contain mainly thin-shelled bivalves (filamentous packstones), juvenile gastropods, benthic foraminifers and crinoidal ossicles. Thin-shelled ostracods, foraminifers (*Ophthalmidium* sp., *Lenticulina* sp., *Patellina* sp, *Spirillina* sp., *Dorothia* sp.), sessile nubecularid foraminifers, nodosariid foraminifers and "microforaminifers" also occur. Detritus from thicker-walled bivalves (commonly dissolved and replaced by micrite) and brachiopods, rare gastropods, juvenile ammonites, echinoid spines are quite common. Rare quartz grains occur, too. Filamentous microfacies are replaced by the *Protoglobigerina* microfacies, suggesting their Oxfordian age. This passes gradually into *Saccocoma* microfacies. The upper part of the formation contains microfossils *Cadosina parvula* Nagy, *Stomiosphaera moluccana* Wanner, *Colomisphaera pieniniensis* Borza, *C. pulla* Borza, *C. carpathica* (Borza), *C. nagyi* (Borza), *Schizosphaerella minutissima* (Colom), *Carpistomiosphaera borzai* (Borza) documenting Early Kimmeridgian Parvula Zone and Late Kimmeridgian Moluccana Zone. Thickness of the Czorsztyn Limestone Formation is around 7.5 m.

The **Dursztyn Limestone Formation** consists of massive, red and pinkish, micritic limestones up to 8 m thick. Locally, they can be rich in crinoidal ossicles (forming lenses of crinoidal packstones) and fine shelly debris (Rogoża Coquina Member). The deposits are formed by radiolarian-*Saccocoma*-*Globochaete* microfacies (packstones, wackestones). Calcareous dinoflagellate cysts (*Carpistomiosphaera tithonica* Nowak, *Colomispahera pulla*, *C. carpathica*, *C. nagyi*, *Cadosina radiate* Vogler, *Parastomiosphaera malmica* Borza, *Schizosphaerella minutissima*) indicate Early Tithonian to Middle Tithonian Pulla, Tithonica and Malmica Zone. Early calpionellid forms with microgranular lorica (*Chitinoidella dobeni* (Borza), *C. tithonica* (Borza), *Borziella slovenica* (Borza), *Daciella danubica* Pop, *Longicollaria dobeni* (Borza), *Dobeniella bermudezi* (Furrazola-Bermudez)) characterize the Dobeni and Boneti Subzone of the Chitinoidella Zone (Middle Tithonian). The *Saccocoma*-*Globochaete* microfacies passes gradually into the calpionellid-*Globochaete* microfacies of the Korowa Limestone Member. Calcareous dinoflagellate cysts are represented by *Schizosphaerella minutissima*, *Colomisphaera carpathica*, *C. nagyi*, *C. tenuis* Nagy, *Cadosina semiadiata semiradiata* Wanner. The occurrence of the *Crassicollaria intermedia* (Durand Delga), *C. massutiniana* (Colom), *C. parvula* Remane, *Tintinopsella remanei* (Borza), *T. carpathica* (Murgeau et Filipescu), *Calpionella grandalpina* Nagy and rare *Calpionella alpina* Lorenz indicate Intermedia Subzone of the Crassicollaria Zone (Late Tithonian). The Early Tithonian to Late Tithonian age of the formation is based in calcareous dinoflagellates and calpionellids.

The strata of the klippe are steeply south-dipping with younging direction towards the north. A distinct, subhorizontal cleavage may be observed, particularly in the red nodular limestones (Fig. 6). The cleavage formed by pressure solution early in the deformation process, probably during the incipient phases of layer-parallel shortening and detachment of a more competent packet of Middle Jurassic – Lower Cretaceous limestones from the underlying, incompetent shaly and marly deposits (see Plašienka, this issue).

The area provides numerous alternative profiles of Jurassic to Lower Cretaceous formations representing the Czorsztyn, Niedzica and/or Czertezik Successions. Some of them have been already evaluated litho-biostratigraphically in detail by M. Jamrichová, e.g. the spectacular Čertova skala klippe ca 1 km to the north. Each klippe appears to show some, at least subtle, but sometimes abrupt differences in their lithostratigraphic profiles, hence indicating sudden lateral and vertical changes in sedimentary environments within the Czorsztyn Ridge and its slopes. Particularly, the uneven thicknesses and differing rheological properties of individual formations, as well as of the whole rigid limestone package, were variously expressed in formation of the tectonic structures (see Fig. 3).

Locality 3 – Jarabina quarry, top stage (Czorsztyn Succession)

Transgressive contact of Cretaceous marls with Jurassic limestones (D. Plašienka)

In the sporadically active Jarabina quarry (Lysá skala klippe, Fig. 2 – GPS N 49˚20'48.5", E 20˚39'01.1"; altitude 660 m), the pale, yellowish and pinkish sandy-crinoidal limestones (Smolegowa Limestone Formation) are excavated for building purposes. Limestones are massive to thick-bedded with strata dipping moderately to the south. At the foot of the cliff near entrance to the quarry, the Smolegowa limestones are overlain by red micritic, weakly nodular limestones of the Bohunice Fm. (Bathonian – Kimmeridgian; Aubrecht et al., 2006). This layer is thinning upslope, thus in the upper quarry stages it is reduced to several dm (see Aubrecht et al., 2006, their Fig. 12 – however, after the recent exploitation in the upper quarry levels, the younger deposits were removed completely). The Bohunice limestones are uncomformably overlain by the Albian to Cenomanian marlstones (Chmielowa and Pomiedznik Fms.), marly limestones and breccias, which also form fissure fillings in underlying limestones. Besides limestone fragments from underlying formations, including Upper Aptian – Lower Albian hedbergellids-bearing limestones not known from primary occurrences, there are frequent phosphatic oncoids and small quartz pebbles. The deep pre-Albian erosion, reworking of older breccias and multiple fissure fillings point to the oscillating sea level and emersion, subaerial erosion and karstification of the shallowest parts of the Czorsztyn Ridge during the Hauterivian – Aptian. As this event roughly corresponds to the global sea-level fall, it would be logical to ascribe the uplift to it. However, it is questionable if solely the eustatic lowstand in the order of tens of metres could account for the relatively deep erosion documented in several Czorsztyn profiles. Shallowing of the Czorsztyn Ridge started already in the Valanginian (Walentowa Breccia, crinoidal limestones of the Spisz Fm.) and its uplift seems to exceed the estimated value of the Barremian sea-level drop. Alternatively, a tectonic trigger could be considered as well – either extensional due to the rift shoulder uplift during breakup of the Magura Ocean (Plašienka, 2003), or due to the passive margin inversion generated by far-field compressional stresses transferred from the Central Carpathians.

Very interesting is the composition of heavy minerals extracted from the basal Chmielowa marls from this locality. Aubrecht et al. (2009) have found that association is dominated by Cr-spinels (more than 40 %) and garnet (30 %), other stable minerals of the zircon-rutile-tourmaline assemblage occur in concentrations below 10 %. Chemistry of garnets indicates their origin from high-grade metamorphic rocks as eclogites, granulites, gneisses and amphibolites, which are similar sources as in established for the Jurassic PKB sediments. Aubrecht et al. (2009) therefore suppose that the sources of garnets should be looked for in the Czorsztyn Ridge basement. On the other hand, the spinels were likely derived from oceanic crustal sources similar to the Meliaticum. Relying on this, Aubrecht et al. (2009) elaborated a completely new paleogeographic scheme of the PKB (Oravic) realm – the Czorsztyn Ridge basement was rifted off the Moldanubian Zone of the Bohemian Massif during the Middle Jurassic to create the Magura Ocean in between, while other Oravic units (e.g. Niedzica, Kysuca-Pieniny) were facing this ocean, i.e. they were located paleogeographically north of the Czorsztyn Ridge. The latter, on the other hand, was juxtaposed to the exotic Andrusov Ridge (source of spinels – a laterally translated part of the Meliata suture) that neighboured the northern CWC margin. This strange arrangement should have resulted from pre-Albian, large-scale sinistral translations along the CWC/PKB intervening zones.

The first description of transgressive contact of Cretaceous marls and Jurassic limestones from this area was published already by Andrusov et al. (1959). However, they mentioned a "small klippe" north of Jarabina, which was probably not the presently quarried large klippe Lysá skala. Above a corroded surface on saccocomid limestones, they observed a tiny limonite crust followed by a thin layer of red marly limestones of the "globigerinid-radiolarian microfacies" with *Ticinella roberti* (Albian, Rudina Beds) and then by variegated globotruncanid marls (Cenomanian).

<u>Locality 4</u> – Jarabina Narrows of the Malý Lipník brook (duplex in the Subpieniny nappe)

Lithostratigraphic-structural profile (D. Plašienka)

The Jarabina Narrows is about 500 metres long gorge excavated by the Malý Lipník brook in massive Jurassic limestones of the Czorsztyn Succession. It is an epigenetic valley modelled by the karst and river erosion processes. Its local Ruthenian name is "Medžy pecy"; the klippe is called Dutkova skala. The gorge is accessible by a touristic path, but it is hardly passable during the high water stand. It ends by a canyon as narrow as 2–3 metres with rocky cliffs more than ten metres high built by the "ammonitico rosso" limestones, the bottom is formed by an interconnected system of deep potholes.

The upper part of the gorge starts in the gently north-dipping, thick-bedded red nodular limestones of the Czorsztyn Fm. (Bathonian – Kimmeridgian). The main part is cut in subhorizontally lying massive pale crinoidal limestones of the Smolegowa Fm. (Bajocian), the terminal canyon at the southern end of the gorge struggles through Czorsztyn limestones again, moderately south-dipping in this case (Fig. 7). Thus the Jurassic limestones form a wide anticline and are overlain, behind the gorge edges, by variegated Upper Cretaceous marlstones of the "couches rouges" facies known also as the "Púchov marls" in the PKB. The uppermost layer of the rocky cliff on the right (western) side is formed by the pink biomicritic limestones of the Tithonian – Berriasian Dursztyn Fm. Below the canyon mouth to the south, the Jarabina quarry and the

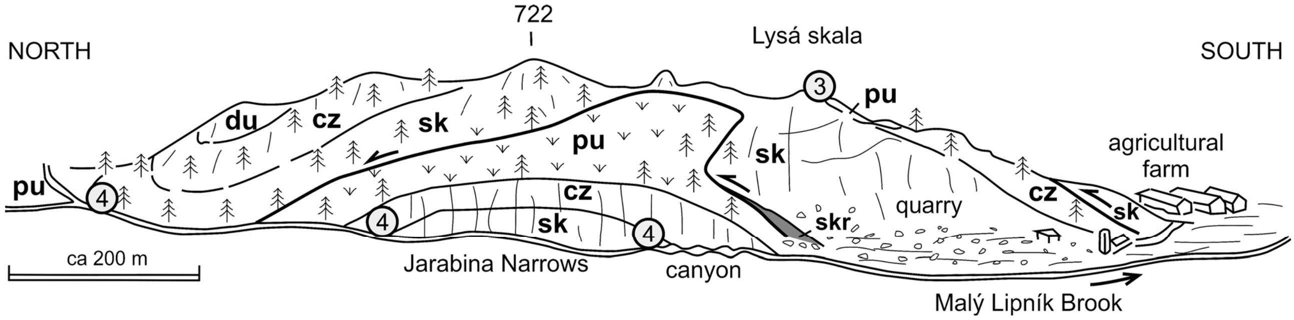

Fig. 7. Schematic view of the eastern slopes of the Malý Lipník brook Valley (Jarabina Narrows section, localities 3 and 4). Abbreviations: pu – "Púchov marls"; du – Dursztyn Fm.; cz – Czorsztyn Fm.; sk – crinoidal limestones (Smolegowa and Krupianka Fms.); skr – Skrzypny Shale Fm.

above Lysá skala klippe exposes a similar Czorsztyn Succession (locality No. 3), but forming a higher slice of this large-scale duplex structure. At the sole of this thrust imbricate, dark shales of the Aalenian – Lower Bajocian Skrzypny Fm. were exposed (Fig. 7). At the entrance to the quarry, this Lysá skala slice is overridden by the still higher, third imbrication of the same composition. Altogether, these imbricates create an antiformal thrust stack that is typically composed of ridge-type Czorsztyn Succession. We differentiate it as the Jarabina Subunit of the Subpieniny nappe (Fig. 2). In addition to the Jarabina area, similar duplex structures of the Jarabina Subunit are present north of Stará Ľubovňa (Nemecký vrch Hill) and on the Kamenica castle hill further to the east (Plašienka & Mikuš, 2010). Analogous structures are likely present also in the Polish Pieniny Mts., where they were defined as the "Czorsztyn imbricated unit" by Książkiewicz (1977) – for example the Homole Block near Jaworki (cf. Birkenmajer, 1970; Jurewicz, 1994, 1997). Unlike the Maslienka small-scale imbricates, the Jarabina Subunit consists of duplex structures, in which the individual large slices are reinforced by a thick competent layer of Jurassic limestones, and which are always in the normal position.

Locality 5 – Jar-1 borehole (Maslienka Subunit and Šariš Unit)

Position, lithology and stratigraphy of the borehole log (D. Plašienka, J. Soták, D. Pivko, M. Jamrichová, Š. Józsa, E. Halásová, V. Mikuš)

The Jar-1 drilling was bored on a flat top of a low ridge W about 500 m NW of the northern end of Jarabina village (Fig. 4 – altitude 703 m a.s.l., coordinates N 49°20.882, E 20°38.646). The drilling was realized by the company Envigeo a. s., Banská Bystrica, in winter 2009. Financing was provided by the Slovak Research and Development Agency (project APVV-0465-06 "Tectogen"). The borehole

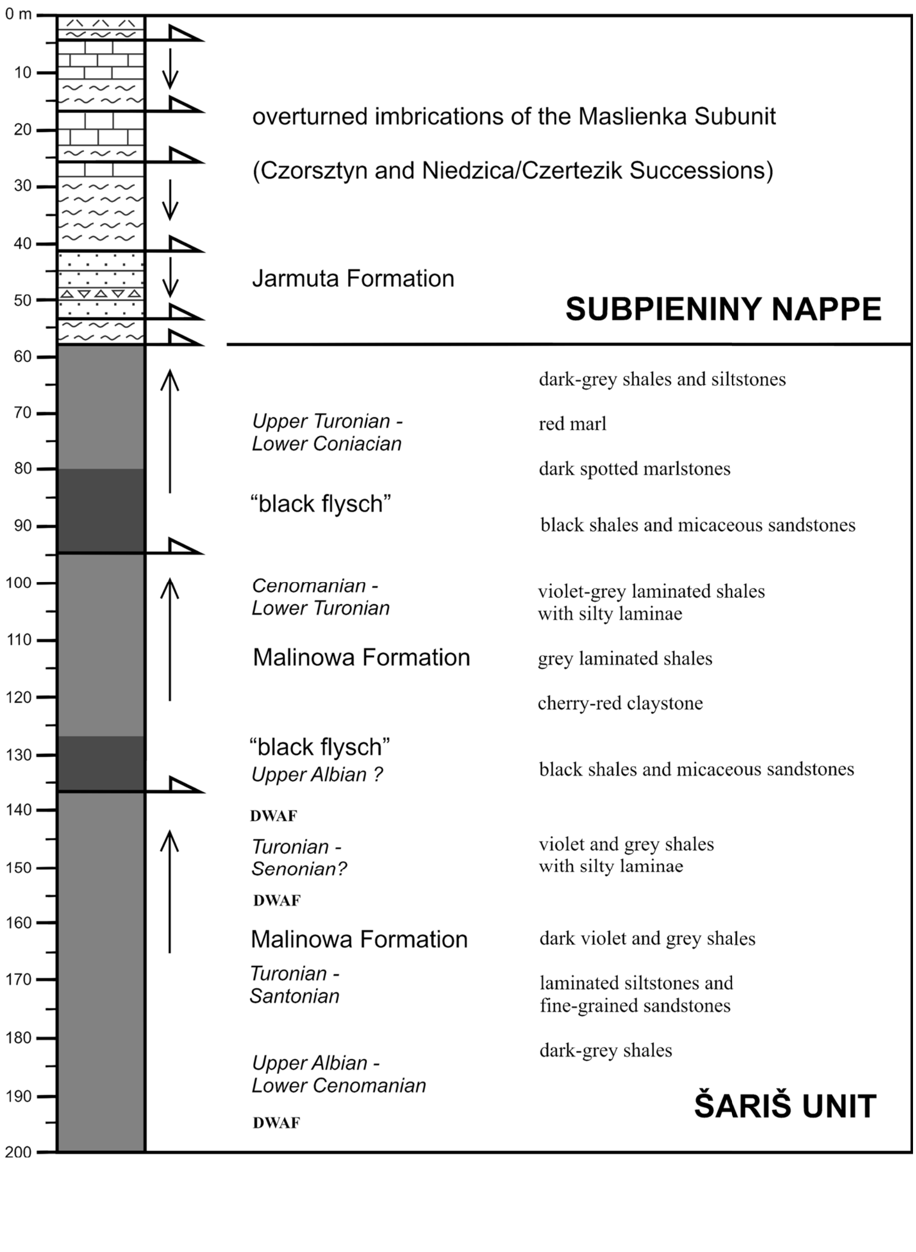

Fig. 8. Overall lithostratigraphic log of the Jar-1 borehole. For detail of the upper part see Fig. 9.

was continuously cored up to final depth 200 m with a core diameter 4 cm. The core material is stored at the Faculty of Natural Sciences, Comenius University in Bratislava. Here we briefly present the preliminary results of lithologic and biostratigraphic investigations of the core material, which is still in progress.

The drilling site was chosen after comprehensive geological mapping and structural research of the area and following interpretation of geophysical profiles (vertical electric sounding, detailed gravimetric profiling – Equis ltd, Bratislava) carried out in the area between Jarabina and Litmanová villages (Mikuš, 2010). The primary aim was to obtain new material for further analytical investigations, especially from the "klippen matrix", which is poorly outcropped in this area, and to ascertain the deeper structure of the PKB in a morphologically not very expressive, grassy region mostly covered by soil and weathering products.

The geological structure of the vicinity of the Jar-1 borehole is rather complex with features typical for the PKB. The grass-covered flat ridge is full of isolated small knobs composed of Jurassic limestones – sandy crinoidal limestones (Smolegowa and/or Krupianka Fms), red nodular limestones (Czorsztyn Fm.) and pink and white biodetrital limestone (Dursztyn Fm.). The matrix of these small klippen is not visible at the surface. It was partly revealed by several shallow drills (up to 7 m) around, which uncovered variegated, mostly dark marlstones with occasional sandstone intercalations. On the other hand, just a few hundred metres east of the drilling site, there is a prominent canyon-like valley (Jarabina Narrows) excavated in a thick, flat-lying sequence of Jurassic

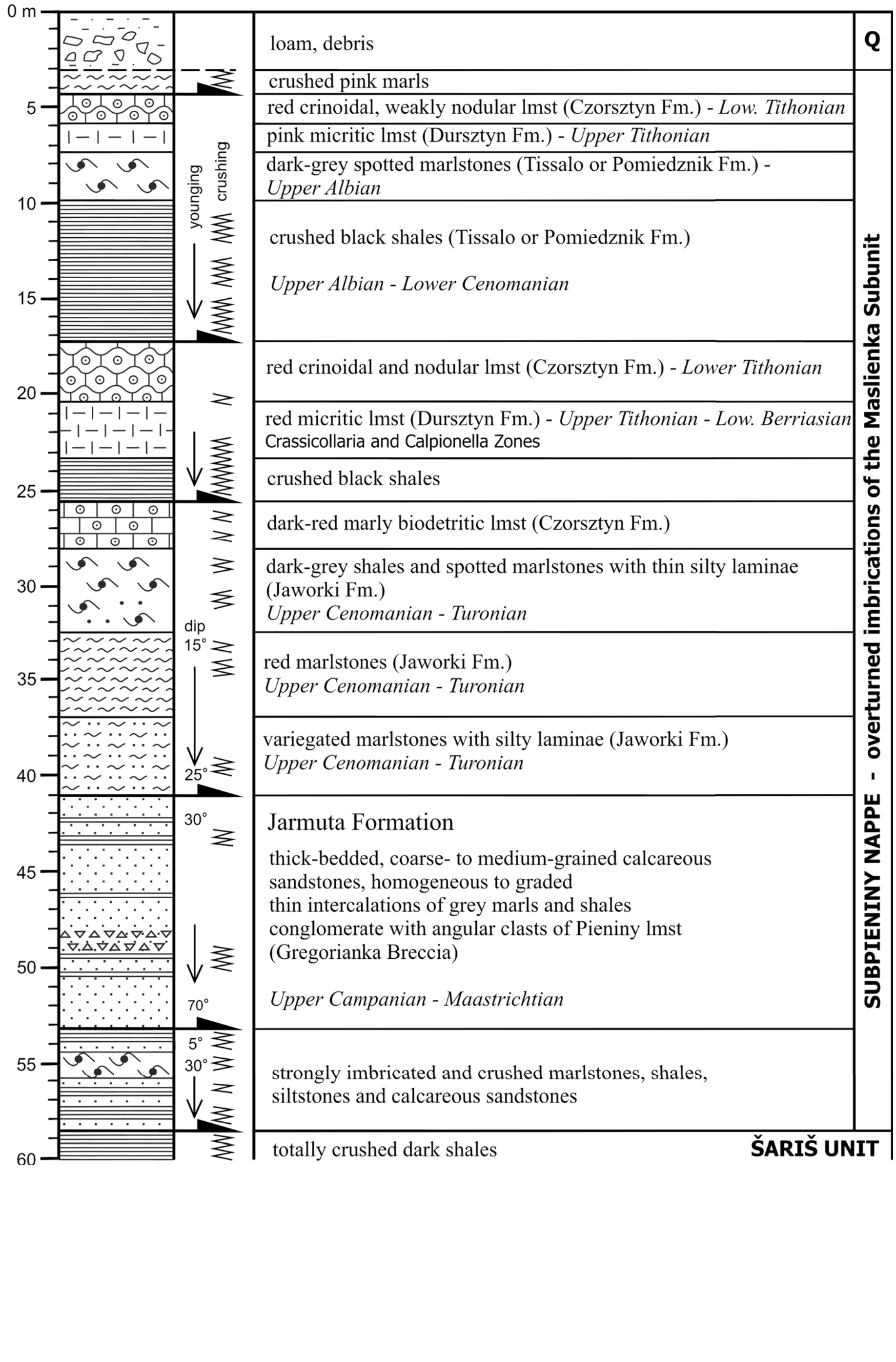

Fig. 9. Lithostratigraphic profile of the upper part of the Jar-1 borehole. Note several slices with repeating, but overturned successions.

limestones typical for the Czorsztyn Succession (see Fig. 6). Thus the intention was to reach this continuous thick Czorsztyn sequence and to find out the inner structure of the Subpieniny nappe. However, as described below, the borehole results, particularly from its lower part, were very different from this supposition.

The generalized profile of the Jar-1 drilling is as follows (Figs. 8, 9):

4–17.5 m: an overturned succession of 2 m of red biodetritic, weakly nodular micritic limestone of saccocomid-radiolarian microfacies (packstone) of most probably Lower Tithonian age (Czorsztyn and/or Dursztyn Fms.); 1 m of grey-green and pink calpionellid-saccocomid biomicritic limestone (wackestone to packstone) of the Upper Tithonian Crassicollaria Zone (Dursztyn Fm.); 2.5 m of dark spotted marlstones and 13 m of crushed black calcareous shales with foraminifers indicating Upper Albian – Lower Cenomanian age: *Hedbergella delrioensis* (Carsey), *Praeglobotruncana delrioensis* (Plummer), *Rotalipora balernaensis* (Gandolfi), *R. appeninica* (Renz), *R. gandolfi* Luterbacher & Premoli-Silva, *R. deckei* (Franke), *R. globotruncanoides* Sigal, *R. cushmani* (Morrow), *Tritaxia gaultina* (Neagu) – Tissalo or Pomiedznik Fm.;

17.5–25.5 m: another overturned slice of red to brown nodular limestone (3 m), crinoid packstone to grainstone of Lower Tithonian age (Czorsztyn Fm.); 3 m of reddish biomicritic limestone (wackestone and mudstone) with calpionellid microfacies of the Upper Tithonian Crassicollaria Zone and Lower Berriasian Calpionella Zone (Dursztyn Fm.), this age is confirmed also by calcareous nannofossils; the slice also contains 2 m of strongly crushed black shales at the base;

25.5–41 m: next overturned slice consists of 2.5 m of dark-red marly biodetritic limestone (Czorsztyn Fm.); 4.5 m dark-grey shales and spotted marlstones with silty laminae; 8.5 m of red and variegated marlstones (Jaworki Fm.), which yielded rich microfossil evidence for the Late Cenomanian – Turonian age, including calcareous nannofossils and planktonic foraminifers *Rotalipora montsalevensis* Mornod, *R. cushmani* (Morrow), *R. gandorfi* Luterbacher & Premoli-Silva, *Praeglobotruncana delrioenisis* (Plummer), *P. gibba* Klaus, *Dicarinella oraviensis* (Scheibnerová), *D. algeriana* (Caron), *D. hagni* (Scheibnerová), *Helvetoglobotruncana helvetica* Bolli, *Marginotruncana coronata* (Bolli), *M. marginata* (Reuss), *M. schneegansi* (Sigal), *M. pseudolinneiana* Pessagno;

41–53 m: probably overturned slice dominated by calcareous, medium- to coarse-grained sandstones, homogeneous to graded in places, forming several metres thick amalgamated packets with thin intercalations of grey shales and marls; at the depth 48–49 m there are several dm-thick beds of clast- or matrix-supported conglomerates composed of up to 3 cm angular clasts of whitish Pieniny-type limestones (Gregorianka Breccia); the assemblage of planktonic foraminifers *Globotruncana arca* (Cushman), *Globotruncana marieri* Banner & Blow and *Gansserina gansseri* (Bolli) encountered in the depth 49.1 m, as well as large foraminifers *Orbitoides aff. gensacicus* (Leymerie), *Pseudosiderolites vidali* (Douvillé) and *Lepidoorbitoides* sp. point to the Upper Campanian – Maastrichtian age of this sandstone-rich sequence, which is classified to the Jarmuta Fm.;

53–58.5 m: strongly deformed zone of crushed spotty dark marlstones, shales, siltstones and calcareous sandstones

58.5–61 m: tectonic breccia – cataclasite of black shales;

61–80 m: dark-grey, calcite-poor shales with thin beds of siliceous shales, laminated siltstones and fine-grained sandstones, intervals of dark spotted and reddish-grey marlstones with sporadic foraminifers *Dicarinella oraviensis* (Scheibnerová), *D. concavata* (Brotzen), *Archaeoglobigerina* sp. (Upper Turonian to Lower Coniacian at 75.8 m), the sequence is ranged to the Malinowa and/or Haluszowa Fm.;

80–95 m: black shales with occasional mica flakes, rarely beds of dark, fine-grained, siliciclastic, micaceous sandstones – this sequence resembles the "black flysch" described under various names and stratigraphic ages from the Polish PKB (Grajcarek Unit – e.g. Birkenmajer, 1977, 2008; Oszczypko et al., 2004);

95–127 m: violet and dark-grey, laminated, carbonate-free or poor shales with silty laminae, grey laminated shales and cherry-red claystones, characterized by the DWAF (Deep Water Agglutinated Foraminifers) associations, with the index fossil *Uvigerinammina jankoi* (97.5 to 106 m) indicating Late Cenomanian to Early Campanian age (Turonian biozone – Morgiel & Olszewska, 1997; Olszewska, 1997); this shaly sequence is ranged to the Malinowa Formation;

127–137 m: "black flysch" – black shales and muscovitic sandstones, occasionally with crinoidal detritus, Lower Albian?;

137–200 m: cherry-red, violet-grey to dark-grey, calcite-poor shales with silty laminae and sporadic thin beds of siltstones and fine-grained sandstones of the Late Cretaceous age (Malinowa Fm.): calcareous nannofossils from 172.1 m indicate Turonian to Santonian age and foraminifers of DWAF association from 187.4 m point to the Late Albian – Cenomanian age: *Bulbobaculites problematicus* (Neagu), *Ammobaculites carpathicus* (Geroch); the lowermost drilled part is composed of dark-grey shales.

The profile of the Jar-1 borehole is interpreted as composed of two parts belonging to different units. The upper, approximately 60 metres consist of at least 5 imbrications with internally overturned successions embracing members typical for the Czorsztyn and/or Czertezic/Niedzica successions (cf. e.g. Birkenmajer, 1977; Wierzbowski et al., 2004). The lower imbrication involves Jarmuta-type sandstones with a few beds of Gregorianka-type breccias. Strata are gently to moderately dipping (15–30°), only the lower part of the Jarmuta Fm.-bearing slice shows steep dips up to 70°. Taking into account the surrounding geological structure, we range this imbricated package to the Maslienka Subunit of the Subpieniny nappe (Fig. 2).

The lower profile, from ca 60 m to the final depth 200 m probably involves three imbrications composed of Cretaceous deep-water, hemipelagic sediments (Fig. 8). These are carbonate-poor, dark-grey and violet shales with occasional distal turbidite beds. Based on poor DWAF associations, they are ranged to the Upper Cretaceous Malinowa Fm. The mid-Cretaceous "black flysch" sediments form the lower parts of the imbrications. Accordingly, sediments should be generally in sequence, in spite that in places overturned and steeply dippnig beds indicate some tectonic disturbances. We interpret these sediments as belonging to the Šariš Unit (see Plašienka and Mikuš, 2010).

Locality 6 – Jar-2 borehole (Maslienka Subunit and Šariš Unit)

Position, lithology and stratigraphy (D. Plašienka, J. Soták, E. Halásová, D. Pivko, M. Jamrichová, Š. Józsa, V. Mikuš)

The Jar-2 drilling was situated on the same ridge as the Jar-1 borehole, about 1 km north of it (Figs. 2 and 4 – altitude 704 m a.s.l., coordinates N 49°21.395, E 20°38.302). It reached the 140 m depth, all other characteristics are the same as for the Jar-1 indicated above (stop 5). The borehole penetrated about 6 m of eluvial loams and then a sedimentary complex that is preliminarily divided into four sequences ranged to two units (Subpieniny nappe and Šariš Unit – see Fig. 10).

6–19.6 m, Sequence 1: strongly deformed grey and red marly shales with fragments of dark spotted marlstones, siltstones and sandstones containing clasts of *Calpionella* and *Saccocoma*-bearing limestones and decimetric to metric blocks of reddish massive limestone – biomicrite (wackestone and packstone) of the calpionellid-radiolarian microfacies, Crassicollaria Zone (Upper Tithonian, Dursztyn Fm.), as well as red nodular limestones (Czorsztyn Fm.?); calcareous nannoplankton from 3.2 and 5.6 m is of Albian – Maastrichtian age, the

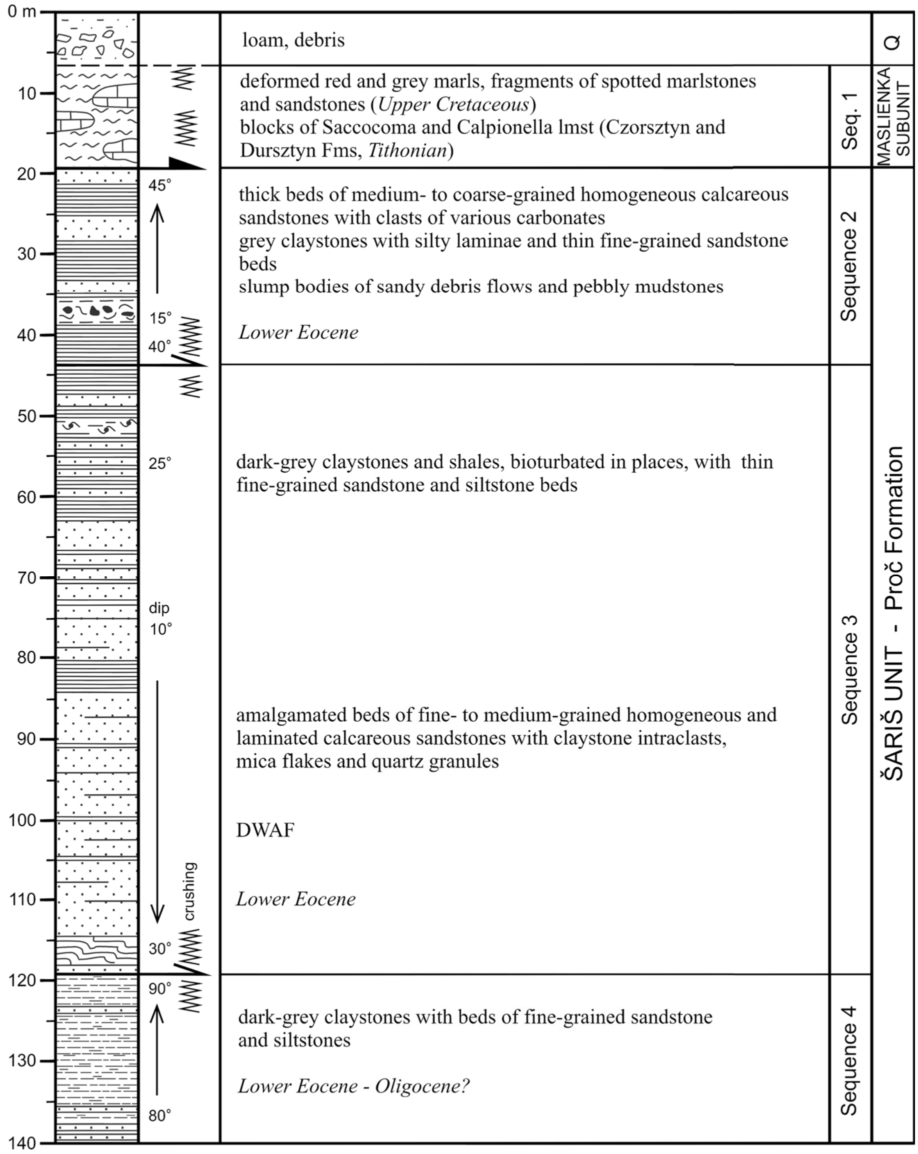

Fig. 10. General log of the Jar-2 borehole.

poorly preserved foraminifers *Rotalipora* cf. *cushmani*, ?*Rotalipora* cf. *appenninica* from the matrix marls indicate Upper Albian? – Cenomanian (13.2 m) to Campanian – Maastrichtian age (19.6 m);

19.6–44.1 m, Sequence 2: crushed grey, greenish and seldom pinkish, massive and laminated, sometimes sandy claystones with silty laminae and thin fine-grained sandstone beds, intercalated by several 10–150 cm thick intervals of homogeneous, medium- to coarse-grained calcareous sandstones with mm-sized, scattered clasts of various limestones, a few thin slump bodies of sandy debris flows and pebbly mudstones; mostly normal position is indicated, strata dips with respect to the borehole axis are gentle to moderate (up to 45°);

44.1–119.4 m, Sequence 3: dark-grey, carbonate-poor claystones and shales, occasionally bioturbated, with several metres thick intervals of fine- to medium-grained, homogeneous, in places laminated calcareous sandstones, which are sometimes mica-rich, or containing quartz granules, with claystone intraclasts and slumping structures (hydroplastically deformed laminae), traces of bitumens (around depth 100 m); the whole sequence seems to be overturned according to sedimentary structures, gentle dips 10–30°;

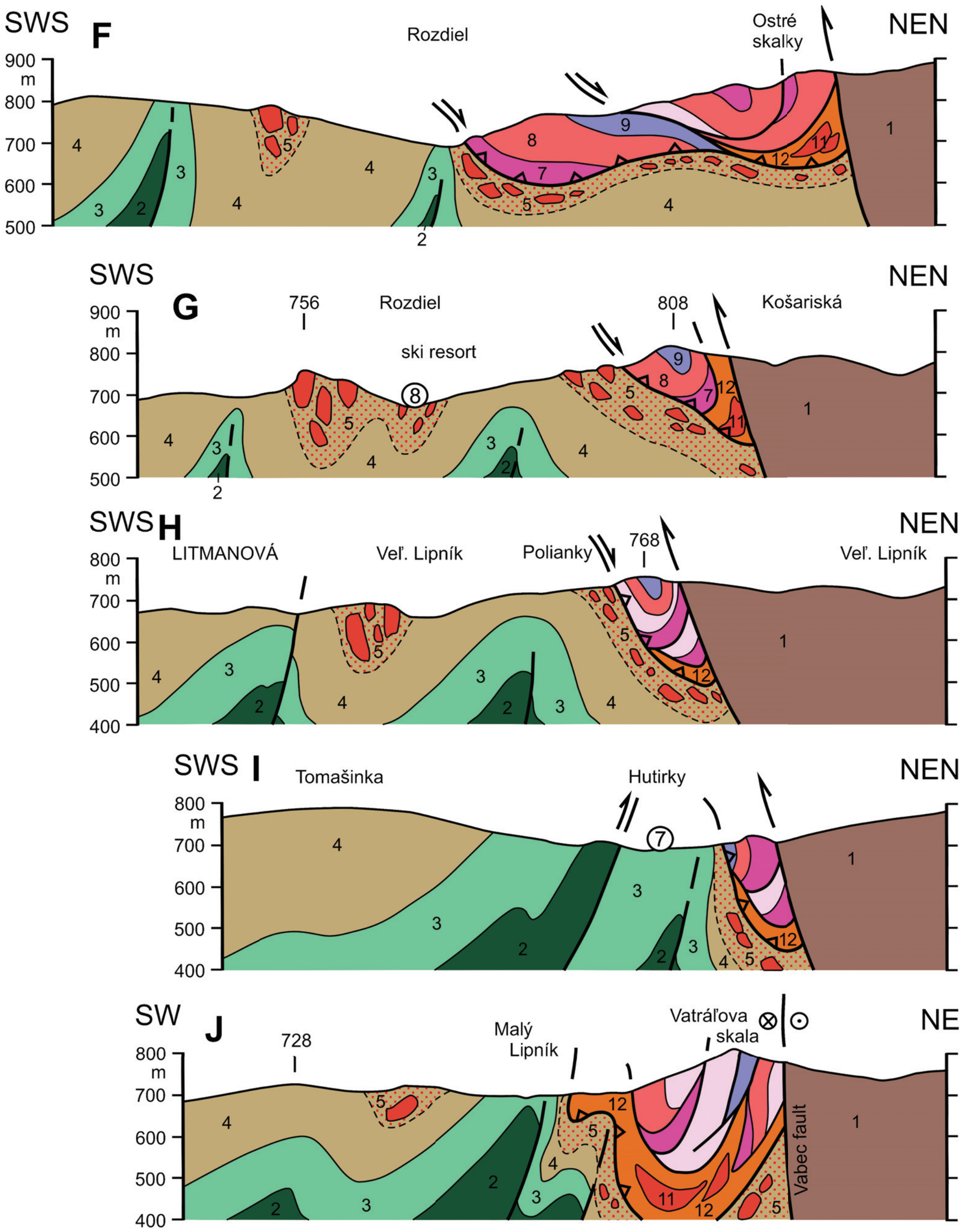

Fig. 11. Geological cross-sections **F–J** of the area north and east of Litmanová. For the legend see Fig. 2 and for their approximate position see Fig. 4.

119.4–140 m, Sequence 4 occurs after a tectonic boundary indicated by a crushed zone, it is composed of dark-grey claystones that prevail over fine-grained sandstones and siltstones; strata are strongly disturbed probably due to both syn-sedimentary and tectonic processes, dips are variable, often steep to vertical, but the sequence is generally in a normal position.

The upper ca 20 m of the borehole profile (Sequence 1) is interpreted as a tectonized block-in-matrix complex of Jurassic limestone fragments embedded in Upper Cretaceous marly matrix. By this it corresponds to the Maslienka Subunit of the Subpieny nappe. The two middle sequences likely represent separate imbrications of Paleogene flysch sediments ranged to the Šariš Unit (Proč Fm.). The age and affiliation of the lowermost Sequence 4 remains problematic.

The Lower – Middle? Eocene age of the Sequence 2 is corroborated by foraminifers *Subbotina boweri*, *Acarinina pentacamerata* and nannofossil species from 29.2 m indicating Lower Eocene and from 39.7 m Eocene age. In the underlying flysch deposits (Sequence 3), agglutinated foraminifers of the abyssal DWAF assemblage occur (genera *Paratrochamminoides*, *Bathysiphon*, *Karrerulina*, *Glomospirella*, *Trochammina* and others), nannofossils are Eocene in age (samples from 47.7, 51.6, 57.3 and 82.2 m). At around 100 m depths, the species Turborotalia cerroazulensis Cole and Lower Eocene nannoplankton were encountered. The lowermost Sequence 4 is characterized by tiny planktonic foraminifers *Paragloborotalia nana* Bolli, *Pseudohastigerina naguewichiensis* Myatliuk, *Tenuitella*, *Protentella*, *Chiloguembelina*, which would not exclude a younger, possibly Oligocene age. On the other hand, only the Eocene age is indicated based on nannoplankton (samples from 123, 132, 134.4 and 139.8 m).

<u>Locality 7</u> – Hutirky valley northeast of Litmanová

Cretaceous formations of the Šariš Unit (D. Plašienka, Š. Józsa, J. Soták)

Hutirky is a wide, flat valley 1 km east of the Litmanová ski resort, near the agricultural farm. Here, the temporal small outcrops in meandering creeks occasionally expose various Cretaceous shaly and marly formations that occur in the core of a large-scale antiform. In its centre, steeply dipping and heavily folded Lower Cretaceous thin-bedded, marly limestones similar to the Pieniny Fm. occur. Owing to the slightly asymmetric shape of the antiform with northern vergency, its limbs are different – the northeastern is formed by a verticalized outlier of the Maslienka Subunit composed of blocky klippen with Niedzica/Czertezik Succession embedded in matrix of Cretaceous marlstone formations (sections H, I and J in Fig. 11). This limb is strongly reduced also due to the immediate contact with the Magura Unit which is partially thrust back. The southwestern limb is less steep and the Cretaceous formations are overlain by the Jarmuta/Proč Fm. with bodies of Milpoš olistostromes including the Litmanová group of klippen (locality No. 8).

From the upper to the lower section of a small creek passing along the eastern fence of the farm, we have observed and partly dated by means of foraminifers the following formations: variegated red and grey marly shales (Cenomanian to Turonian), dark spotted marlstones and black shales, reddish and dark-grey spotted marls (Upper Albian), reddish and grey claystones with thin sandstone beds (Cenomanian), red marly shales, grey shales with silty laminae (Upper Cenomanian – Lower Turonian), dark-red shales (DWAF Turonian – Santonian). The continuation of the profile along the Malý Lipník Strean down from the agricultural farm towards the Litmanová klippen again shows multiple alteration or red and grey pelagic shales and marls. Red marls are very rich in planktonic foraminifers of the Turonian – Coniacian age, while the grey marly shales contain both planktonic and agglutinated foraminifers of Turonian age. In red, non-calcareous shales only Turonian agglutinated foraminifers were found.

The strata are sheared and the contacts between individual formations are always tectonic, therefore it is difficult to reconcile their mutual relationships. Most probably all these strata represent mid- and Upper Cretaceous deposits comparable to those encountered by the Jar-1 borehole (e.g. red pelagic shales with Upper Cretaceous DWAF fauna of the Malinowa Fm. – see loc. 5), consequently we consider them to belong to the Šariš Unit.

<u>Locality 8</u> – Rozdiel valley, ski resort Litmanová (Milpoš Breccia)

Situation, lithological profiles and composition of breccias (J. Madzin, D. Plašienka, Š. Józsa)

The carbonate breccias from this locality were allegedly known already to Uhlig (1890), Andrusov (1945) mentioned them as a “breccia facies” of the Santonian Upohlav conglomerates. A more detailed description comes from Nemčok et al. (1989). It was one of their four localities of Gregorianka breccias (the other were Jarabina – our stop No. 1, Milpoš and Terňa). In their lithological profile, the breccias occur in seven, variously thick layers within a flysch sequence. They described also olistolith of nodular limestone and a body of pebbly mudstone. The flysch sandstones are turbiditic calcareous greywackes with typical with $T_{a\text{-}b\text{-}c}$ Bouma intervals. Among the pebble material they described crinoidal and filamentous limestones, *Saccocoma* and *Calpionella* limestones, variegated *Globotruncana* marls and rare radiolarites. In the sandy matrix of breccias and in marly shales they found Paleogene foraminifers (*Globorotalia* cf. *crassata*, *Globigerina* sp., *Turborotalia* sp.).

Our new investigation confirmed that the Milpoš breccias form here lenticular to tabular bodies inserted within turbidite sandstones and shales of the Jarmuta-Proč Fm. (Fig. 12). Rare planktonic foraminifers of Upper Paleocene to Lower Eocene age were found in the claystones. Breccias are unsorted, coarse-grained, clast-supported with chaotic internal structure. Occasional matrix consists mainly of fine-grained sandstone, but mostly it is lacking and the space between individual clasts is filled with carbonate cement. Clasts are unsorted; their size ranges from a few mm to boulder dimensions. Roundness of clasts varies from angular to subrounded shape. The pebble analysis showed

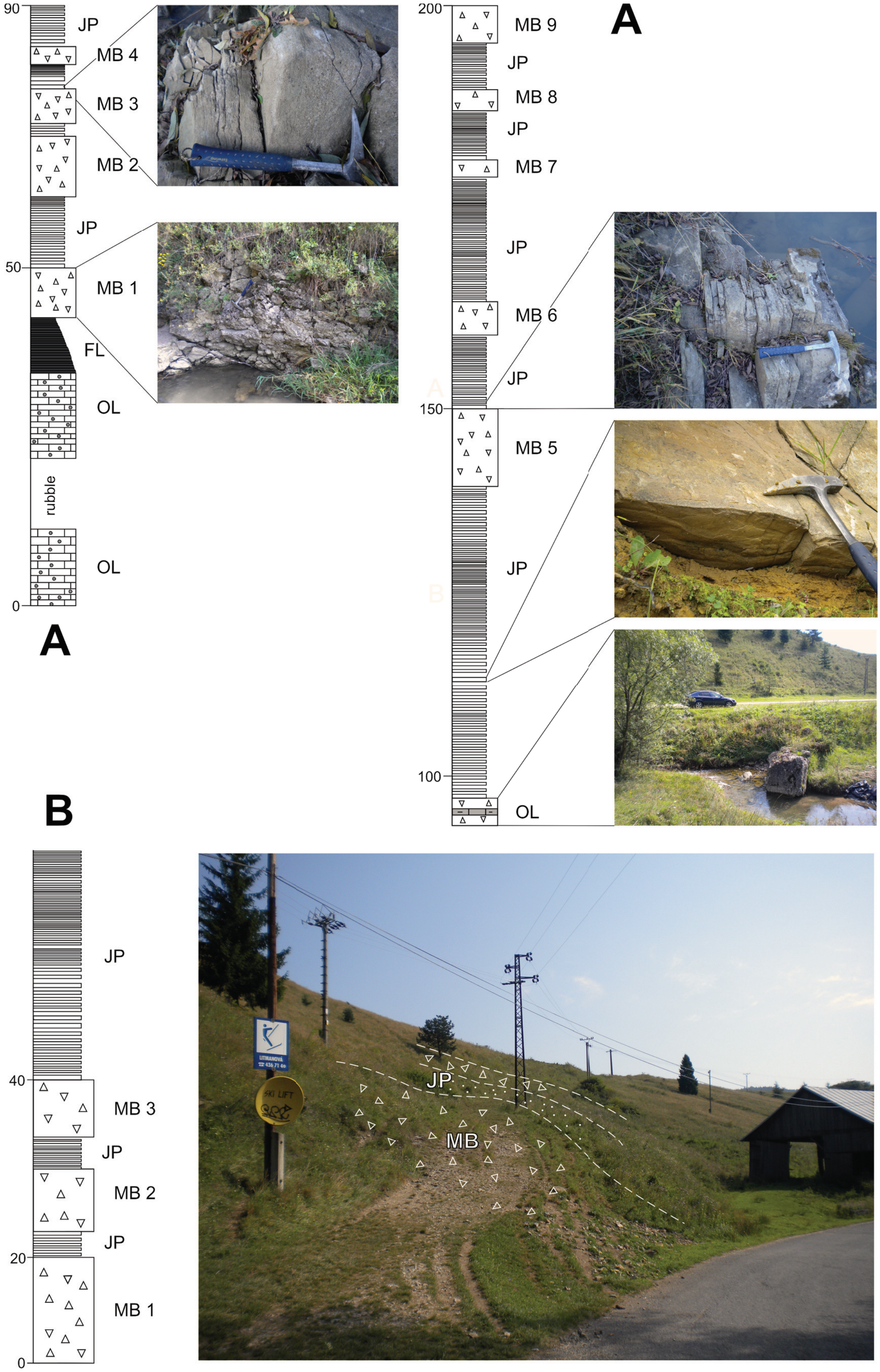

Fig. 12. Lithological sections of the Milpoš Breccia Member, Jarmuta-Proč Fm., around the ski resort Litmanová in the Rozdiel valley. **A** – profile upstream the Rozdiel brook; **B** – profile along a field trail towards the north from the Rozdiel and Malý Lipník brooks junction. FL – dark marlstones of the Fleckenmergel lithofacies; MB – Milpoš Breccia bodies; OL – olistolites of the Upper Jurrasic red nodular limestones of the Czorsztyn Fm.; JP – the Jarmuta-Proč Fm., fine to coarse-grained calcareous sandstones, mainly massive – facies of the proximal sandy debris flows.

that the most common clasts are the Jurrasic red and white crinoidal limestones, red nodular limestones, the Lower Cretaceous light *Calpionella* limestones, red radiolarites and radiolarian limestones and black shales (Skrzypny Fm.?). The youngest identified clasts are brick-red marls, well known as the Púchov marls of the Upper Cretaceous age; however, these occur sporadically. In addition to the material derived from the klippen successions, the breccia contains also rock fragments of siltstones, dolomites, metamorphic rocks, rare clasts of basic volcanics and relatively abundant quartz and feldspar grains.

The breccias are closely juxtaposed to the spectacular row of the Litmanová group of blocky klippen. A closer observation reveals that it is in fact a chaotic mixture of blocks of various sizes (up to 100 m), with variously oriented internal fabric. Majority of blocks are decametric and include only one formation (mostly red modular limestones), but the largest klippe just at the Rozdiel-Veľký Lipník junction contains a complete Jurassic to lowermost Cretaceous succession, which was studied in detail by Wierzbowski et al. (2004, their Fig. 6) and was classified as the Czertezik Succession. However, these authors indicated that the differences between the Czertezik and Niedzica (Pruské) successions, as originally defined by Birkenmajer (1977), are very subtle. They also reconstructed the paleogeographic arrangement of these successions in a new way – Czorsztyn-Niedzica-Czertezik-Branisko (Kysuca) from north to south. However, this concept was criticized by Birkenmajer (2007) who provided arguments in favour of his older scheme Czorsztyn-Czertezik-Niedzica--Branisko. In any case, we have not distinguished between the Niedzica and Czertezik klippen successions during our mapping research, since possible differences can only be recognized by detailed biostratigraphic profiling, which is seldom possible, and klippen with both successions, along with the typical Czorsztyn Succession as well, are usually mixed together either in the Maslienka Subunit of the Subpieniny nappe, or as olistoliths in the Jarmuta/Proč Fm. of the Šariš Unit. Only locally, e.g. in the Ostré skalky klippen NW of Litmanová, the Niedzica/Czertezik Succession forms more-or-less continuous imbricated thrust sheet of the Maslienka Subunit resting on the Czorsztyn-type sheet (see sections F and G in Fig. 11). These structural circumstances are analogous to those of the Czajakowa skala klippe just a few km to the west in Polish territory, where the nappe outlier of the Niedzica nappe overrides the thick Czorsztyn Unit of the “Homole Block” (cf. Birkenmajer, 1970).

The Litmanová klippen occur in a narrow pinched syncline squeezed between two narrow anticlines of Cretaceous formations of the Šariš Unit (cross-sections F, G and H in Fig. 11). They are resting in various matrix – most commonly in various Cretaceous marlstones, Jarmuta/Proč-type sandstones, and around the klippe described by Wierzbowski et al. (2004), also by black spherosideritic shales of the Skrzypny Fm. (Murchisonae Beds in older literature). The Litmanová locality of these shales (bedrock of the Veľký Lipník Stream from the northern side of the klippen) is famous by occurrences of excellently preserved pyritized ammonites in the cores of pelocarbonatic, disc--shaped concretions, which prove their Aalenian to Lower Bajocian age (Scheibner, 1964, 1967). Owing to the poorly outcropped matrix of the Litmanová blocky klippen, it is difficult to recognize whether they represent tectonic slices in the Maslienka Subunit, or olistoliths in the Milpoš Breccia. The latter possibility is preferred here, since klippen are closely related to outcrops of the Milpoš-type breccias. However, as suggested by Plašienka and Mikuš (2010), this differentiation is partly artificial – the tectonic and sedimentary processes were closely related, since the olistoliths and sliding masses were derived from the tectonically dismembered front of the Subpieniny nappe (see also Jurewicz, 1997). Thus the blocky klippen, which are at least partly embedded in their original Cretaceous (and also Jurassic) marly and shaly matrix and overlie the flysch deposits of the Jarmuta/Proč Fm., may be equally considered either as gravitational nappe outliers (tectonosomes), or as mass-transport sliding masses (olistostromes) in a tectonically active sedimentary setting. Each of the process caused their internal disorganization, maybe a bit more pronounced in the latter case.

Another important feature of the klippen is their structural record. As described in the collateral structural paper (Plašienka, this issue), both the Maslienka blocky klippen and Milpoš olistoliths bear the same structural elements, namely the bedding-perpendicular cleavage indicative for layer-parallel shortening. This is interpreted as a result of an early contraction event resulting in detachment of mechanically stratified sedimentary successions and their subsequent thrusting along weak décollement horizons (as e.g. the Skrzypny shales – see Fig. 3). The competent layers of mostly massive limestones show only the very low-grade deformation mechanisms like the mass-transfer by pressure solution and precipitation, while the incompetent “scaly” shales and marls are strongly sheared in places. This partly applies also for the post-nappe deformation events dominated by the dextral transpression that finally shaped the present structure of the PKB in Eastern Slovakia (e.g. Ratschbacher et al., 1993).

Conclusions

Based on detailed lithological and structural mapping, geophysical profiling, logs of two boreholes up to 200 metres deep, as well as biostratigraphical data from the majority of formations distinguished, we have defined three superposed thrust sheets in the investigated part of the PKB in Eastern Slovakia. All three are ranged to the Oravic Superunit, which paleogeographically represents an independent domain surrounding the Czorsztyn Ridge in the Middle Penninic position. The stacking progression of Oravic units is documented by the sedimentary record – by tectonosedimentary breccias that terminate the coarsening- and thickening-upward synorogenic sequences of individual nappe units. Among the most prominent features of these breccias are their ages and compositions. The Maastrichtian to possibly Lower Paleocene Gregorianka Breccia is a member of the Subpieniny Unit that was overridden by the Pieniny nappe at that time, as it is documented by their composition. Similarly, the Maastrichtian to Lower Eocene Milpoš Breccia of the lowermost Šariš Unit consists of material, including also huge olistoliths in this case, which was derived from the overthrusting Subpieniny nappe carrying also the piggy-back Pieniny sheet.

Summing up, the area presented here at eight localities provides a beautiful field example of sedimentary recording of superficial thrusting processes. The structural record, whatever important in general, can offer merely supplementary information in this particular case. Earlier structural works from this area (Ratschbacher et al., 1993; Nemčok and Nemčok, 1994) emphasized the role of transpression processes in formation of the intricate PKB structure. Indeed, dextral transpression was crucial for formation of the present shape of the PKB. However, the PKB sector presented in this paper, as well as in papers by Plašienka and Mikuš (2010) and Plašienka (this issue), clearly preserves relics of deformation and sedimentary structures inherited from the early thrusting stages of the PKB development.

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The Zlatník Group – Variscan ophiolites on the northern border of the Gemeric Superunit (Western Carpathians)

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Abstract

Northern margin of the Gemeric Superunit is build up by various lithostratigraphic units of Early Paleozoic. Upper Carboniferous and Permian in age. Detailed petrographic, mineralogical and geochemical studies of the rock complexes originally termed as the Zlatník Fm., classified as a part of the Upper Carboniferous Dobšiná Group and supposed to be composed mostly of black shales and epimetamorphosed basic volcaniclastics led us to complete revision of this knowledge and to definition of new individual lithostratigraphic unit – the Zlatník Group. The group forms narrow (max. 2 km wide) arcuate belt ca. 70 km long with interruption in its central-eastern part. Geological position of the Zlatník Group is tectonic – it is underlaid by rock complexes of the Klátov Group (Early Paleozoic) and Rudňany Fm. (Upper Carboniferous) and overlaid by the Krompachy Group (Permian). Lithologically it could be characterized as dismembered incompleted metamophosed ophiolites. The Zlatník Group can be divided into two formations: (1) the Grajnár Fm., a complex of lava flows containing the aphyric or plagioclase--phyric metabasalts with the redeposited dacitic metapyroclastics in its upper part and (2) the Závistlivec Fm., represented by ophiolite mélange with blocks, enclaves and clasts of metabasalts, metadolerites, metagabbros and rarely also acid differentiates embeded in metamorphosed pelitic and psammitic matrix. Metabasites display transitional character among N-MORB, E-MORB and BABB types. Chemical compositions of the metamorphosed sedimentary rocks point to three sources of the sedimentary material: (1) acid arc volcaniclastics, (2) disintegrated basic igneous rocks of the Zlatník Group and (3) disintegrated and altered mantle ultrabasic rocks. The Grajnár Fm. underwent very low-grade metamorphism partly overprinted by the metamorphism under the greenschist facies conditions. Polymetamorphic evolution is typical for the Závistlivec Fm. – besides same events as in the Grajnár Fm. also ocean-ridge type and blueschist facies metamorphism has been identified. The Zlatník Group represents originally upper part of the oceanic basin crust formed nearby an active volcanic arc and obducted afterwards (Grajnár Fm.) or destroyed and transformed into sedimentary mélange (Závistlivec Fm.) in the accretion prism. The age of the group is probably Upper Devonian (ca. 385 Ma). The Zlatník Group is a relic of Variscan ofiolite suture tectonically reworked during the Alpine orogeny separating originally two paleoplates with the different Variscan geological history. It is speculated, that together with the similar Pernek Group (Little Carpathians) they could be represented relics of the same ocean termed as the Pernek Ocean.

Key words: lithostratigraphy, ophiolites, Upper Devonian, Western Carpathians

Introduction

The northern border of the Gemeric Superunit belongs probably to the most lithologically variable areas in the Western Carpathian realm. No wonder that it has been attracting geologists´ attention as early as the 19th century. History of its geological study seems to be a continual story of new concepts of geological evolution or definitions and re-definitions of the lithostratigraphic units, which reflects not only the complicate geological structure of this area but its great theoretical and practical importance as well. Therefore it is not so surprising that our study concerning the Paleozoic basic volcanics and related sedimentary rocks during several last years resulted in the continuation of the above mentioned tradition – in a definition of a new lithostratigraphic unit – the Zlatník Group. More surprising seems to be the fact, that on the northern border of the Gemeric Superunit there has been untill now overlooked lithostratigraphic unit potentially of great importance for the interpretation of the geological structure of the Western Carpathians – an ophiolitic unit as a vestige of the ancient Variscan ocean. Data on its lithology, petrography, geochemistry and metamorphic as well as tectonic history are presented in this paper.

Review of previous findings and arguments for the definition of the Zlatník Group

Metamorphosed igneous rocks in the Paleozoic rock complexes of the northern border of the Gemeric

Superunit belong to the most widespread rock types. They were originally accepted as a part of one lithostratigraphic unit – the Early Paleozoic Rakovec Group (termed as the Phyllite-Diabase Series at this time; e.g. Kamenický and Marková, 1957). Some geologists (Ogurčák, 1954; Pecho and Porpreňák, 1962; Rozložník, 1963; Hudáček, 1963) pointed out lately that a part of metabasalts in the area between Dobšiná town and Rudňany village together with surrounding metasediments could be the Upper Carboniferous in age. Bajaník et al. (1981) classified the Late Paleozoic sequences here into lithostratigraphic units and their classification with some modifications has been used till now. The term the Zlatník Formation (Fm.) was firstly applied in this classification as a name of one from four formations of the normal stratigraphic sequence of the Carboniferous Dobšiná Group. Zlatník Fm. was defined as volcano-sedimentary formation of the Upper Carboniferous age, overlying psefitic-psammitic sediments of the Rudňany Fm. and extending in the western part of the northern border of the Gemeric Superunit (area between Dobšiná town and Rudňany village) and in the eastern part of the Gemeric promontory (area between Ochtiná and Brádno villages). According to Bajaník et al. (1981) graphitic phyllites with sandstone intercalations are present in the lower part of the Zlatník Fm., locally (Dobšiná town, Mlynky village) also with carbonates and sporadic products of basaltic volcanic activity. In the middle, dominant part of the formation, the mostly fine-grained metamorphosed basic volcaniclastic rocks occur. In less amounts also bodies of aphanitic, fine-grained and locally porphyroblasic metabasalts are present together with intercalations of graphitic schists and sandstones. Metamorphosed graphitic schists with intercalations of fine-grained psammitic schists and sandstones would built up the uppermost part of the Zlatník Fm., locally also with thin layers of carbonates. In the same way the Zlatník Fm. was presented in the geological map of the Slovenské rudohorie Mts. 1 : 50 000 and related explanations (Bajaník et al., 1983, 1984), as well as in the synthetic monography on the Late Paleozoic in the Western Carpathians (Vozárova and Vozár, 1988). This concept of the Zlatník Fm. has not been changed in the relevant geological papers concerning to the northern part of the Gemeric Superunit during next thirty years. The Zlatník Fm. was accepted as a component of the normal Upper Carboniferous stratigraphic sequence all the time, which follows under the underlying Rudňany Fm. and is highly dominated by sedimentary or volcanosedimentary rocks. In the scenario of geodynamic evolution the Zlatník Fm. is considered as a constituent of the Carboniferous molasse – i.e. of the infill of basins created during collapse of the Variscan orogeny (Grecula, 1994a, 1994b; Ebner et al., 2008; Grecula et al., 2009). However, substantial changes took place in the concept of the geological structure of the northern border of the Gemeric Superunit as well as in lithostratigraphic division of the Carboniferous rock complexes. From the Rakovec Gr. there was detached the complex of amphibolites and gneisses previously regarded as plutonic rocks and designated as the Klátov Gr. (Hovorka et al., 1984; Spišiak et al., 1985). Occurrences of this group in the form of discontinuous belt are located to the north of the Rakovec Gr. belt. Maheľ (1986) assumed, that four formations comprised in the Carboniferous Dobšiná Gr. could be in fact individual lithostratigraphic units. Ivan (1996) based on petrographic and geochemical study of the metamorphosed igneous rocks from these formations supported such opinion. Vozárová (1996) detached from the Dobšiná Group the Ochtiná Fm. and redefined it as individual lithostratigraphic unit – the Ochtiná Group.

Detailed petrographic and geochemical studies, which we performed along the whole extention of the Zlatník Fm., indicated dominantly effusive character of included rocks and the geochemical signatures of metabasalts close to those from the recent back-arc basins and very different from riftogeneous metabasalts of the Rakovec Gr. Metagabbros and metadolerites have been found here and the lithology of this complex was interpreted as similar to uppermost parts of the oceanic crust (Ivan, 1997). Newly obtained results of the ongoing geochemical studies indicate, that source rocks of the metamorphosed sediments of the Zlatník and Rudňany Fms. are quite different (Méres et al., 2007, 2008b), moreover preliminary results of the geochronological dating point to Upper Devonian age of the Zlatník Fm (Putiš et al., 2009). In the light of these new findings seems to be the original concept of the Zlatník Fm. no more tenable.

Definition of the Zlatník Group

As for the extent of the Zlatník Group in the western and central parts of the northern border of the Gemeric Superunit, it is largely identical with the extent of the original Zlatník Fm. in the official geological map 1 : 50 000 by Bajaník et al. (1983). We preferred to maintain for the practical reasons the original name also after its redefinition in the new individual lithostratigraphic unit, repeating the procedure used in the case of the Ochtiná Gr. (cf. Vozárová, 1996).

The Zlatník Gr. (similarly to the original Zlatník Fm.) was named after the Zlatník brook S of village Poráč, where it builds up both slopes of the valley. However rightfully its name could be equally derived from the Zlatník hill (969.3) E of settlement Štolverk near the village Hnilčík, where the Zlatník Gr. is present in the typical form.

As the Zlatník Gr. we designate a rock complex including mainly metamorphosed basaltic effusives and their subvolcanic and abyssal equivalents accompanied in the lower and uppermost parts of this complex by the metamorphosed sediments containing dominantly the volcaniclastic material or detritus of magmatic rocks.

Geological position of the Zlatník Group

According to the contemporary knowledge the Zlatník Gr. is located nearby northern border of the Gemeric Superunit in the form an attenuated belt of rocks variable in width (from ca. 100 up to 2 000 m) conformably oriented with arcuate shape of main geological structures in this area (Fig. 1). The belt begins near the Lányiho huta settlement on the west, continuing eastward up to the area N of the Poráč village. In the stretch between Poráč and Veľký Folkmar villages no rock complexes belonging to the Zlatník Gr. have been identified yet. More to east, the Zlatník Gr. probably forms, as can be concluded from several individual occurrences, thin belt extended probably up to Jahodná area (NW of Košice town).

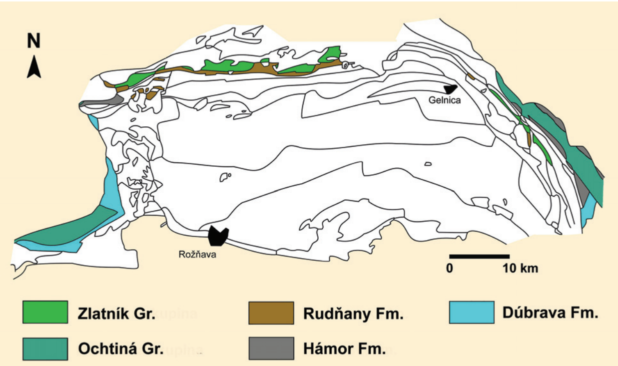

Fig. 1. Geological sketch-map of the extension of the Zlatník Group in the northern part of the Gemeric Megaunit (Ivan, 2008).

The western part of the Zlatník Gr. belt is tectonically restricted from the south by the significant Mlynky line (Maheľ, 1983). Along this line the belt is in contact mostly with slices of the strongly tectonically reduced Carboniferous sediments of the Rudňany Gr. (Fig. 2). Taking into account the subsurface geological structure in the vicinity of the Mlynky and Rudňany ore deposits (e.g. Bajaník and Hovorka, 1981; Jančura, 1995), it could be assumed, that rocks of the Rudňany Fm. together with close related metamorphic rocks of the Klátov Gr. (cf. Méres et al., 2008b) represent tectonic underlier of this belt. On its opposite side the belt of the Zlatník Gr. is overlaid by conglomerates of the Knola Fm. representing of the lowermost part of the Permian Krompachy Gr. In the eastern part the thickness of the belt is strongly reduced and rocks are intensively tectonically deformed. In the present day geological structure of the northern border of the Gemeric Superunit represents the Zlatník Gr. similarly to other related lithostratigraphic units a tectonic sheet finally formed during the nappe stacking in the Cretaceous time.

In the sense of our definition is the Zlatník Gr. absent in the Gemeric Superunit westward of the Štítnik fault. Rock

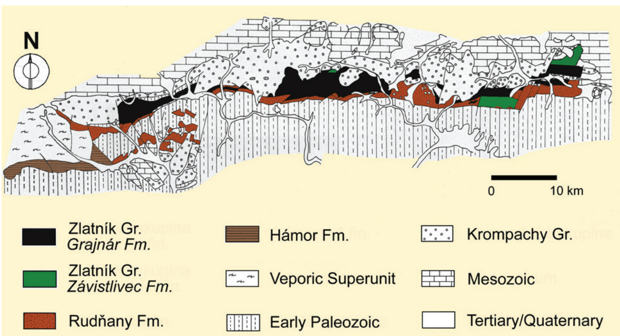

Fig. 2. Spatial extension of the Zlatník Group in the western part of the northern border of the Gemeric Superunit in the area between the Dobšiná town and Poráč village.

complexes, regarded as the Zlatník Fm. by Bajaník et al. (1981, 1983), are quite different in lithology and rather they seem to be an equivalent of the unit, which was designated by Fusán (1959) as the Dúbrava Fm. and later included into the Meliatic Superunit. Also layers of graphitic schists locally with carbonate lenses originally included in the former Zlatník Fm. are not components of the newly defined Zlatník Gr.

Lithology of the Zlatník Group

Idealized lithological scheme of the Zlatník Gr. is showed in Fig. 3. The Zlatník Gr. consists of two formations: (1) upper one, which we designate as Grajnár Fm. according to the pass near the Hnilčík village and lower one, which we named as the Závistlivec Fm. after small settlement near to the village Rudňany.

The ***Grajnár Fm.*** is dominantly composed of the various petrographic types of metabasalts alternating vertically in profiles, more evolved derivates are present in the subsidiary amount only. Primary structural and textural features of metabasalts were considerably obliterated, but preserved relics indicate that this formation is represented by a complex of subaquatic lava sheets. It follows from the petrographic variability in the scale lower than several metres and findings of thin (several cm) intercalations of metamorphosed sedimentary rocks between metabazalt bodies in the Chmeľová záhrada (Hopfgarten) area near the Dobšiná town. Also structures resembling the pillow

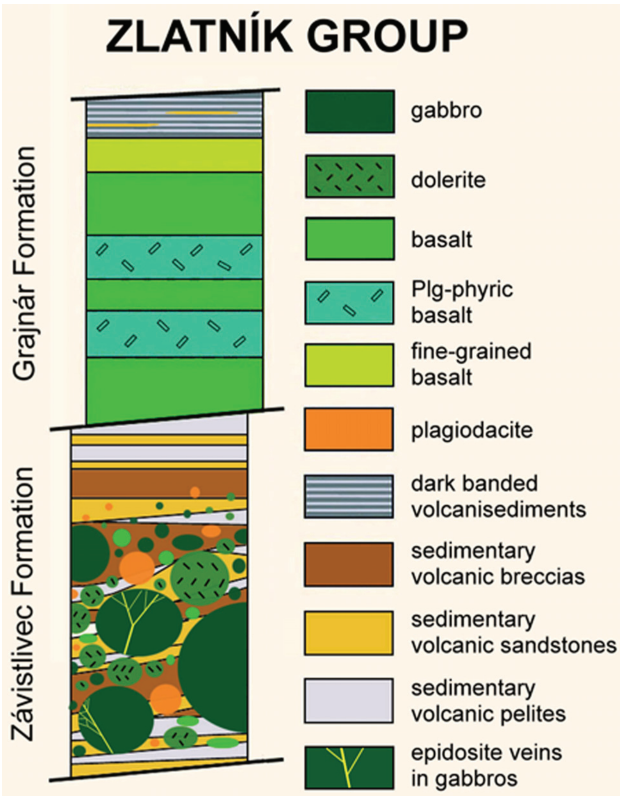

Fig. 3. Lithological column of the Zlatník Group.

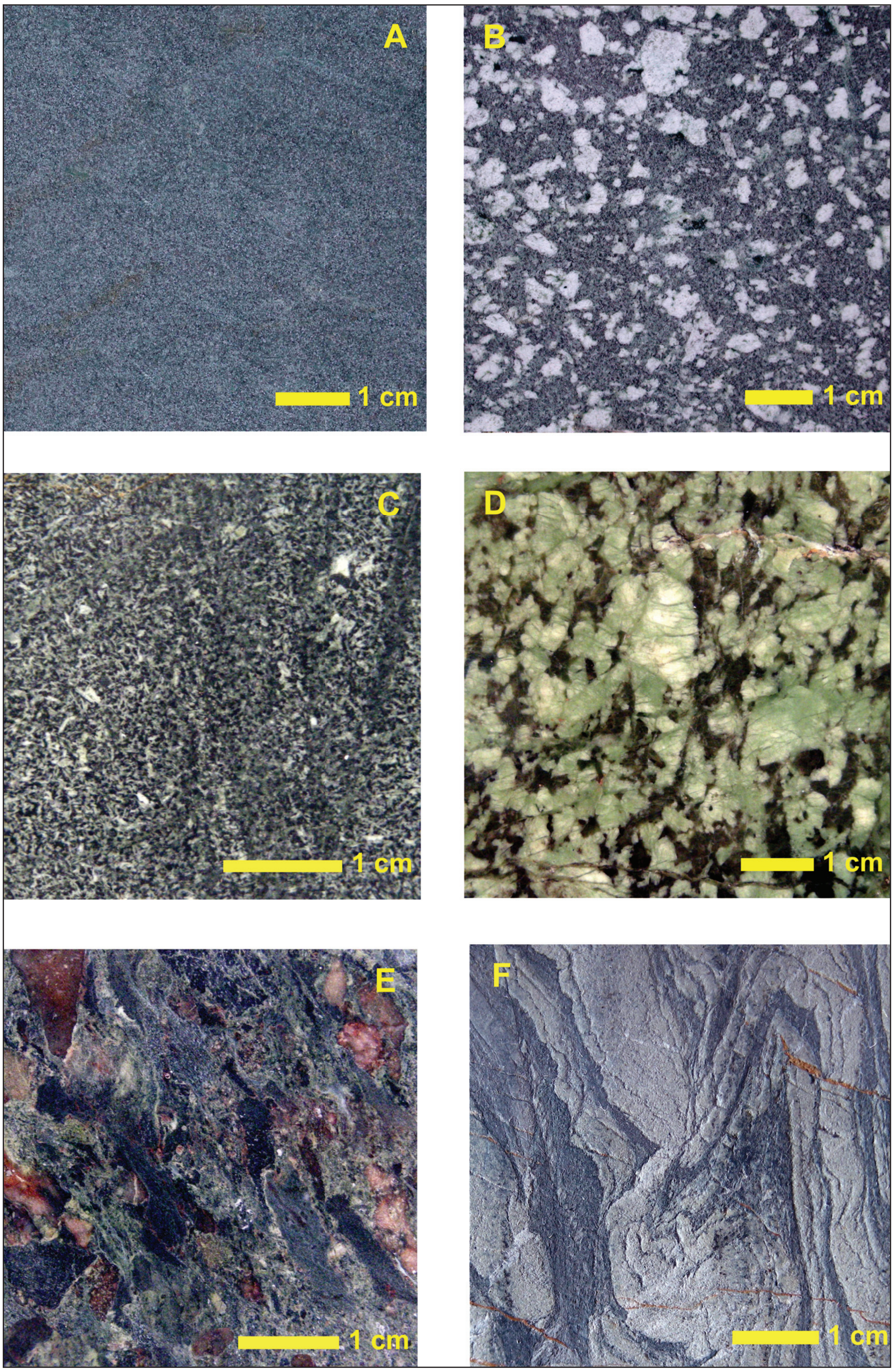

Fig. 4. Macroscopic view on some typical rock types of the Zlatník Group. **A** – aphyric metabasalt from the Grajnár Fm., locality Grajnár saddle, sample FD-312;; **B** – porphyric metabasalt from the Grajnár Fm., locality Grajnár saddle, sample FD-217; **C** – doleritic metabasalt from the Závistlivec Fm., locality Rudňany-Závistlivec village, sample FR-428; **D** – metagabbro from the Závistlivec Fm., locality Rudňany--Závistlivec village, sample FR-343; **E** – metamorphosed breccia from the Závistlivec Fm., locality Rudňany-Závistlivec village, sample FR-496; **F** – banded metamorphosed pyroclastic rock of dacitic composition from the Grajnár Fm. – surface of the drill core, locality Mlynky village, borehole BM-1. 511 m, sample FR-496.

lavas have been observed here. Changing of aphyric and plagioclase-phyric types of metabasalts seems to be the main manifestation of their petrographic variability. The upper part of the Grajnár Fm. consists of metamorphosed sedimentary rocks representing partly by the material of the sea floor weathering of basalts, however dominantly by the redeposited volcaniclastic material of dacitic composition. These rocks were mostly mapped as graphitic phyllites/phyllitic shists of the Zlatník Fm. in the geological map 1 : 50 000 by Bajaník et al. (1983). The type profile across the Grajnár Fm. is observable from the Štolwerk settlement (W of Hnilčík village) in parallel direction with the way to the Grajnár saddle, along its eastern side up to altitute ca. 980 m, then along its western side, where the metamorphosed sediments followed by various types of metabasalts could be observed in small cliffs and stony debris occurrences. The same profile can be studied in the parallely oriented Hliniskový potok valley.

The ***Závistlivec Fm.*** builds up tectonically bordered area, rhomboidal in shape, located to the S of Rudňany village between the eastern branch of Zimné valley and parallelly oriented valley to the east of Závistlivec settlement. Other less important occurrences have been found in the Zlatník valley near Poráč village and in the eastern branch of Slatviny valley cca 1.5 km S from the southernmost promontory of the Ružín dam, The Závistlivec Fm. represents sedimentary mélange containing blocks of metagabbros, metadolerites, metabasalts, including their differentiates and epidosites, variariable in size (from more than several tens meters up to small clasts of psammitic fraction), which are embedded in the metamorphosed sedimentary matrix. Although this area seems to be relatively rich in outcrops and stony debris occurrences, it is very difficult to get reliable idea about the real geological structure here. Individual enclaves are directly observable near the summit of the Sivá skala hill (862.2), typify profile with individual blocks and matrix rocks is observable along the eastern ridge of the Rudniansky les valley.

Petrography of the rocks of Zlatník Goup

Magmatic origin is typical for the majority of rocks included in the Zlatník Gr. Moreover, also sedimentary rocks are closely related with the igneous rocks, because redeposited volcaniclastic rocks or less frequently weathered and disintegrated igneous rocks also seem to be prevailing source material of sediments. Extensive petrographic variability caused by multistage metamorphic alteration is a typical feature of originally magmatic rocks in the Zlatník Gr. Petrographic variability combined with the loss of some textural features was the cause of erroneous identification of these rocks in the past.

The rocks of magmatic origin in the Zlatník Group can be divided by their petrography as follows: (1) effusive metabasalts, (2) subvolcanic metadolerites, (3) intrusive metagabbros, (4) intermediate to acidic differentiates and (5) hydrothermalites.

Metabasalts belong to most widespread rock types of the Grajnár Fm. Even by the naked eyes the following types can be discerned: (1) aphyric, (2) porphyric with variable content of plagioclase phenocrysts and (3) cumulitic types, where plagioclase phenocrysts substantially prevailed over matrix (Figs. 4A and 4B). Metabasalts with small phenocrysts of clinopyroxene have been rarely found. Significant part of metabasalts of the Grajnár Fm. displays unusually pale white-greenish or grey-greenish colours and contain disseminated pyrite impregnation. Other ones are grey-green to green in colour and typically occur in the neighbourhood of tectonic faults or hydrothermal veins. Aphyric metabasalts were originally characterized by ophitic or subophitic textures and were composed of clinopyroxene, basic plagioclase and Fe-Ti oxides. Potential presence of olivine cannot be revealed due to intensity of alteration. For the relatively less altered types the presence of clinopyroxene with pink or brownish-pink shades in microscope is typical. Plagioclase was replaced by the small alternating aggregates of fine-grained albite and radially oriented fine-grained muddied clinozoisite (Fig. 5A). Fe-Ti oxides were leucoxenized. Replacing of plagioclase does not show characteristic pseudomorphosis, moreover metabasalts during the alteration easily undergo plastic deformation, so magmatic texture is not preserved. As alteration intensity increased, the clinopyroxene was gradually replaced by colourless tremolite-actinolite and/or chlorite, the clinozoisite and carbonate blasts appeared as well. Plagioclase phenocrysts in the porphyric metabasalts were transformed into intensively dimmed radially oriented intergrowths of zoisite/clinozoisite/epidote and albite together with some chlorite. White mica, fine-grained aggregate of albite and carbonate infill the fissures in former phenocrysts.

Further increasing of the alteration intensity was characterized by the appearance of the epidote blasts and also greenish actinolite and chlorite, which replaced last relics of magmatic clinopyroxene. Along hydrothermal veins and tectonic faults due to higher water/rock ratio the metabasalts were altered to green rocks of epidote-chlorite-albite or carbonate-chlorite-albite compositions. At immediate contacts with hydrotermal veins the grey or yellow albit-quartz-carbonate metasomatic rocks formed.

Subvolcanic metadolerites occur in small amount only in association with dominant metabasalts in the Grajnár Fm., where they can be discerned mostly on the basis of the size of their clinopyroxene grains. More frequently they are present as constituent of the Závistlivec Fm. forming here individual bodies or dykes in the gabbros. Macroscopic variability is typical feature of these rocks – their colour is changeable in the wide span from grey through greenish-white up to dark green or bluish green (Fig. 4C). Structure of metadolerite textures is also variable – they vary from the massive blastoporphyric up to oriented lepidoblastic-heterogranoblastic and mylonitic textures. Minerals of the magmatic origin were fully replaced by the metamorphic mineral assemblage, which only poorly follows the original textural arrangement. Mineral composition varies depending on the metamorphic grade and intensity. Plagioclases were replaced by microscopic overgrowths clinozoisite/epidote and albite (saussuritization) eventually

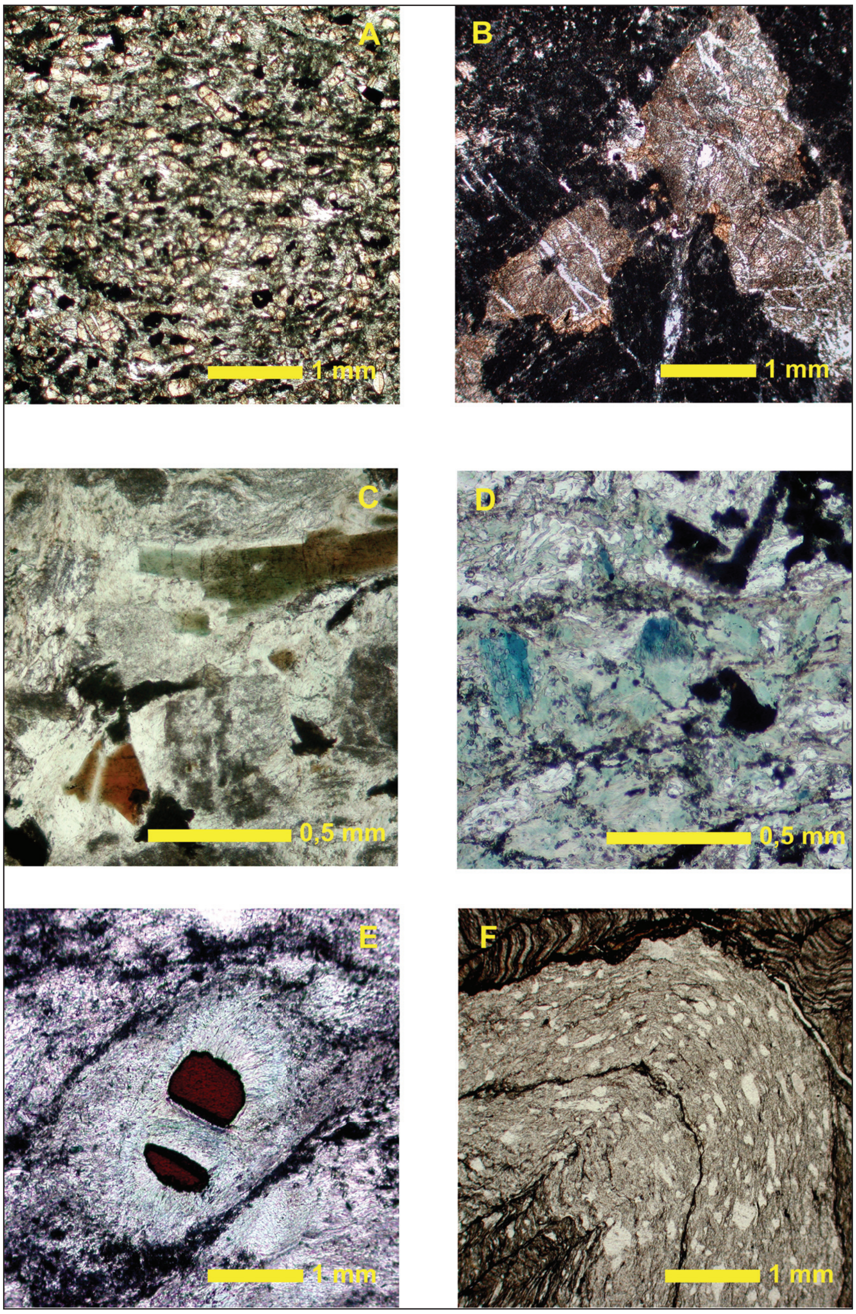

Fig. 5. Microscopic view on some important rock types from the Zlatník Group and their mineral constituents. **A** – aphyric metabasalt originally with the ophitic texture deformed during very low-grade metamorphism, II N. Magmatic clinopyroxene (pink) was practically unaffected by alteration, basic plagioclase was replaced by aggregates of clinozoisite/epidote and albite together with less chlorite. Leucoxenized ilmenite and pyrite are also present, Grajnár Fm., locality Grajnár Saddle, sample FD-312. **B** – polymetamorphosed gabbro originally of clinopyroxene-plagioclase in composition, II N. Plagioclase was transformed into cloudy fine-grained aggregate of clinozoisite with some albite (grayish-black), relic magmatic clinopyroxene is replaced from the edge by brown amphibole and penetrated by framework of veins filled by greenish to colorless amphiboles, Závistlivec Fm., locality Rudňany-Závistlivec settlement, sample FR-367. **C** – Growing--up of the brown amphibole by brown-green, green, bluish-green and colorless amphiboles respectively created as a result of the ocean ridge-type metamorphism. A part of the colorless amphibole (mostly uralite) seems to be a product of the very low-grade metamorphic overprint. Clinozoisite/epidote (dark grey, cloudy), chlorite (light grey) and leucoxenized ilmenite (black) are also present, II N. Metadolerite from the Závistlivec Fm., locality Rudňany-Závistlivec settlement, sample FR-307. **D** – relic sodic amphibole (magnesioriebeckite, blue) in metabasalt of the Závistlivec Fm. Albite, chlorite (greenish) and titanite together with iron oxides are further mineral components of this rock. **E** – chromspinelide (brown with black rim) with aureole of chlorite (yellow-greenish) and fuchsite (greenish) in the metamorphosed sandstone of the Závistlivec Fm., IIN. Locality Rudňany-Závistlivec settlement, sample FR-341. **F** – banded metamorphosed pyroclastic rock dacitic in composition from the upper part of the Grajnár Fm., intensively folded, II N. Light band is composed mostly by fine-grained albite with volcanogenic quartz grains, dark band contains mostly white mica, black pigment is represeted by iron oxides. Locality: Dobšiná town. Dobšinský kopec Mt., sample KG-30.

even by the aggregate of albite and epidote. Clinopyroxene was gradually replaced by amphiboles variable in colour even in the framework of one sample or by chlorite. Zonal amphiboles with the gradual or strictly defined boundaries between individual zones frequently occur. Metadolerites containing the oldest brown amphiboles followed or rimmed by amphiboles of brown-green or green colour and youngest colourless (usually acicular) or bluish amphibole frequently occur (Fig. 5C). Also varieties with dominate bluish-green and bluish amphiboles are relatively common (Fig. 5D). Leucoxenized ilmenites originally mostly forming automorphic crystals belong to the important mineral constituents of metadolerites, whereas carbonate, pyrite, white mica and locally also axinite and tourmaline are present in less amounts.

Metagabbros relatively widespread in the Závistlivec Fm. are characterized by the gabbro texture and variability in size of their mineral components frequently more than one order of magnitude at the distance of several first cm (Fig. 4D). They were originally composed mostly of clinopyroxene and plagioclase in variable proportions. Clinopyroxene is preserved in some metagabbros. Actual mineral composition of metagabbros is practically the same as in metadolerites with only difference in better preservation of progression in transformation of magmatic mineral association to its metamorphic derivatives. Alteration has evolved gradually along intergranular and cataclastic fissures (Fig. 5B). Furthermore the metagabbros are penetrated by veinlets of the pale yellow fine-grained epidosites (see e.g. Kornprobst, 2003 for definition) variable in thickness and with aureole of more intensive alteration along them characterized by the absence of clinopyroxene relics and plenty of albite, epidote and carbonate inside.

Evolved metaigneous rocks, intermediate to acidic in composition, have been found in the Závistlivec Fm. in the form of clasts or blocks up to several metres in diameter. They are macroscopically massive rather fine-grained rocks intersected by framework of thin quartz veins and composed mostly of quartz and/or albite. Microscopically they resemble the keratophyres. Sodic plagioclase dominates in composition whereas quartz, chlorite, epidote. Fe-oxides and titanite are secondary components. Preserved texture relics indicate that they were consisted mainly of plagioclase phenocrysts together with secondary phases as mafic phenocrysts and basic xenoliths, which were embedded in fine-grained matrix. Also primary oriented types of these differentiated rocks (tufs?) have been identified.

Hydrothermalites are in the Zlatník Gr. presented by epidosites and also by hydrothermal-metasomatic rocks mostly of sericite-quartz-carbonate composition from the periphery of sulphide-siderite veins. Epidosites are fine-grained rocks, yellow-green in colour, composed almost solely of aggregate of epidote crystals. They formed veins up to several tens cm thick or also small blocks in the mélange of the Závistlivec Fm.

The rocks of sedimentary origin in the Zlatník Gr. are petrographically very variable. They largely maintained not only their primary lithological variability but also the original sedimentary textures. Magmatic rocks were unequivocally dominated source of the clastic sedimentary material. Differences in petrography however exist between the metamorphosed sediments of the Grajnár and Závistlivec Groups.

Metamorphosed sediments of the Grajnár Gr. display mostly pelitic character. Based on petrographical properties they can be classified into following types: (1) greenschists, (2) sericite-chlorite phyllites, (3) chlorite-sericite phyllites and (4) albitic rocks with sericite admixture (Méres et al., 2007).

Greenschists are related to the base of sedimentary succession of the Grajnár Gr., rarely also as the thin (several cm) intercalations between the metabazalt bodies. They are very fine-grained rocks, grey-green to dark grey-green in colour. Planar-parallel, schistose or banded structures as well as heteroblastic or lepidogranoblastic textures are typical. Very fine-grained matrix is composed mainly of chlorite, albite, quartz and carbonate. The ore pigment and epidote are present as secondary phases. Typically they contain lithic clasts of basic rocks.

Sericite-chlorite phyllites are the grey to grey-green rocks, very fine-grained and usually strongly detailed folded. Alternation of light grey laminas (1 mm) with darker grey--green ones can be usually observed. Schistose, planar--parallel, banded, striped or detailed folded structures and heteroblastic, lepidogranoblastic and microfolded textures characterize this category of the rocks. In the very fine-grained matrix the chlorite, sericite, albite and quartz have been identified as the main components. Ore minerals, tourmaline and apatite are present as secondary phases. Quartz aggregates as metamorphosed clasts of volcanic quartz and chlorite aggregates as metamorphosed clasts of mafic minerals/rocks have been also found here.

Chlorite-sericite phyllites are macroscopically light to dark grey rocks, being usually detailed folded, fine-grained, oriented with linear cleavage. Alternation of light and dark grey bands as well as dark colour of the foliation planes similar to graphitic phyllites are typical features of these rocks (Fig. 4F). They are characterized by mostly parallel, fine-banded or schistose structures and by heteroblastic, lepidogranoblastic or microfolded textures. Clasts of altered mafic minerals or basic rocks are fully absent. Main mineral components are represented by quartz, chlorite, albite, sericite and chlorite. Ptygmatic folded bands composed of quartz, albite and chlorite (grain size ca. 0.01 mm) are alternated with bands with significantly prevailing sericite (up to 1 mm thick). Numerous small sharply angular quartz grains (0.1 mm) with traces of magmatic corrosion are concentrated in some bands of chlorite-albite-quartz composition (Fig. 5F). Submicroscopic Fe-oxide pigment follows the rock foliation and is closely related to sericite--rich bands.

Albitic rocks with small proportion of sericite are typically fine-grained, green rocks, with angular disintegration and conchoidal fracture, white in colour, when are weathered. They form thin (up to 15 cm) intercalations in above-mentioned metamorphosed sediments. Albitic rocks are comprised of fine-grained albite aggregate (grain size ca. 0.01 mm) with some disseminated minute flakes of sericite.

Metamorphosed sediments of the Závistlivec Fm. represent matrix of mélange and are characterized by wide variability in terms of their sedimentary material and granularity as well. Thickness of individual layers is considerably variable from laminar (mm) up to rudely bedded (several metres). Due to poor exposition of these rocks in the field it is impossible to observe them in any significant continuous profiles. Based on petrographic standards, three fundamental rock types can be discerned there: (1) metamorphosed sedimentary breccias, (2) metapsammites and (3) phyllites variable in composition.

Metamorphosed sedimentary breccias are macroscopically variegated rocks mostly in various green tones depending on intensity of alteration. Albite, chlorite, amphibole and quartz prevail above in their mineral composition, in less amount also sericite and leucoxenized ilmenite are present. Clasts highly prevail matrix and their

Tab. 1

Selected whole-rocks analyses of metabasalts metadolerites, metagabbros and metamorphosed sediments from the Zlatník Group

	1	2	3	4	5	6	7	8	9	10	11	12	13
Sample	FD-398	FD-210	FD-222	FD-233	FR-305	FR-350	FR-352	FR-343	FR-367	FR-463	FD-268	KG-4	FR-414
Form.	Gr. fm	Gr. fm	Gr. fm	Gr. fm	Gr. fm	Záv. fm	Záv. fm	Záv. fm	Záv. fm	Záv. fm	Gr. fm	Záv. fm	Záv. fm
Rock	mbaz	mbaz	mbazp	mbazp	mbazp	mdoler	mdoler	mgabro	mgabro	aciddif	ChlSerf	mpsam	zelbridl
SiO_2	46.03	46.92	47.08	44.29	44.31	47.39	48.57	45.85	48.32	69.33	72.71	70.50	50.67
TiO_2	1.32	1.95	1.49	1.28	1.35	2.18	2.24	0.31	0.05	0.34	0.51	0.55	1.38
Al_2O_3	17.90	16.82	19.11	19.02	17.84	14.94	13.60	20.92	17.58	13.54	11.39	13.08	15.03
Fe_2O_3	9.68	10.05	8.38	8.77	9.16	14.06	12.86	5.71	5.78	5.58	4.56	4.71	14.52
MnO	0.13	0.15	0.13	0.17	0.14	0.19	0.20	0.11	0.12	0.05	0.06	0.05	0.13
MgO	7.48	6.49	5.34	8.73	6.26	5.27	7.21	5.66	8.51	1.86	1.55	2.50	4.51
CaO	10.20	9.91	10.81	9.49	11.55	12.23	7.98	11.84	11.93	1.01	1.69	0.26	3.09
Na_2O	2.58	3.53	3.21	2.92	3.42	1.49	4.03	1.97	1.96	5.78	2.34	3.92	6.32
K_2O	0.88	0.39	0.97	0.28	0.21		0.17	1.12	1.16	0.43	1.65	1.71	0.82
P_2O_5	0.10	0.20	0.16	0.12	0.15	0.30	0.36	0.06	0.14	0.06	0.11	0.15	0.25
LOI	3.50	3.22	2.99	4.68	5.50	3.29	2.62	4.58	3.82	2.00	3.40	2.40	3.30
Sum	99.80	99.63	99.67	99.75	99.89	101.34	99.84	98.13	99.36	99.98	99.97	99.83	100.02
Cr	274	234	249	261	219	108	119	575	575		55	82	21
Co	45	52	48	52	36	28	50	31	57	7	10	8	30
Ni	118	56	72	98	76	41	56	120	203	2	24	16	15
Sc	36	35	31	30	31	59	47	41	48	18	9	11	40
V	241	203	154	152	215	435		110		11	70	113	328
Rb	21.1	5.8	14.2		4.8					21.1	59	60.4	19.2
Sr	212	311	365	126	291	400	365	160		57	46	21	21
Ba	44		59		19			230		78	237	362	92
Zr	74	140	105	81	96	107		9		140	161	139	46
Y	28	32	25	23	25					53	19	11	19
Hf	2.3	4.0	3.2	4.5	2.6	4.3	3.6		1.0	4.8	4.5	4.3	1.7
Th	0.20	0.36	0.28		0.30					2.60	5.30	7.60	0.80
Ta	0.10	0.19	0.21	0.12	0.10					0.30	0.50	0.70	0.10
Nb	1.1				1.8					5.6	7.2	8.9	1.4
La	2.6	7.6	5	4.3	3.8	12.0	8.6	0.5	2.3	10.5	19.9	7.7	2.4
Ce	7.4	23.3	17.5	14.5	11		23.6		6.0	27	43.4	17.9	5.5
Pr	1.49				1.98					3.96	5.18	2.31	0.98
Nd	8.7	19.3	14.1	11.5	10.5	25.4	16.2		5.5	17.1	20.8	10.3	5.8
Sm	2.9	4.6	3.7	3.2	3.1	6.0	5.2	0.8	1.8	5.1	3.8	1.7	1.9
Eu	1.18	1.75	1.30	1.30	1.21	2.10	1.90	0.42	0.56	1.45	0.87	0.35	0.80
Gd	4.06				3.99		3.10		6.30	6.26	3.31	1.56	2.68
Tb	0.79	0.96	0.76	0.74	0.74	1.20	1.20		0.43	1.30	0.61	0.32	0.49
Dy	4.80				4.39					8.57	3.25	1.86	2.93
Ho	0.90				0.94					1.86	0.64	0.39	0.54
Er	2.75				2.69					5.82	1.90	1.24	1.87
Tm	0.37	0.52	0.35	0.35	0.37					1.00	0.28	0.21	0.25
Yb	2.53	3.00	2.45	2.00	2.40	3.70	4.10	0.53	1.25	6.03	1.58	1.42	1.77
Lu	0.39	0.55	0.36	0.31	0.36	1.20	0.71	0.15	0.19	0.97	0.29	0.28	0.32

Explanations: mbaz – metabasalt; mbazp – Plg-phyric basalt; mdoler – metadolerite; mgabro – metagabbro; aciddif – acid differenciate; ChlSerf – chlorite-sericite phyllite; mpsam – metapsammite; zelbridl – greenschist (of sedimentary origin). Analyses 2–4 were taken from Ivan (1997). Analyses 1, 5, 10–13 were performed in the ACME Laboratories Ltd., Vancouver, Canada. Major elements, Cr, Ni and Sc were analysed by ICP AES, others by ICP MS. Major elements in other analyses were performed by XRF (2–4) or ICP OES. trace elements by INAA (Mega Inc., Stráž pod Ralskem, Czech Republic).

size varies significantly, most frequently to the several first cm (Fig. 4E). Angular clasts were originally formed by various types of basalts with diverse solidification rates from the vitritic type up to dolerites. Coarse-grained clasts together with the individual large crystals of ilmenite or epidote probably come from gabbros. Clasts of metamorphosed acid aphyric or porphyric rocks are also present. Albitic rocks with arborescent textures represent most likely devitrified acid glassy volcanics. Matrix of metamorphosed breccia is composed of fine-grained aggregate of albite maybe with some quartz and angular volcaniclasts of both these minerals.

Metapsammites are typically grey to greenish-white moderately oriented rocks with variable granularity (0.5 mm to 1 cm). Planar-parallel and schistose structures are most widespread. Palimpsest blastopsammitic to heteroblastic or lepidogranoblastic structures are characteristic for these rocks. Mineral association is the same as in the case of metamorphosed breccias. Pre-metamorphic granularity and inhomogeneity of metapsammites is indicated by volcanogenic quartz, epidote blasts replacing basic plagioclase, grains of the leucoxenized ilmenite and the metamorphosed lithoclasts of basalts, ultrabasic rocks or acid volcanics. In the metamorphosed lithoclasts of ultrabasic rocks composed of the chlorite aggregate the microscopically identifiable brown chromspinelide grains in various stages of metamorphic alteration are frequently present (Fig. 5E). Matrix in metapsammites is the same like in metamorphic breccias. Identification of metapsammites is usually complicated not only by metamorphic trans-ormation but by hydrothermal alteration and similarity to blastomylonites of the metabasic rocks as well.

Phyllites represent originally the most fine-grained sediments of the Závistlivec Fm. Lamellar to schistose textures and various composition of sedimentary material are typical. Combination of the plastic deformation up to convolute folded forms and brittle deformation resulted in the formation of foliation planes. Numerous microdislocations are frequently observed. Differences in composition of individual lamellas or layers are results of variations in quantity of the individual main mineral components – albite, chlorite, amphibole, epidote and hematite/magnetite. Sericite and carbonate are secondary components only. In some samples blue sodic amphibol as relic mineral was preserved. Although the fine-grained fraction (ca. 0.01 mm) prevailed in the pre-metamorphic fraction of sediments the frequently present crystalloclasts of quartz, plagioclase, leucoxenized ilmenite and epidote as well as lithoclasts mostly of basic rocks point to its unsorted character. Thin intercalations of originally psammitic sediment are also common in phyllites.

Geochemical characteristics of the Zlatník Gr. rocks

Selected analyses of major and trace elements in typical rocks of the Zlatník Gr. are summarised in Tab. 1.

Varied association of rock types included in the newly defined Zlatník Gr. has not been geochemically studied yet. Metabasalts of the Grajnár Gr., which were found as different from the metabasalts of the Rakovec Gr. (Ivan, 1997) were only an exception. Distribution of major elements in the metamorphosed basic magmatic rocks corresponds to their basaltic composition, although there are some specifics. Increasing of loss on ignition (2.70–5.90 %) and also Na_2O at the expense of CaO as a result of metamorphic alteration and sodic metasomatosis (spilitization) respectively are typical for samples altered to greenschists. As follows from the TiO_2 vs. Al_2O_3 diagram (Pearce, 1983; Fig. 6) only a part of them is compositionally close to basaltic liquids, others represent cumulates or differentiates of Fe-Ti-basalt type. Distribution of the trace elements indicates, that parental basaltic magma which these rocks were formed from was close to tholeiites of MORB type as is obvious e.g. from diagrams Zr vs. TiO_2 (Pearce, 1982) or Ti/1000 vs. V (Shervais, 1982). However more detailed specification of its geochemical type displays some differences from the typical oceanic N-MORBs as resulted e.g. from the diagram Zr vs. Y (le Roex et al., 1983) or from the chondrite normalized REE patterns (Fig. 7).

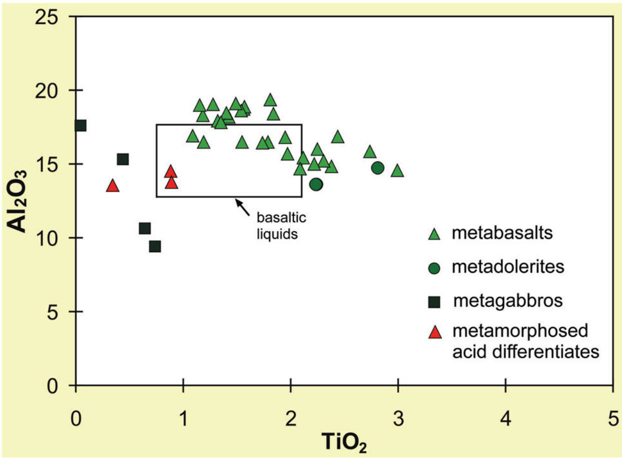

Fig. 6. TiO_2 vs. Al_2O_3 diagram (Pearce, 1983) for metabasalts, metadolerites and metagabbros of the Zlatník Group.

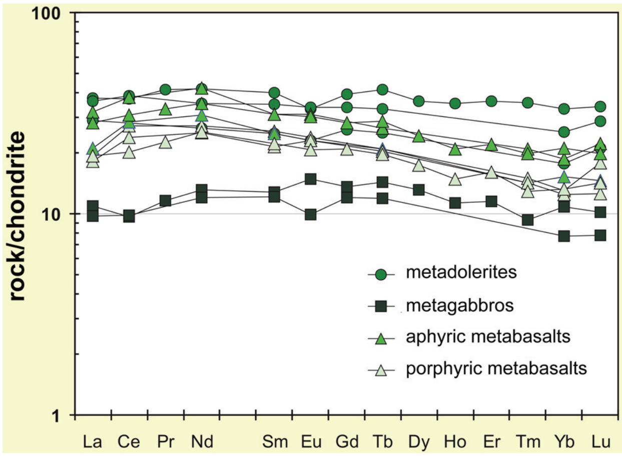

Fig. 7. Chondrite normalized REE patters for the selected metaigneous rocks from the Zlatník Group. Normalization by McDonough and Sun (1995).

Diagrams used for detailed discrimination, which are based mostly on relatively immobile HFS elements (Hf/3-Th-Ta, Wood, 1989; 3Tb-Th-2Ta, Cabanis and Thiéblemont, 1988; La/10-Y/15-Nb/8, Cabanis and Lecolle, 1989) plot the metabasalts of the Zlatník Gr. on boundary of BABB, N-MORB and E-MORB types. The same follows from the Nb/Yb vs. Th/Yb diagram (Pearce and Peate, 1995; Fig. 8).

Metagabbros correspond to the identical geochemical type as metabasalts and metadolerites but display lower concentrations of total REE and other incompatible elements. Some of them bear the evidence to plagioclase fractionation as follows the negative Eu-anomalies. Acid differentiates are characterized by the low total REE content and also LREE enrichment is absent (Fig. 9), which is similar to oceanic plagiogranites (e.g. Rollinson, 2009). Variations in their REE patters could be a result from the difference in fractionation mechanism and/or parental magma.

Petrographic variability of the metamorphosed sedimentary rocks of the Zlatník Gr. is reflected by their chemical composition (Tab. 1). Mostly stable Al_2O_3 concentrations (around 18 %) in comparison to variability of related SiO_2 contents (52 to 75 %) display the samples analysed up to date. Lowest SiO_2 contents characterize the greenschist, whose whole-rock composition approximates to metabasalts (Méres et al., 2008).

Chlotite-sericite and sericite-chlorite phyllites of the Grajnár Fm. are relatively homogeneous in composition and they are plotted in the SiO_2 vs. Al_2O_3 diagram in the field of sediments with low mineralogical and chemical maturity, what is typical for rocks derived from less altered and unsorted acid to intermediate arc magmatic rocks (Fig. 10). Metapsammites of the Závistlivec Fm. are plotted in this diagram in the same field but specific trend of SiO_2 decrease with Al_2O_3 content is observable. The same results supporting similarity in composition of metabasalts and metamorphosed sediments of greenschist type, influence the basic source material on the composition of sericite-chlorite phyllite and also close analogy between the composition of chlorite-sericite phyllites and dacitic

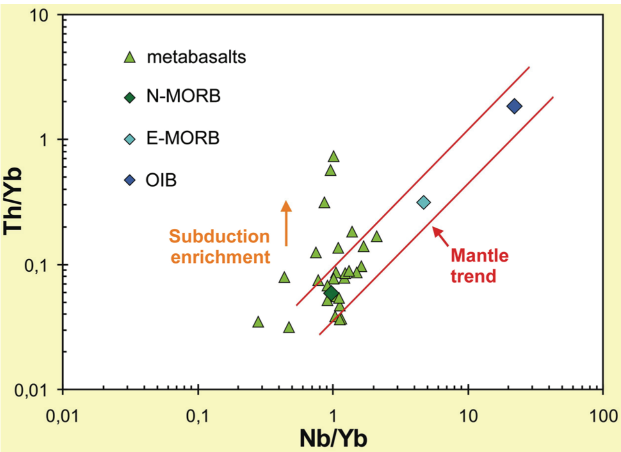

Fig. 8. Metabasalts of the Zlatník Group in the Nb/Yb vs. Th/Yb diagram by Pearce and Peate (1995).

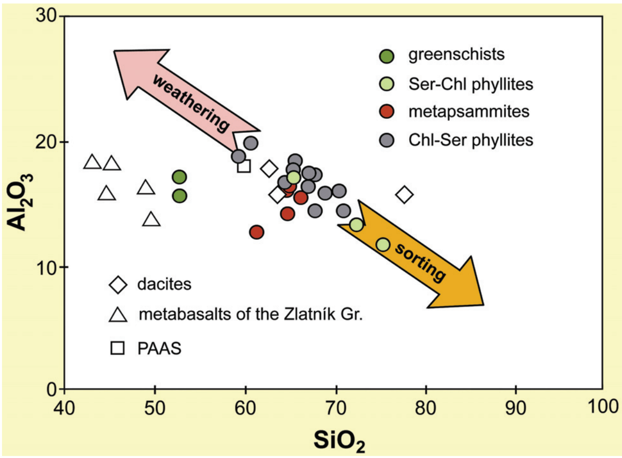

Fig. 10. Metamorphosed sedimentary rocks of the Zlatník Group in the diagram SiO_2 vs. Al_2O_3. Except for greenschists they are similar in composition to dacites of magmatic arcs.

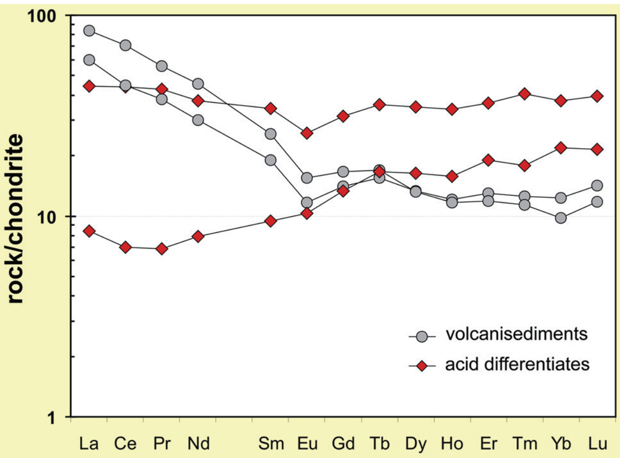

Fig. 9. Chondrite normalized REE patterns for the metamorphosed acid magmatic differentiates from the Zlatník Group. Normalization by McDonough and Sun (1995).

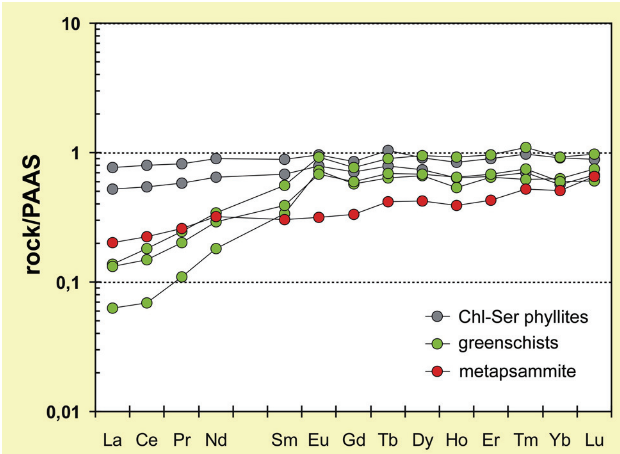

Fig. 11. PAAS-normalized REE patters for the selected types of the metamorphosed sediments from the Zlatník Group. PAAS normalizing values by Taylor and McLennan (1985).

volcanics without any sign of the weathering trend follow from the ternary diagram A-CNK-FM (Nessbit and Young, 1989). Immature and unsorted character of the original sediments seems to be obvious also from the SiO_2/Al_2O_3 vs. Na_2O/K_2O (Pettitjohn et al., 1972; not shown) where they are plotted in the fields of lithic arenites and greywackes. Domination of the volcanic source material, basaltic or dacitic in composition, is indicated also by the diagram Zr/TiO_2 vs. SiO_2 (Winchester and Floyd, 1977), being commonly used for the classification of volcanic rocks. The sedimentary greenschists likewise the metabasalts of the Zlatník Gr. are projected in the basalt field, whereas metapsammites, sericite-chlorite and chlorite-sericite phyllites create the continual linear trend which is compatible with differentiation trend of volcanic rocks from andesites to dacites/rhyodacites. Differences in the source material are demonstrable also from PAAS-normalized REE patterns, where the greenschists are distinctly depleted in LREE relatively to PAAS and their patterns are identical with metabasalts of the Zlatník Gr. Metapsammites and sericite--chlorite phyllites are less depleted in LREE as greenschists and chlorite-sericite phyllites patterns are similar to PAAS and identical to calc-alkaline dacites.

Chemical compositions of phyllites and metapsamites are close to dacites (Fig. 11).

Mineral associations, compositions of mineral phases and metamorphic evolution

The only preserved magmatic mineral phase in metamorphosed magmatic rocks of the Zlatník Fm. is clinopyroxene found in metabasalts and metagabbros. Selected analyses of clinopyroxene are presented in Tab. 2. Classification diagram by Morimoto et al. (1988) classifies it as augite and diopside. As follows from the discriminant diagrams by Leterrier et al. (1982), its composition is similar to clinopyroxenes from the anorogenic and alkaline basalts (Ivan, 1997). In the discriminant diagram $SiO_2/100 – Na_2O$--TiO_2 by Beccaluva et al. (1989), clinopyroxenes from the metabasalts display composition similar to those from E-MORB less N-MORB basalt types (Fig. 12). Relic magmatic clinopyroxenes from the metagabbros seems to be rich in diopside component and display lower concentrations of TiO_2 and Al_2O_3. Curiosity thin rims of metamorphic diopside on the magmatic clinopyroxene have been found (Černák, 2011).

Only partial pseudomorphic replacement of the magmatic mineral assemblage by the metamorphic one is observed. Non-equilibrium seems to be typical feature of the majority of the observed metamorphic associations. Compositional inhomogeneity and zoning of the metamorphic mineral phases or replacement effects are common.

Although there are some similarities between the metamorphic associations of the Grajnár and Závistlivec Fms., both formations differ substantially in the metamorphic history. Metabasalts of the Grajnár Fm. usually contain association Cpx(magm.) + Ab + Zo/Czo/Ep + Act + Chl + Lx ± Pmp ± Ser ± Cal ± Py, less frequently also Cpx(magm.) + Ab + Act + Ep + Lx + Chl (abbreviations by Whitney and Evans, 2010). Radially arranged overgrowths Zo/Czo/Ep and Ab in the place of former magmatic plagioclase phenocrysts were probably created at the expense of prehnite. Increase in intensity of alteration resulted in increasing of abundance of Chl and Cal at the expense of Cpx and Ep or Ab + Ser at the expense of Zo/Czo. Large parts of the occurrences however display association Ab + Ep + Chl + Lx ± Ser ± Cal only, in proximity of hydrothermal veins Ab + Chl + Lx ± Ser ± Cal or Ab + Dol/Sid + Ser just at their contacts. All these associations indicate that the metabasalts of the Grajnár Fm. were metamorphosed in the prehnite-pumpellyite facies conditions, followed by the greenschist facies metamorphism, which characterizes significant activity of fluids (Černák and Ivan, 2006; Černák, 2011). In the metamorphosed sediments of the Grajnár Fm., the only association Ab + Ser + Chl + Q ± Cal with variable proportions of individual components has been found.

Typical feature of the metamorphosed magmatic rocks of the Závistlivec Fm. is extensive variability in included mineral phases as a result of more complex metamorphic evolution in comparison to the Grajnár Fm. No original magmatic minerals are preserved in metadolerites except small sporadic relics of clinopyroxene. Representative association is Czo/Ep + Amp + Chl + Lx + Ab ± Ax ± Pmp ± Ser ± Cal ± Py, where the composition of amphibole is changed in order Prg → Ed → Mhb → Ac (Tab. 2). Prg contains significant concentration of Cl. Also the association Ab + Czo/Ep + Amp + Lx + Chl + Ser ± Cal occurs relatively frequently and it is characterized by amphiboles Mhb → Ac and important presence of Ab and Ser. Peculiar association Ab + Chl + Lx + Mag + Amp + Ser + Ep + Bt, where Amp is mostly Na-Act usually with Mrbk/Rbk and eventually also Wnc has been found in some metabasalts or metadolerites. Similarly to the metabasalts

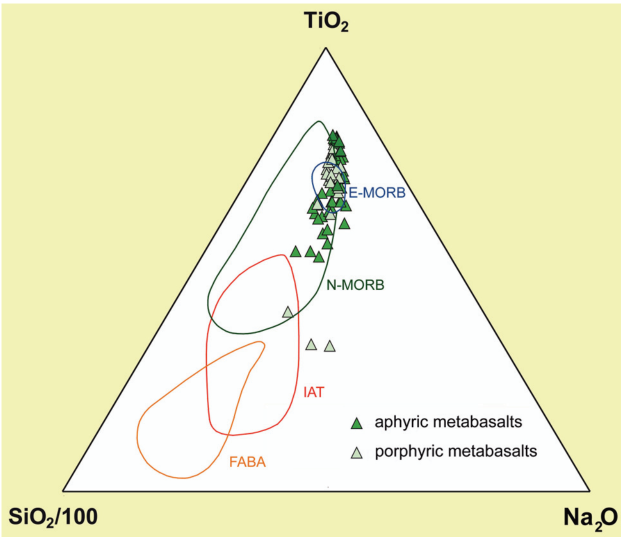

Fig. 12. Magmatic clinopyroxenes from metabasalts of the Zlatník Group in the dicriminating diagram $SiO_2/100 – Na_2O – TiO_2$ by Beccaluva et al. (1989). Explanations: FABA- fore-arc basin basalts.

Tab. 2
Representative analyses of minerals in studied samples

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Sample	FR-351b	FD-221	FD-381	FD-421	FR-351b	FR-351b	FR-351b	FR-411	FR-411	FR-411	FR-411	FD-222	FD-214	FR-446	FR-446	FD-420	FD-420	FD-214	FD-214
Mineral	Cpx	Cpx	Cpx	Cpx	Prg	Ed	Act	Ed	Mg-Ktp	Fe-Act	Act	Act	Act	Mg-Rbk	Na-Act	Czoi	Ep	Pmp	Pmp
Analysis	ana10	ana1	ana55	an31	ana61	ana14	ana5	M4_4	M4_2	M5_10	M5_7	ana17	M4_11	M7_2	M3_3	M4_2	M3_2	M1_2	M1_3
Rock	mgabro	mbaz	mbaz	mbaz	mgabro	mgabro	mgabro	mdoler	mdoler	mdoler	mdoler	mbazp	mbaz	mdoler	mdoler	mbaz	mbaz	mbaz	mbaz
Origin	magm	magm	magm	metam	ocmet	ocmet	pumpact	ocmet	ocmet	ocmet	pumpact	pumpact	pumpact	vystlak	zelbridl	pumpact	zelbridl	pumpact	pumpact
SiO_2	51.76	51.00	47.20	53.32	43.66	44.28	55.71	44.95	49.66	52.28	54.94	54.72	56.35	54.82	53.98	39.60	38.62	36.72	38.30
TiO_2	0.53	1.30	4.47	0.01	2.77	1.54	0.00	3.33	1.96	0.09	0.00	0.06	0.00	0.00	0.00	0.04	0.01	0.02	0.05
Al_2O_3	1.85	1.92	4.07	0.06	11.49	9.62	0.33	8.42	4.50	2.23	1.01	1.24	0.84	1.87	1.43	31.96	26.86	25.06	26.12
Cr_2O_3	0.07	0.11	0.12	0.05	0.07	0.02	0.01	0.00	0.01	0.02	0.01	0.00	0.02	0.01	0.00	0.00	0.05	0.00	0.00
FeO	6.75	9.82	11.98	9.49	10.98	12.78	9.21	13.98	15.59	21.91	12.83	10.97	8.04	25.06	17.50	2.06	7.49	6.91	2.11
MnO	0.26	0.13	0.28	0.64	0.10	0.22	0.15	0.25	0.35	0.43	0.22	0.29	0.17	0.24	0.41	0.08	0.05	0.14	0.28
MgO	15.30	14.07	9.73	12.30	14.24	14.10	18.62	13.77	14.17	9.58	16.30	16.94	18.99	7.52	12.96	0.00	0.00	1.03	3.63
CaO	23.22	20.12	21.89	24.33	11.74	12.00	13.56	10.52	9.08	12.55	13.32	13.47	13.11	1.21	9.43	24.91	23.99	23.20	23.35
Na_2O	0.27	0.52	0.62	0.09	2.53	2.10	0.06	3.66	2.75	0.31	0.14	0.24	0.00	6.12	1.73	0.02	0.02	0.08	0.16
K_2O	0.01	0.00	0.00	0.00	0.21	0.20	0.02	0.32	0.57	0.07	0.00	0.05	0.02	0.02	0.08			0.00	0.00
Sum	100.01	98.99	100.35	100.30	97.81	96.86	97.67	99.50	99.10	99.50	98.84	97.98	97.55	96.87	97.52	98.66	97.10	93.17	94.00
Si	1.923	1.927	1.801	2.002	6.345	6.535	7.922	6.565	7.241	7.732	7.833	7.820	7.930	7.973	7.878	2.998	3.019	5.951	6.016
Al^{IV}	0.077	0.073	0.183	0.000	1.655	1.465	0.056	1.435	0.759	0.268	0.167	0.180	0.070	0.000	0.122	2.851	2.475	4.787	4.835
Al^{VI}	0.004	0.012	0.000	0.005	0.313	0.208	0.000	0.013	0.014	0.120	0.002	0.028	0.069	0.322	0.124				
Fe^{3+}	0.090	0.034	0.001	0.000	0.202	0.305	0.000	0.075	0.079	0.029	0.010	0.000	0.000	1.423	0.285	0.131	0.490	0.331	0.170
Cr	0.002	0.003	0.004	0.002	0.008	0.003	0.001	0.000	0.002	0.003	0.001	0.000	0.003	0.001	0.000	0.000	0.003	0.000	0.000
Ti	0.015	0.037	0.128	0.000	0.303	0.171	0.000	0.366	0.215	0.010	0.000	0.006	0.000	0.000	0.000	0.003	0.001	0.003	0.005
Fe^{2+}	0.118	0.276	0.381	0.298	1.133	1.272	1.224	1.632	1.822	2.681	1.520	1.350	0.949	1.638	1.850			0.605	0.107
Mn	0.008	0.004	0.009	0.020	0.013	0.027	0.018	0.031	0.043	0.054	0.026	0.035	0.020	0.029	0.050	0.005	0.003	0.019	0.037
Mg	0.848	0.792	0.553	0.689	3.086	3.102	3.947	2.997	3.081	2.111	3.463	3.609	3.983	1.637	2.820	0.000	0.000	0.248	0.849
Ca	0.924	0.814	0.895	0.978	1.829	1.897	2.065	1.646	1.419	1.989	2.034	2.063	1.977	0.190	1.474	2.020	2.010	4.029	3.930
Na	0.019	0.038	0.046	0.007	0.714	0.602	0.016	1.036	0.776	0.089	0.039	0.067	0.000	1.734	0.490	0.002	0.002	0.026	0.049
K	0.000	0.000	0.000	0.000	0.040	0.038	0.003	0.060	0.106	0.014	0.000	0.008	0.003	0.004	0.014				
Sum kat.	4.029	4.010	4.000	3.999	15.640	15.624	15.123	15.856	15.557	15.099	15.096	15.127	15.002	14.987	15.109				
Na^B					0.114	0.016	0.000	0.240	0.324	0.003	0.000	0.000	0.000	1.734	0.396				

Explanations: abbreviations for rock types – see Tab. 1. Abbreviations for processess resposible for the mineral origin: magm – magmatic; ocmet – ocean-ridge metamorphism; pumpact – very low-grade metamorphism in the pumpellyite-accinolite subfacies; vystlak – high-pressure subduction-related metamorphism; zelbridl – final metamorphism in the greenschist facies conditions. Mineral analyses were performed by electron microprobe Cameca SX-100 at the State Geological Institute of Dionýz Štúr in Bratislava. Microprobe operated at 15 kV accelerating voltage and 20 nA beam current. counting time 20 s and beam diameter 2–10 μm.

of the Grajnár Fm. the associations Ab + Ep + Chl + Lx ± Ser ± Cal or Ab + Chl + Lx ± Ser ± Cal are located in places of the most intensive alteration. Mineral associations in metagabbros are resembling those in metadolerites, but they are even more variable due to gradual growth of newly formed minerals by replacing of the original magmatic minerals from their boundaries in the coarse-grain textures and also due to wide span of the alteration intensity at the all metamorphic stages. Relics of the magmatic clinopyroxenes are frequently preserved and occur in the same associations as are typical for metadolerites, but additionally Mrbk/Rbk, Wnc a Na-Act may be present. In some samples is magmatic ilmenite instead common Lx replaced by combination of aggregates of Rt and Spn. Metamorphic associations and relative mineral successions indicates that metamorphic history of metagabbros and metadolerites include several stages. During the first stage of alteration they underwent the oceanic ridge-type metamorphism characterized by the relatively fast continual transition from the thermal conditions corresponding to the high-graded amphibolite facies to the greenschist facies conditions, both at relatively low pressures (Ivan and Černák, 2010). This stage is overprinted by the another one at the very low-grade metamorphic conditions (prehnite-actinolite subfacies of the prehnite-pumpellyite facies) with the transition up to high-pressure low-temperature (HP/LT) metamorphism in the blueschist facies conditions. During the last stage, the metamorphism in the greenschist facies conditions, related mostly to the vicinity of tectonic zones, took place. Variability of P-T conditions during the whole metamorphic history is reflected in changes in composition of amphiboles (Fig. 13).

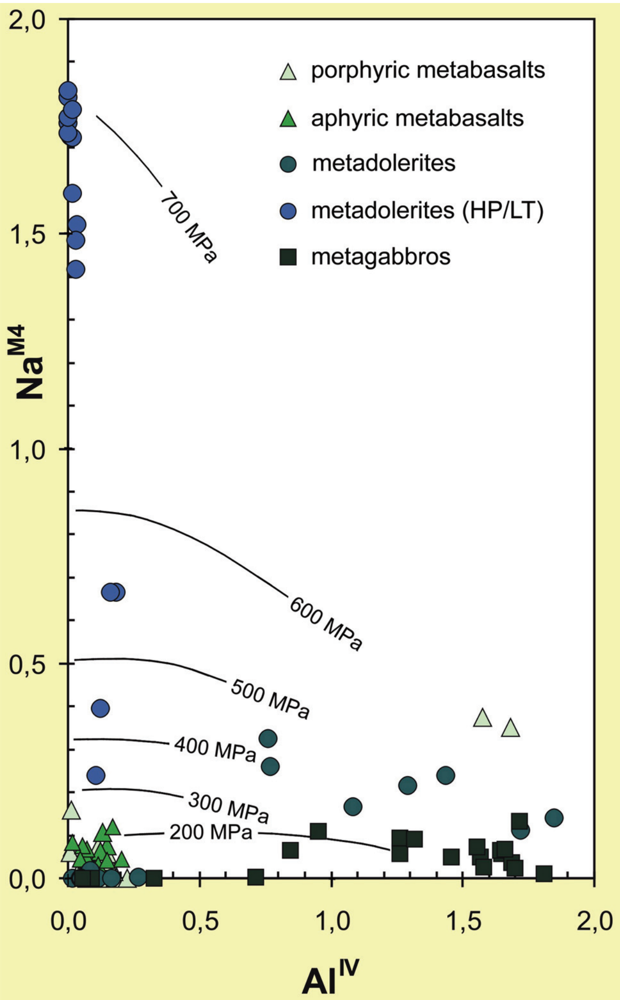

Fig. 13. Al^{IV} vs. Na^{B} diagram for amphiboles from the various types of the metamorphosed basic magmatic rocks from the Zlatník Group documents variability of p, T conditions during their metamorphic history. Pressure values are displayed using empirical geobarometer by Brown (1977).

Mineral associations in the metamorphosed sediments of the Závistlivec Fm. include except rarely preserved clastic grains of magmatic origin the metamorphic minerals only. As a result of variability in source material they are varying extraordinary in the mineral components and their proportions also at short distances. The association Ab + Chl + Hem/Mag ± Amp ± Czo/Ep ± Ser ± Cal ± Bt ± Qz is typical, amphibole is represented by Act or Na--Act, insignificantly also by Mrbk/Rbk and Wnc. The hydrothermally altered samples usually contain association Ab + Ser + Qz ± Dol/Sd ± Py. In some metapsammites the relatively abundant clastic brown spinel (Al-chromite), together with its metamorphic derivatives (Fe-chromite with the higher Zn content), have been found. As a source of spinels the ultramafic rocks of the suprasubduction origin are supposed (Méres et al., 2008a). Preserved metamorphic mineral associations in the metamorphosed sediments of the Závistlivec Fm. are the result of the metamorphism in the greenschist facies conditions, which was preceded by the HP/LT metamorphism in the greenschist facies conditions.

The epidosite veins with the association Ep ± Ab ± Py ± Cal in metagabbros represent the infill of the migration paths of hydrothermal solutions circulated in the oceanic rift environment (cf. Gillis, 2002; Kornprobst, 2003).

Geodynamic setting and geological evolution of the Zlatník Group

The continual profile composing of the metamorphosed basaltic lava flows in the Grajnár Fm. as well as the transitional geochemical signature of these metabasalts among N-MORB, E-MORB and BABB types indicate that the Grajnár Fm. was probably formed as the uppermost part of oceanic crust in the small oceanic basin opened after the rifting in the ensialic magmatic arc environment. The age of metabasalts was preliminary dated as ca. 385 My (Upper Devonian; SHRIMP, U-Pb method on zircon, Putiš et al., 2009). Limited extent of the basin opening is indicated by redeposited arc volcaniclastics in the uppermost part of the sequence (Méres et al., 2008). Very low-grade metamorphic alteration of the Grajnár Fm. could be probably related to obduction at the termination of the closure of the basin (Černák and Ivan, 2006).

In the present day geological structure of the Gemeric Superunit the Grajnár Fm. seems to represent the strongly reduced ophiolite nappe finally emplaced and metamorphosed during the Alpine nappe stacking.

The Závistlivec Fm. as ophiolite mélange resembles of mélanges frequently forming the lowermost part of some ophiolite complexes (e.g. Bortolotti et al., 2009; Ghikas et al., 2010). Blocks in this formation are derived from the deeper part of the oceanic crust than is present in the Grajnár Fm., whereas detritus contains also fragments of ultramafic rocks from the lowermost part of the ophiolite sequence and some effusive basaltic rocks. The sedimentary mélange matrix is partly derived from the altered and disintegrated rocks of the ophiolite sequence but its significant proportion represented by redeposited volcaniclastic material mostly acidic in composition was originally generated in volcanic arc. Metagabbros and metadolerites bear witness to their formation in the spreading zone in the form of the oceanic ridge-type metamorphism (Ivan and Černák, 2010). Overprinting of this metamorphic stage by very low-grade metamorphism in the prehnite-pumpellyite facies with transition to the HP/LT stage evidently reaching the blueschists facies conditions reflects probably the transport of the oceanic crust from the oceanic rift to accretion prism of the subduction zone. Based on all these facts the Závistlivec Fm. mélange could be classified as subduction mélange according to classification scheme by Festa et al. (2010). The age of the slab subduction and mélange creation are unknown for the present, the Lower Carboniferous as the upper limit could be probable for the reasons summarized bellow, although Jurassic age for HP/LT metamorphic stage (the age of the Meliata Ocean subduction in the inner Western Carpathians) cannot be still fully excluded. The latest metamorphic overprint in the greenschist facies conditions in the Závistlivec Fm. seems to be related to the Alpine tectonic activities and nappe stacking. In present day geological structure forms the Závistlivec Fm. a relatively small tectonic sheet underlie locally the Grajnár Fm.

Because the material generated originally in the oceanic crust prevails in the Zlatník Gr. it can be regarded as an ophiolitic rock complex despite the fact that it comprises a dismembered and incomplete ophiolite sequence. As indicated by the geochemical signature of basalts, the Zlatník Group seems to be most similar to P-type ophiolites in the present-day geochemical ophiolite classification by Pearce (2008). The volcanic rifted plate margin is a frequent geodynamic setting for this ophiolite type. The Alpine ophiolites from the Corsica (Saccani et al., 2008), which are the very close geochemical analogue of the Zlatník Gr. ophiolites, belong to the P-type ophiolites as well.

Potential correlation of the Zlatník Group with analogical units of the Western Carpathians and its significance for the recognizing of the geological structure of the region

Lithologies similar in petrography and geochemistry to the Zlatník Gr. rocks (metabasalts, metadolerites, metagabbros and metaultramafites) are located directly in the northern margin of the Gemeric Superunit and build up the Hrádok and Črmeľ Fms. of the Ochtiná Gr. (Vozárová, 1996; Ivan and Ježová, 2003). Both mentioned formations remind of the Závistlivec Fm. – they are probably mélanges too. The age of the metamorphosed magmatic rocks could be also similar, because the dating of the Ochtinná Gr. (Late Visean to Serpukhovian) is related to conodonts found in the carbonates of the uppermost formation of the group – the Ľubeník Fm. (Kozur et al., 1976). A very close analogue of the Zlatník Gr. in the area outside of the Gemeric Superunit is the Pernek Gr. – an ophiolitic unit from the crystalline complexes in the Malé Karpaty Mts., Považský Inovec Mts. and Suchý and Malá Magura Mts. (Tatric Superunit; Ivan et al., 2001; Ivan and Méres, 2006, 2011; Méres and Ivan, 2005, 2008; Méres, 2005). The Pernek Gr. comprises the rocks geochemically identical to the Zlatník Gr. and it is also close in age (360–380 Ma, Putiš et al., 2006). It seems to be very probable that the dismembered ophiolites, which are components of the Pernek, Ochtinná and Zlatník Grs. represent in current geological structure of the Western Carpathians relics of an ophiolite suture reactivated in Alpine era. This suture would be actually a record of the final evolution stage of the Upper Devonian/Lower Carboniferous oceanic basin, which was termed as the Pernek Ocean (Ivan, 2009). The suture could be interpreted as a fossil boundary separated two lithospheric paleoplates with different Variscan tectono-thermal evolution where the southern plate (in present day coordinates) was spared of the extensive plutonic activities and metamorphic reworking. On the other hand the northern plate displays quite different history – magmatic activity related to the subduction of the Pernek Ocean and formation of the magmatic arc led also to the intensive metamorphic alteration in the upper crust mainly due to increased thermal flow related to granitoid plutonism (cf. Barton and Hanson, 1989). Lower Carboniferous I- and S-type granitoids in the Veporic and Tatric Superunits of the Western Carpathians could be products of this plutonism. Evidence for the existence of the Upper Devonian/Lower Carboniferous ocean, mostly indirect for the time, has been detected also in the Eastern Alps. Neubauer and Handler (1999) supposed that such ocean separated the Noric Terrane (the Upper Austroalpine Superunit) from the more intensively metamorphosed Lower and Middle Austroalpine Superunits. Analogicaly it can be speculated that the northern part of the Gemeric Superunit together with some most external parts of the Tatric Superunit would be equivalents of the Upper Austroalpine Superunit. As possible relics of the Pernek Ocean in the Eastern Alps could be considered e.g. volcanic rocks with the geochemical signatures close to oceanic basalts from the Almont-Selztal area in the eastern part of the Greywacke zone (Schlaegel-Blaut, 1990; Loeschke and Heinisch, 1993).

If the global tectonic schemes (e.g. Stampfli et al., 2002) are taken into consideration then, interpretation of the Pernek Ocean as a small intraterrane basin in the framework of the Hun Terrane seems to be most possible. In the light of new interpretation of Variscan orogeny in the

Eastern Alps (cf. Frisch et al., 2011) also possibility that the Pernek Ocean could be originally an embayment of the Paleotethys Ocean scissors-like widened to the east cannot be excluded. In the Variscan Europe are the ophiolite relics thought to be almost exclusively the Cambrian or Devonian in age. Devonian ophiolites have been described from the NW Spain (Arenas et al., 2007; Sánchez Martinez et al., 2007). Cornwall (Great Britain), Giessen (Germany; Pin, 1990). Vosges (France; Skrzypek et al., 2012) or from the French Massif Central (Berger et al., 2005).

Conclusions

Based on interpretation of data obtained from our field, petrografic and geochemical studies we came to following conclusions:

• In the northern part of the Gemeric Superunit we define a new ophiolitic lithostratigraphic unit probably the Upper Devonian in age – the Zlatník Group (Gr.) has been defined

• The name of the group is preserved from the previously used term – the Zlatník Formation (Fm.), but its position, lithology, age, geodynamic setting and geological history have been fully redefined

• The Zlatník Gr. is divided into two formations: (1) upper the Grajnár Fm. and (2) lower the Závistlivec Fm.

• The Grajnár Fm. is dominated by metabasalts, in the upper part are also metamorphosed sediments present formed mostly from dacitic volcaniclastic material

• The Závistlivec Fm. is represented by sedimentary mélange where blocks of metagabbros, metadolerites, acid differentiates and epidosites are embedded in matrix composed of the sedimentary material with variable granularity (from pelites to breccias) derived from magmatic rocks

• Geochemical signature of the metamorphosed basic magmatic rocks of the Zlatnik Gr. is transitional among N-MORB, E-MORB and BABB types

• Three sources of sedimentary material have been discerned: (1) acid volcaniclastics of the volcanic arc origin, (2) disintegrated and altered basic magmatic rocks of the Zlatník Gr. and (3) disintegrated and altered ultrabasic mantle rocks

• The Grajnár Fm. rocks are metamorphosed in the prehnite-pumpellyite facies variable overprinted by the greenschist facies metamorphism, the Závislivec Fm. underwent the multistage metamorphism from the oceanic ridge type metamorphism trough metamorphism in prehnit--pumpellyite and blueschist facies up to greenschist facies metamorphism

• The Zlatník Gr. was formed as the upper crust of small oceanic basin during its opening in the proximity of volcanic arc and lately obducted (the Grajnár Fm.) or destroyed, transformed on mélange and partly subducted in the accretion prism related to subduction zone (the Závistlivec Fm.)

• The Zlatník Gr. together with the analogous Ochtiná and Pernek Groups probably represent relics of the Upper Devonian/Lower Carboniferous Pernek Ocean

• The Pernek Ocean relics are interpreted as an ophiolite suture which seems to be the boundary between two lithospheric paleoplates with the different Variscan tectono-thermal and magmatic history

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Appendix:

Lokalization of samples presented in the paper:

FD-210: Hnilčík village, Hliniskový potok valley, N 48°52'16.15''; E 20°31'42.08''

FD-214: Hnilčík village, Hliniskový potok valley, N 48°52'12.78''; E 20°31'42.36''

FD-221, FD-222: Hnilčík village, Zimná dolina valley, SE slope, N 48°52'18.60''; E 20°31'32.27''

FD-233: Grajnár saddle, way to Štolwerk settlement, N 48°51'47.38''; E 20°30'44.66''

FD-268: Mlynky village, Havrania dolina valley, borehole BM-1, 511 m, N 48°51'51.80''; E 20°26'20.49''

FD-381: Grajnár saddle, way to Štolwerk settlement, N 48°51'44.17''; E 20°30'43.81''

FD-398: Dobšiná, Kolkova stodola hill, N 48°50'54.89''; E 20°21'18.57''

FD-420: Hnilčík village, Hliniskový potok valley, N 48°52'13.94''; E 20°31'46.03''
FD-421: Hnilčík village, Hliniskový potok valley, N 48°52'14.26''; E 20°31'49.95''
FR-305: Poráč village, Zlatník valley, ridge of W slope, N 48°53'23.87''; E 20°42'30.60''
FR-343: Rudňany village, Závistlivec settlement, Sivá skala hill, N 48°51'53.69''; E 20°39'33.06''
FR-350: Rudňany village, Závistlivec settlement, Rudniansky les area, N 48°52'00.75''; E 20°39'58.82''
FR-351, FR-352: Rudňany village, Závistlivec settlement, Sivá skala hill, N 48°51'49.20''; E 20°39'37.56''
FR-367: Rudňany village, Závistlivec settlement, Sivá skala hill, N 48°51'48.57''; E 20°39'39.13''
FR-411: Rudňany village, Závistlivec settlement, Rudniansky les area, N 48°51'50.54''; E 20°40'01.79''
FR-414: Rudňany village, Závistlivec settlement, Sivá skala hill, N 48°51'47.90''; E 20°39'39.86''
FR-446: Rudňany village, Závistlivec settlement, N 48°52'03.27''; E 20°40'26.79''
FR-463: Poráč village, Zlatník valley, N 48°53'27.60''; E 20°43'02.94''
KG-4: Rudňany village, Závistlivec settlement, N 48°52'00.06''; E 20°39'32.82''

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Allochthonous position of the Meliaticum in the North-Gemeric zone (Inner Western Carpathians) as demonstrated by paleopiezometric data

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Abstract

Article presents new paleopiezometric data of calcite marbles, contributing to solution of principal geological and tectonic problem of autochthonous (cover) vs. allochthonous position of carbonatic suite north of the village of Jaklovce in the eastern part of the North-Gemeric zone (Inner Western Carpathians). The Triassic-Jurassic sequences in the Kurtová skala hill are from the 1970s linked with Meliaticum – so-called Jaklovce Meliaticum, but direct tectonic and structural evidences about its allochthonous position were still missing. Moreover, due to the corresponding appearance of both – autochthonous and allochthonous carbonates, the dividing boundary between both complexes is not clearly determined, or even both sequences were put together into autochthonous position with primary lithological transitions.

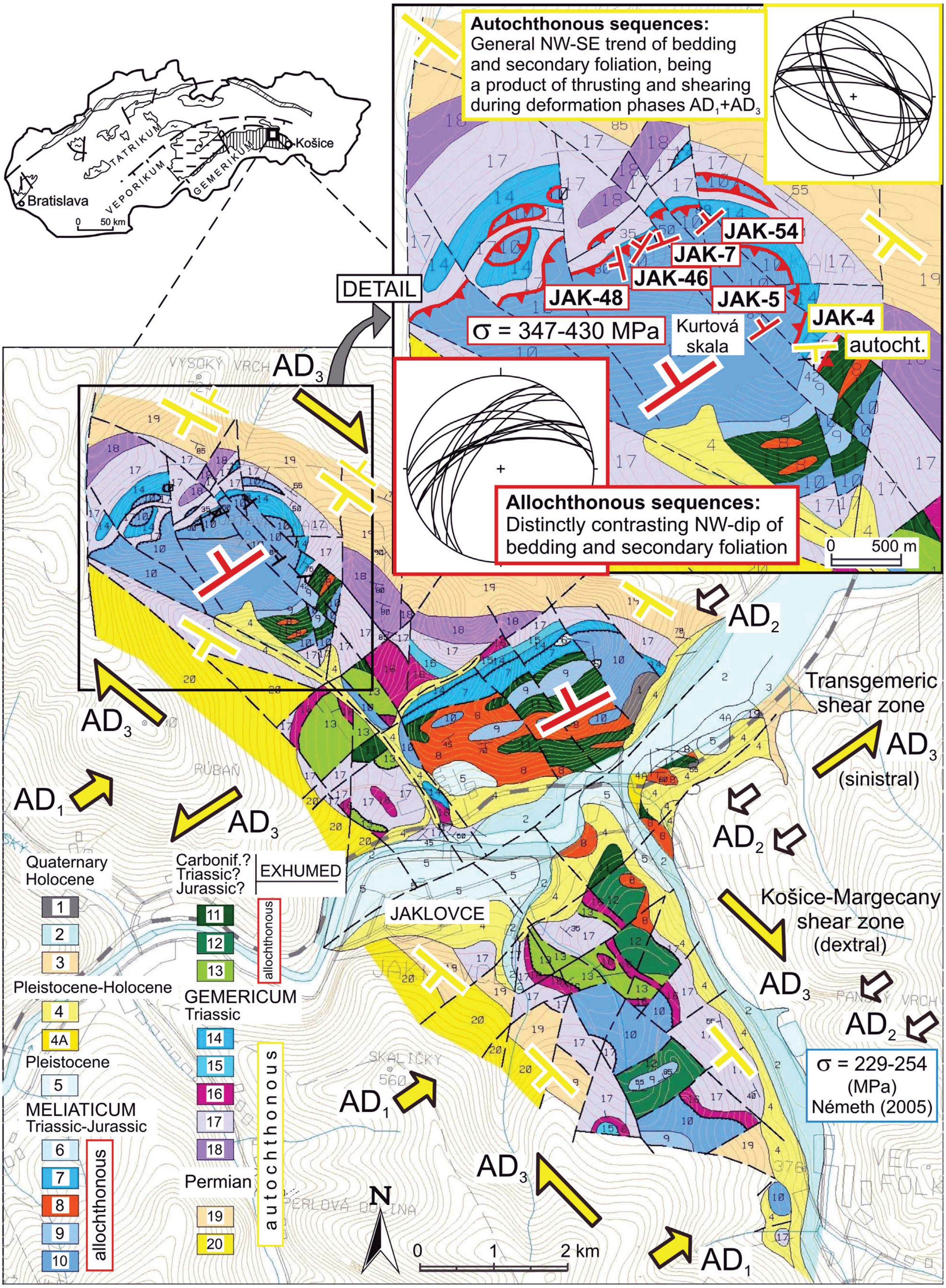
The dynamic recrystallization of the whole volume of allochthonous calcite marbles, being found by our recent research, caused the origin of deformation twins nearly in each calcite grain (Twinning incidence up to 100 %). The high number of deformation twins per 1 mm of perpendicular diameter of the grain (D = 173.05–646.25) at the very small size of grains (23.7 to 42.7 μm) was caused by their recrystallization at high differential stresses σ = 347.49–429.55 MPa. This differs the allochthonous bodies of Meliaticum from those of autochthonous Permo-Triassic cover of the Northern Gemericum, which do not exhibit deformation twins and ductile overprint. This difference simultaneously indicates that the total dynamic recrystallization of allochthonous marbles should occur in conditions of subduction zone, but their post-exhumation transport on autochthonous carbonates without their whole-volume plastic deformation should occur in “could conditions”, corresponding with the transport of the superficial nappe. The exhumed suite (besides carbonates also radiolarites, mafic and ultramafic rocks, etc.,) was overprinted by two principal Alpine deformation phases AD_1 and AD_3 of tectonic imbrication and horizontal shearing, causing the origin of brittle-ductile and brittle disjunctive structures. Despite the overprint, the primary bedding (gen. 330/55) of allochthonous carbonates remained preserved, and contrasts to general NW–SE trending bedding and secondary foliation of autochthonous sequences.

Key words: exhumed suite, tectonic setting, paleopiezometry, Twinning incidence, Twin density, differential stress, Meliaticum, Gemericum, Western Carpathians

Introduction

According to recent knowledge, the rocks of Meliata Unit, being defined in the type locality at the village Meliata in the Slovak Karst (Southern Gemericum; Rožňava suture zone), are represented by mélanges of ophiolites and sediments from the bottom and marginal parts of Triassic--Jurassic Meliata ocean. The rocks were overprinted by metamorphic processes and transported on Gemericum, being a part of the north-vergent Jurassic accretion prism (Mello et al., 1997, 1998, 2000; Németh, 1994, 1996; Ivan, 2002; Ivan et al., 2009; Putiš et al., 2011).

The occurrences of Meliaticum at Jaklovce after biostratigraphic proof of the presence of Jurassic sequences in this zone (Kozur and Mock, 1995), were firstly interpreted in autochthonous position as a part of so-called northern branch of the Meliata ocean (with Gemericum as an island between both branches). Later there prevailed the interpretations of the Meliatic tectonic outlier in the North-Gemeric zone, consisting of relatively thick Jurassic schistose formation with olistoliths and olistostromes of older, mainly Permian-Triassic formations, including metabasalts (Kamenický, 1957; Mock et al., 1998 – the Jaklovce Formation, Hovorka and Spišiak, 1998; Faryad et al., 2005), metasilicites and serpentinites. The ultramafic rocks located in this outlier at Jaklovce (Jacko in Polák, 1997) form isolated bodies either in the sandy-schistose sequence or at the contact with overlying Middle Triassic


Autochthonous sequences:
General NW-SE trend of bedding and secondary foliation, being a product of thrusting and shearing during deformation phases AD1+AD3
Allochthonous sequences:
Distinctly contrasting NW-dip of bedding and secondary foliation
σ = 347-430 MPa
JAK-54
JAK-7
JAK-46
JAK-48
JAK-5
JAK-4
autocht.
Kurtová skala
0 500 m
DETAIL
Bratislava
Košice
TATRIKUM
VEPORIKUM
GEMERIKUM
0 50 km
AD3
AD2
AD1
Transgemeric shear zone
(sinistral)
Košice-Margecany shear zone
(dextral)
σ = 229-254 (MPa) Németh (2005)
JAKLOVCE
Quaternary
Holocene
Pleistocene-Holocene
Pleistocene
MELIATICUM
Triassic-Jurassic
allochthonous
Carbonif.?
Triassic?
Jurassic?
EXHUMED
GEMERICUM
Triassic
autochthonous
Permian
0 1 2 km
N

carbonates, as well as they are infolded or tectonically placed inside the carbonate sequence (cf. Radvanec, 2000). The petrological research (l. c.) revealed their complex exhumation trajectory and defined them as the ultra-high pressure metamorphosed peridotite. The higher--pressure metamorphism of exhumed blocks of Meliaticum in the Jaklovce zone is indicated also by the finding of magnesioriebeckite to riebeckite, resp. ferrowinchite in metabasalt veins and metasilicite by Ivan et al. (2009) and Putiš et al. (2011), but even by the finding of three occurrences of retrograde eclogite in association with metaperidotite and metagabbro by Radvanec et al. (2011).

Used methodology

Geological mapping and reambulation of existing maps

The compiling of a new geological map of the Meliaticum and underlying sequences north of the village Jaklovce was based on prior archive retrieval of old maps and the results of old drilling works (Kobulský and Gazdačko in Radvanec et al., 2011). New geological mapping allowed to compile a new map at a scale 1 : 25 000, reflecting new findings concerning lithology of distinguished rock sequences and their tectonometamorphic overprint.

Meso-scale structural analysis and lithotectonic observations

Outcrop-scale structural research consisted from registration of planar and linear structures and determining of overprinting relations of individual structures. Deformation gradient of rocks was investigated also among particular outcrops in in-situ samples of the debris. Computer processing of data led to construction of stereograms with separated structures attributed to particular tectonic events. Oriented representative samples were taken from outcrops, attempting to cover the complete range of lithological types of various deformation gradients.

When considering the Alpine deformation overpring in investigated area (and s.l. the whole eastern part of the North-Gemeric zone), the following earlier defined deformation phases were applied (cf. Németh, 2002 and following works):

AD_1 – Lower Cretaceous N-vergent (in our studied territory NE-vergent) thrusting and imbrication of pre-Cretacesous sequences related to collisional ovethrusting of Gemericum on Veporicum.

AD_2 – Upper Cretaceours post-collisional unroofing due to the metamorphic core complex dynamics and gradual uplift of superposed megaunits; in the eastern contact zone of Gemericum with Veporicum the unroofing is trending to SW.

AD_3 – Tertiary; conjugate system of regional shear zones trending NW–SE and NE–SW. In the eastern part of the contact zone the NW–SE trending shearing is dominant along the Košice–Margecany shear zone (cf. Grecula et al., 1990). The Jaklovce area is affected also by the ENE–WSW trending Transgemeric shear zone (l. c.). The very complicated tectonic puzzle originated by this way at the Jaklovce village (cf. Fig. 1).

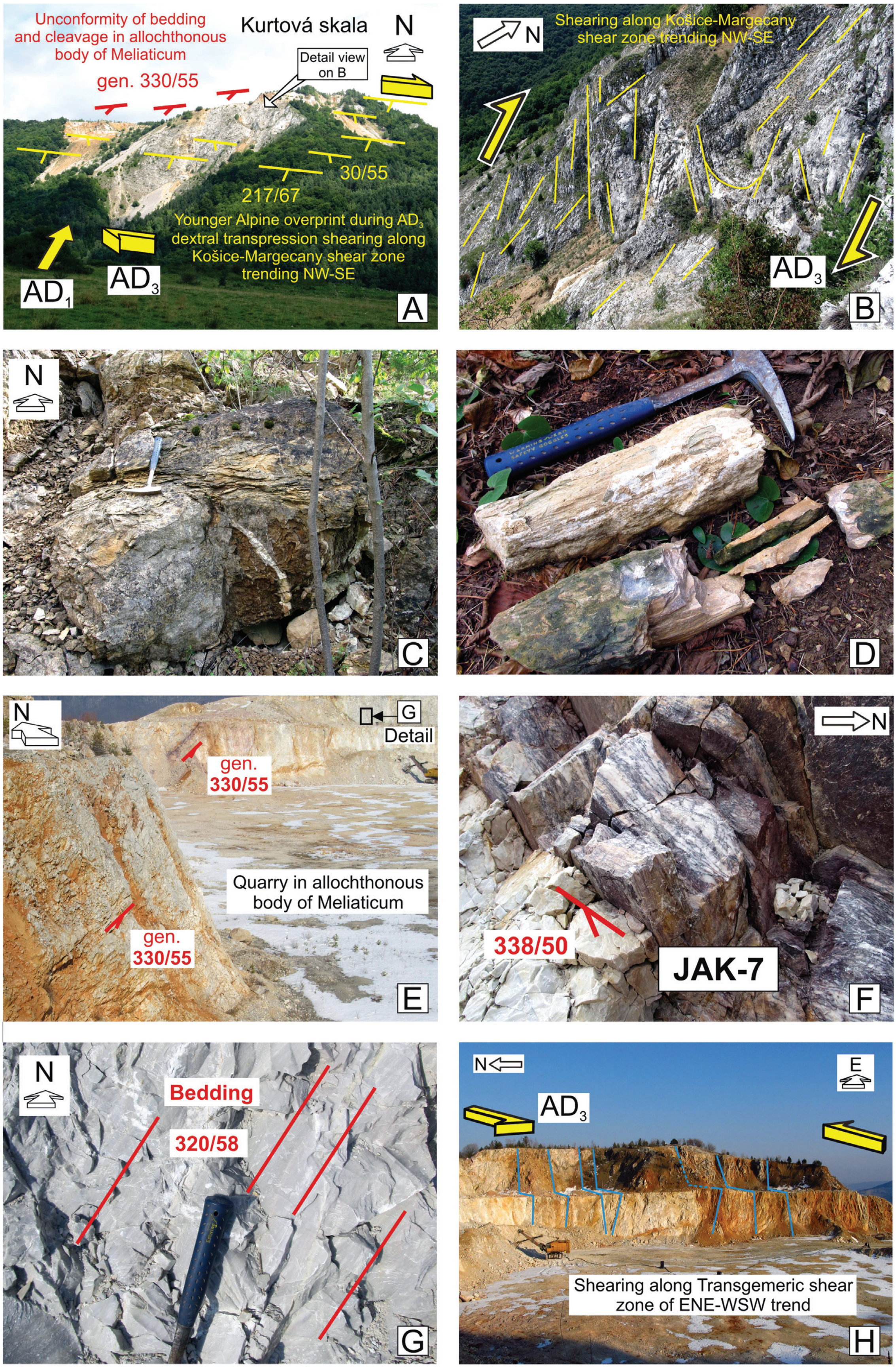
Paleopiezometry

Paleopiezometry applied on calcitic marbles represented the principal investigation method, attempting to find criterion for distinguishing of autochthonous and allochthonous carbonates. Its application was motivated by the earlier finding of a very high differential stress recrystallization in one sample from the Kurtová skala hill (396.66 MPa) by Németh (2005).

The numeric determining of differential stresses in MPa, based on calcite paleopiezometry, takes into account the size of dynamically recrystallized calcite grains, but also the number and character of deformation twins. We used two independent numeric procedures based on *Twinning incidence* and *Twin density* methods (Rowe and Rutter, 1990). Final processing followed the methodology by Németh (2005), by this way allowing to compare new results with previously found differential stresses from three principal shear zones in the Gemeric region.

Twinning incidence, I_t, is defined as the percentage of grains of the distinguished size interval that demonstrate

◀ **Fig. 1.** Position of Meliaticum in the North-Gemeric zone and direction of principal thrusting (AD_1, top-to-the NE), unroofing (top-to-the SW; more external – relates the contact of superunits Gemericum and Veporicum, AD_2; Németh, 2002), as well as conjugated NW–SE trending dextral shearing (AD_3, Košice–Margecany shear zone; Grecula et al., 1990) and NE–SW trending shearing (Transgemeric shear zone, l. c.). Geological map is taken after Kobulský and Gazdačko in Radvanec et al. (2011). The map, as well as detail of the Kurtová skala hill visualize the angular discordance of NW-dipping bedding in allochthonous bodies with the general Alpine structural plan of NW–SE trend, including NW–SE trending bedding of sequences in the North-Gemeric zone. The differences are shown in two stereograms (lower hemisphere; each plane represents one outcrop). Detail shows the position of the oriented samples of carbonates, being studied by calcite paleopiezometry. JAK-4 represents the autochthonous limestone in the tectonic window SE of the quarry and JAK-5, JAK-7, JAK-46, JAK-48 and JAK-54 the calcitic marbles of allochthonous body of Meliaticum. *Lithology: Quaternary – Holocene:* 1 – anthropogeneous deposits, dumps; 2 – fluvial loams, alluvial sandy and gravel loams; 3 – proluvial loams with gravels and rock fragments. *Pleistocene--Holocene:* 4 and 4A – undivided deluvial sediments and debrises. *Pleistocene:* 5 – fluvial sandy gravels of terrace accumulations and the Wurmian. *Meliaticum: Triassic – Jurassic:* 6 – claystones, siltstones, sandstones – radiolarites, locally with belemnites (Middle Jurassic); 7 – dark-grey nodular limestones, marly schists, grey limestones with schistose interbeds (Carnian – Upper Ladinian); 8 – red and green quartzy schists, silicites (with radiolarians), limestone interbeds (Upper Anisian – Middle Jurassic?); 9 – grey, dark-grey cherty limestones with interbeds of red limestones and schists (Upper Anisian – Lower Ladinian); 10 – light and light-grey bedded limestones (Anisian – Lower Ladinian). *Carboniferous?-Triassic?-Jurassic?:* 11 – coarse- to medium-grained gabbro, fine-grained amphibolite; 12 – retrograde eclogite; 13 – metaperidotite, metalamprophyre. *Gemericum – Triassic:* 14 – light-grey, grey and dark-grey dolomites (Lower Anisian); 15 – dark-grey and grey limestones (Lower Anisian); 16 – rauchwackes, rauchwacke dolomites and limestones (Lower Anisian); 17 – green and grey--green calcareous shales and sandstones with interbeds of grey marly limestones (Scythian); 18 – variegated shales and sandstones with rare interbeds of quartzites and limestones (Scythian), *Permian* (Krompachy Group of Gemeric cover): 19 – sandstones, shales, locally evaporites and conglomerates; 20 – sandstones, shales, conglomerates, rhyolites, dacites, andesites and their pyroclastics.


Unconformity of bedding
and cleavage in allochthonous
body of Meliaticum
gen. 330/55
Kurtová skala
N
Detail view
on B
30/55
217/67
Younger Alpine overprint during AD3
dextral transpression shearing along
Košice-Margecany shear zone
trending NW-SE
AD1
AD3
A
N
Shearing along Košice-Margecany
shear zone trending NW-SE
AD3
B
N
C
D
N
G
Detail
gen.
330/55
Quarry in allochthonous
body of Meliaticum
gen.
330/55
E
N
338/50
JAK-7
F
N
Bedding
320/58
G
N
E
AD3
Shearing along Transgemeric shear
zone of ENE-WSW trend
H

microscopically visible twins. In our case the very small grains required the high magnification (objective x25, eyepieces x12.5; total magnification x312.5). Altogether 240 grains were measured in each sample. The value of differential stress $\sigma(\sigma_1\text{-}\sigma_3$; MPa) was determined by following equation, where d represents the size of grains in μm:

$$\sigma = 523 + 2.13\, I_t - 204 \log d \text{ [MPa]}$$

Twin density, D, is defined as the number of twins regarding the grain diameter, measured perpendicularly to the twins. Input data were restricted by the variation coefficient 0.25 (Ranalli, 1984). The relation of differential stress on twin density D is as follows:

$$\sigma = -52.0 + 171.1 \log D \text{ [MPa]}$$

To guarantee the maximum representativeness of data, measurements were done systematically on profiles through oriented thin sections, taking into account each neighbouring grain.

Obtained data

Meso-scale structural analysis

New geological mapping and structural research confirmed the prevailing NW–SE trending outcrop-scale planar structures (bedding – the primary foliation, in schistose formations usually reactivated with the origin of the secondary foliation, cleavage and more extended dislocations; Fig. 1 – upper stereogram in the detail map). Prevailing dip of the primary and secondary foliation was to SW (generally 217/67°), with minor opposite dipping planes (gen. 30/55°; Figs. 2A, B). The succession of the meso-scale structures confirmed the previous extended regional structural research of this research team in eastern Gemericum (cf. Németh, 2002; Gazdačko, 1994; Grecula et al., 1990) and the Alpine dextral transpression shearing along the Košice–Margecany shear zone has attributed the crucial role in forming of the recent course of lithological units in the eastern part of the North-Gemeric zone. This shearing is attributed to AD_3 deformation phase (Tertiary, cf. division of Alpine deformation phases in Németh, 2005; Figs. 1 and 3 ibid.). The maximum shearing was localized along the boundary of Gemericum with underlying Veporicum app. 2 km to NE of studied area, so the horizontal stretching lineations trending NW–SE usually were not distinct in the studied area of the Kurtová skala hill. The NW–SE trending shearing preferably used the disjunctive structures of previous tectonic phase AD_1 (NE-vergent imbrication, Lower Cretaceous, cf. l. c.). The effects of the AD_2 phase (SW-trending Upper Cretaceous unroofing in the eastern contact zone of Gemericum with Veporicum) were not revealed in the studied area because of their location close to tectonic contact of both units 2 km to NE of the Kurtová skala hill.

The distinctly differing structural inventory was found in the quarry located in the apical parts of the Kurtová skala hill, where also oriented samples of calcitic marbles for the paleopiezometric investigation were taken (Fig. 1 detail and general map; Figs. 2E–G). The bedding (generally 330/55°) manifested a principal angular unconformity with the dominant NW–SE trending structural plan of the Jaklovce area. As revealed by microstructural research and paleopiezometry, this bedding concerned the calcitic marbles with strong dynamic recrystallization, representing allochthonous (nappe) outlier. This whole-volume bedding azimuth and dip parameters hardly can be attributed to shearing along the Transgemeric shear zone of ENE–WSW direction, which applies in the quarry with steeply dipping brittle faults (AD_3 conjugate system; Fig. 2H), penetrating marbles with earlier ductile recrystallization (and bedding).

Attempting to found the displacement plane between autochthonous and allochthonous rock sequences, we found large rounded blocks of silicitic rocks and carbonates (Fig. 2C), but also ultramafics, which indicate the prior exhumation kinematics. Strongly stretched limestones and silicitic rocks were found only in the debris along the basal parts of the Kurtová skala hill, so no spatial orientation of tectonic transport could be attributed by the impossibility to learn their in-situ (outcrop) orientation (Fig. 2D).

Paleopiezometry

Six studied fine-grained limestones from the apical part of Kurtová skala hill (Fig. 1 Detail) encompassed five calcitic marbles with strong recrystallization (JAK-5, JAK-7, JAK-46, JAK-48, JAK-54) and one sample, taken on the

◀ **Fig. 2.** Field-scale evidences of the allochthonous position of Meliaticum in the Jaklovce zone. **A** – The Kurtová skala hill consists of strongly recrystallized calcitic marbles (being recently exploited in the quarry), as well as the suite of mafic and silicitic rocks in eastern continuation of the hill. The allochthonous sequences were together with their underlier overprinted by the north-vergent Alpine thrusting (AD_1), but mainly by the AD_3 dextral shearing in the Košice–Margecany shear zone. General trend of planar structures (217/67, 30/55, visualized by the yellow signs) is tied with phases AD_1-AD_3, but reflects also the general trend of bedding in this zone. Contrary to this, the planar structures dipping to NW (330/55; bedding, often reactivated by secondary cleavage; red coloured), represent an unconformity with the AD_1–AD_3 tectonic plan and are remnants of the pre-AD_1 evolution. **B** – View on the unforested southern steep slope of the Kurtová skala hill from the upper edge of the quarry indicates numerous disjunctive structures related with AD_3 shearing. **C** – At the base of allochthonous body numerous rounded blocks were found, consisting mainly of silicites, radiolarites and mafic/ultramafic rocks. **D** – Shearing during displacement of allochthonous body is indicated also by stretching of rocks. **E** – The NNW side of the quarry demonstrates the bedding dipping to NW, being usually reactivated with the origin of secondary cleavage (gen. 330/55). The NNW side of the quarry is bearing several decimetres wide shear zone with fragmented calcitic marble, being penetrated by the Fe-bearing fluids. This shear zone is supposed to represent the pre-AD_1 structure (detail in F); **F** – detail of the shear zone being penetrated by the Fe-bearing fluids of pre pre-AD_1 phase. Note – the orientation of photo F is nearly opposite to that in photo E, the dip of the shear-zone is to NW and corresponds to that in photo E. **G** – Bedding of dynamically recrystallized marbles in the NNE side of the quarry. **H** – The allochthonous bodies of Meliaticum in Jaklovce zone were penetrated also by disjunctive structures related with the Transgemeric shear zone and trending ENE–WSW.

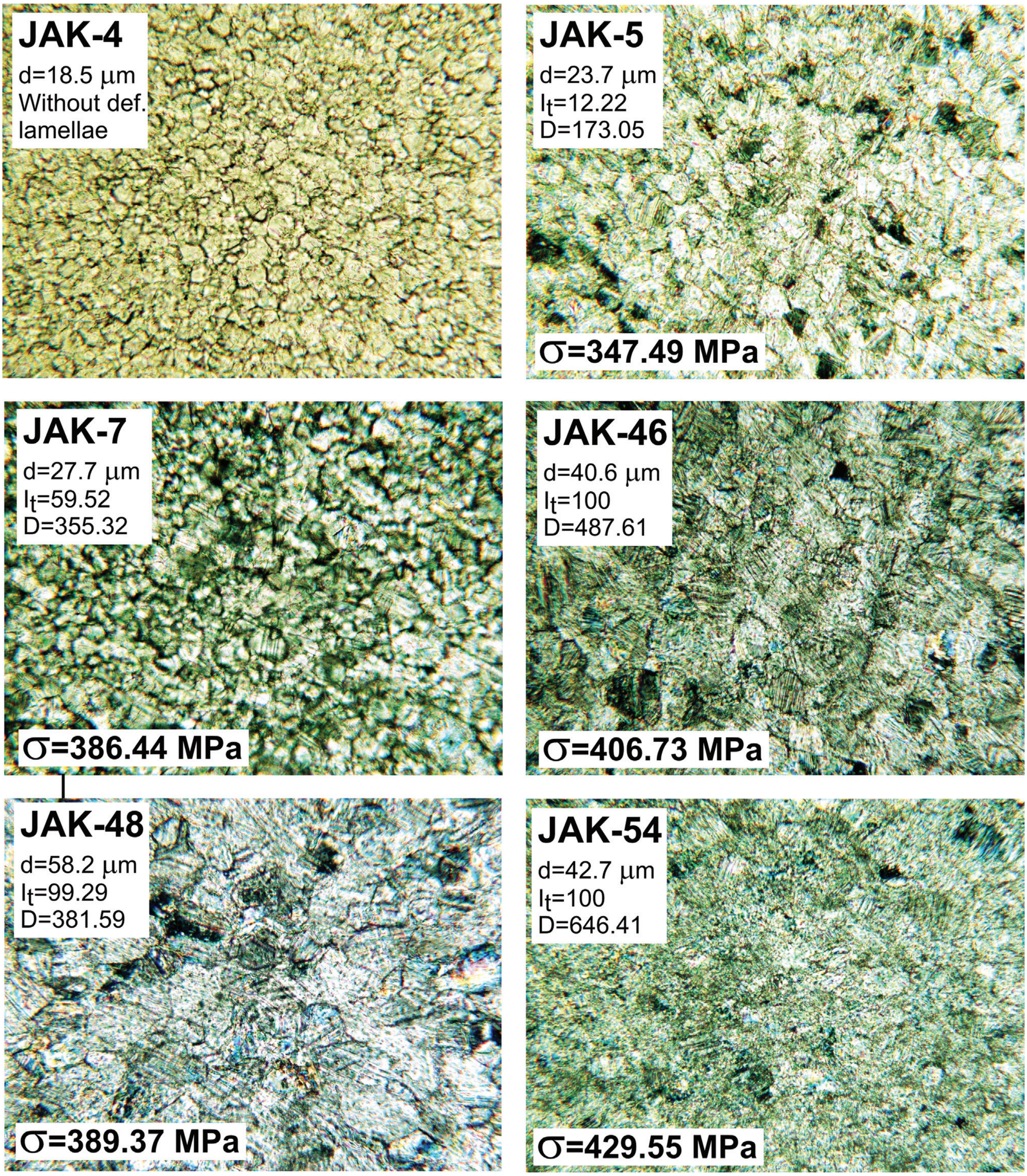


Fig. 3. Microphotographs of studied samples with principal parameters: d – average grain-size; I_t – Twinning incidence – the percentage of grains with deformation twins; D – Twin density – the average number of twins per 1 mm of perpendicular diameter of the grain; σ – differential stress ($\sigma_1 - \sigma_3$) causing recrystallization of grains. Sample JAK-4 represents autochthonous limestone without twins. The revealed differential stresses of allochthonous samples of Meliaticum in the Jaklovce zone represent the highest values until found in the Western Carpathians.

Tab. 1
Results of paleopiezometry applied on carbonates of the Kurtová skala hill. The laboratory paleopiezometric microscopy and computing done by Zákršmidová (2012)

		TWINNING INCIDENCE					TWIN DENSITY		
	Representative grain-size	Calcul. without variation coeffic. / Calculat. with weight. mean	It for interval determined by variation coefficient	Calculation with variation coefficient			D – no. of twins per 1 mm of perpend. diameter	Calculat. without variation coeffic.	Calculat. with variation coeffic.
				Calculat. with the whole It	Arith. mean of σ for size classes	Weight. mean of σ for size classes			
	µm	σ(MPa)	It	σ(MPa)	σ(MPa)	σ(MPa)	D	σ(MPa)	σ(MPa)
Autochthonous sequences of Jaklovce Meliaticum									
JAK-4	18.5	*No deformation lamellae are present in autochthonous limestone*							
Allochthonous sequences of Jaklovce Meliaticum									
JAK-5	23.7	269.40	12.22	268.72	272.07	269.40	173.05	330.95	**347.49**
JAK-7	27.7	356.45	59.52	355.62	353.29	281.27	355.32	384.41	**386.44**
JAK-46	40.6	411.63	100	407.79	405.79	408.52	487.61	407.93	**406.73**
JAK-48	58.2	208.46	99.29	374.42	373.43	375.30	381.59	389.71	**389.37**
JAK-54	42.7	407.15	100	403.40	403.73	404.25	646.41	428.88	**429.55**

eastern slope of the hill (JAK-4) and manifesting a weak tectonometamorphic overprint.

The stress field and recrystallization of the whole volume of calcite marbles of the first group caused the origin of deformation twins nearly in each calcite grain (Twinning incidence up to 100 %; Fig. 3, Tab. 1). The high number of deformation twins per 1 mm of perpendicular diameter of the grain (D = 173.05–646.25) at the very small size of grains (23.7–42.7 µm) was caused by their recrystallization at high differential stresses σ = 347.49–429.55 MPa.

This differs the allochthonous limestone bodies of Meliaticum from those of autochthonous Permo-Triassic cover of the Northern Gemericum, which do not exhibit deformation twins and ductile overprint.

Discussion and interpretation

The bedding planes (gen. 330/55°; Fig. 2E), manifesting the angular unconformity of the allochthonous block of the Kurtová skala hill with the contrasting structural plan of surrounding tectonized cover sequences of Gemericum in the North-Gemeric zone, correspond with that of further (exhumed) block of silicitic and mafic sequences in the zone of Jaklovce Meliaticum, located to SE closer to the Jaklovce village. Nearly perpendicular bedding to that present in this part of the North-Gemeric zone, resp. in the zone of so-called Jaklovce suture zone indicates the need of exhumation in other place of accretion prism and the N (NE)-trending nappe transport of the exhumed body. This "cold" transport is indicated also by preserved state of maximum dynamic recrystallization, without signs of static recrystallization, as discussed below. Meso-scale kinematics is consistent with that derived from the calcite textural patterns of marbles in the neighbouring Murovaná skala Meliatic fragment (Putiš et al., 1999).

Obtained values of the differential stresses are extremely high, reaching at least by 30 % higher values than those, found previously in other most important regional shear zones in Gemericum (cf. Németh, 2005; Tab. 1 ibid.): The recrystallized Lower Paleozoic carbonates manifested in previous research the σ values 168.06–230.98 MPa and in the ductile shear zone between Gemericum and Veporicum there were found differential stresses 228.82–253.71 MPa.

The previous research (Németh, 2005) of the calcitic marbles of the Bôrka nappe (the sequences of Meliaticum in allochthonous position on Gemericum) found notable relation: The frontal parts of the Bôrka nappe – among which also the Kurtová skala occurrences belong – revealed high differential stresses 244.79–396.66 MPa, but the rear parts of the nappe near the suture zone (Rožňava discontinuity zone) manifested the lower values (187.56–277.92 MPa). This paradox was explained (l. c.) by the evidences of onset static recrystallization in the warm rear zones of the exhumed body, causing the static growth (recrystallization) of calcite grains at gradually and moderately lowering values of the pressure and temperature, despite the calcite marbles in the frontal parts of transported sequence contain the "frozen" conditions closer to maximum affecting differential stress, the processes of the strain softening by diffusion and dynamic recrystallization like in the rear parts of exhuming body were restricted.

Conclusion

The main contribution of the research consists of (1) revealing the principal angular unconformity in the structural plan of allochthonous body vs. autochthonous sequences, and (2) paleopiezometric finding of the highest values of differential stresses until found in the Gemeric region, as well as the Western Carpathians, distinctly contrasting with undeformed limestone in the underlier of allochthonous body. This finding is important even in the particular case of the Kurtová skala hill, when both carbonate types were for many decades undistinguishable by the hand sample-scale observations, having the same appearance.

By this way the method of paleopiezometry appears to be a principal differing tool for distinguishing the deformation and stress gradients in monomineral lithologies.

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Ramp folds and fracturing in the Southern Rifian Ridges between autochthonous Atlasic domain and allochthonous formations of the Rif Cordillera (Northern Morocco)

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Abstract

Through geometrical modelling of fold-thrust structures in the Southern Rifian Ridges (Northern Morocco), we propose a new kinematic evolution of the southwestern front of the Rif Cordillera. Our reconstruction implies a generalized detachment within the Triassic evaporites. The Miocene--Pliocene fault-propagation folds were confronted with the theoretical results of kinematic model (Suppe, 1985) as well as the mechanical model (Mercier and Mansy, 1995; Salvini and Storti, 1997), developed above inherited extensional faults. The E–W trending normal faults inherited from Jurassic determine the position of the ramps and folds, whereas the N–S trending faults are reactivated lateral ramps. These compressive structures were reactivated during Plio-Quaternary as a sinistral strike-slip overthrusts. We analysed tectonics of the frontal faults from the southern boundary of the Jebel Zerhoune (20 km north of Meknes). This fault considered by Moratti et al. (2003) as a surface rupture originating due to the earthquake of November 18, 1755, two weeks after the Lisbon earthquake. The structural analysis done on the mirror of this fault shows the calcareous crusts and Quaternary formations bear no trace of friction. Similarly, the axis of principal stresses determined from measurements on the mirrors of this fault indicates a NNE–SSW shortening direction compatible with the regional Plio-Quaternary shortening phase. The Plio-Quaternary limestones of the Saïss basin located on the northern side at the Jebel Aïcha Mouguettaya are verticalized and affected by submeridional vertical faults. The latter are interpreted by Ahmamou and Chalouan (1988) as synsedimentary normal faults due to an extensive Pliocene phase. Previously, Ait Brahim (1983) has considered these fractures as a dextral strike slip faults. Our works in this region, based on analysis of fracturing, show that these faults affect both sub-vertical and tabular limestones. These fractures are mainly concentrated in the surrounding Oudaya diapir and gradually diminish towards the Saïss basin. This geometry corresponds probably to salt tectonics during regional compressive phases.

Key words: modelling, fault-propagation folds, tectonic inversion, microtectonics, South Rifian Ridges, Morocco

Introduction

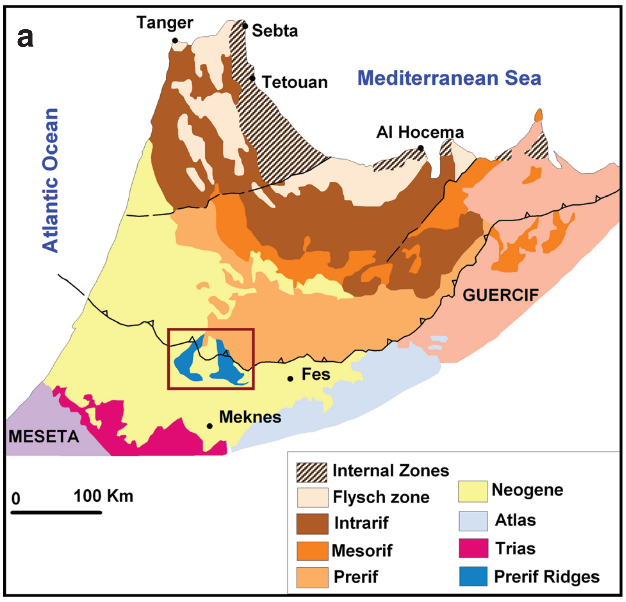
The Neogene deposits of the western part of northern Morocco are often at the periphery of the Rif chain and are well developed in the furrow southern Rif. The Saïss Basin, constituting the middle part of that groove is characterized by thick formations of Neogene, corresponding to the blue marls deposits, sands and lacustrine limestones, directly overlying the Liasic dolomitic limestones.

At the northern edge of Saïss basin, South Rifian ridges form two more or less concentric arcs, forming the most external reliefs of the Rif cordillera. They are formed mainly by Jurassic deposits involving an extensive context related to the Atlantic and Thetyan oceans.

After a long period of emersion, the Mio-Pliocene sedimentation was performed as part of a general compression due to the closure of the Mesogean and the opening of the Mediterranean Sea during the construction of the surrounding Mediterranean Alpine chains.

In previous work, the structural models proposed for the contact between these Ridges and the Saïss Basin the different tectonic setting. Two structural models were presented, one assumes that the ridges overlapping of Saïss basin (Delga Durand et al., 1960–1962; Leblenc, 1986), and the other considers these ridges as a simple monoclinal, with flanks slightly inclined towards the North and the contact with the Saïss basin corresponds to a vertical fault (Vidal and Faugères, 1975; Faugères, 1978).

Through a structural analysis and microtectonics, as well as geological surveys in Jebel Zerhoune and Jebel Aïcha Mouguettaya, we present new observations and we propose a reinterpretation of the northern edge of the Saïss basin and its transition with the front of the Rif chain.



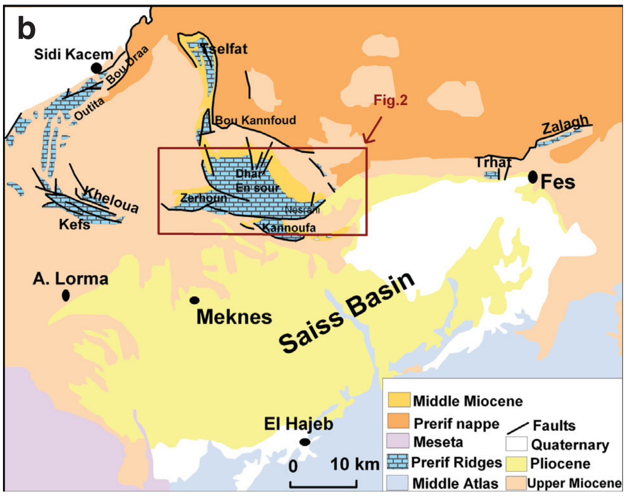


Fig. 1. a – geological map of northern Morocco and location of the study area; **b** – detailed map of the Prerif ridges.

Jebel Zerhoune

The Zerhoune ridge is the principal relief of the Eastern Arc of the Southern Rifian Ridges and forming the transition between the Rif in the north and Saïss basin in the south (Figs. 1 and 2). It corresponds to an E-W anticline interpreted as a fault-propagation fold (Haddaoui, 2000; Sani et al., 2007). The oldest outcrops are Aaleniano--Bajocian, they are overlain by a slight unconformity of Upper Miocene detrital series.

Microtectonic analysis

The work in this Ridge aimed to study the fault front which makes the ridge of Zerhoune in contact with the Saïss basin. The observations were made in two sectors at the western end and in the middle part of this ridge for several reasons. First, because of the outcrop conditions allowing observation, and also because the recent work have focused on the region deserve to be clarified (Moratti et al., 2003; Sani et al., 2007; Chalouan et al., 2007). Indeed, in the west end of the ridge of Zerhoune (Fig. 2 site 1), the E–W trending fault that can be observed along the road Meknes-Moulay Idriss Zerhoune, which crops out as a trench in the same direction. It was considered by Moratti et al. (2003) as a surface rupture due to an earthquake of 18. November 1755. The earthquake, which devastated two cities of Meknes and Fez, occurred few days after the earthquake of 1. November 1755, known as the Lisbon earthquake. Moratti et al. (2003) suppose

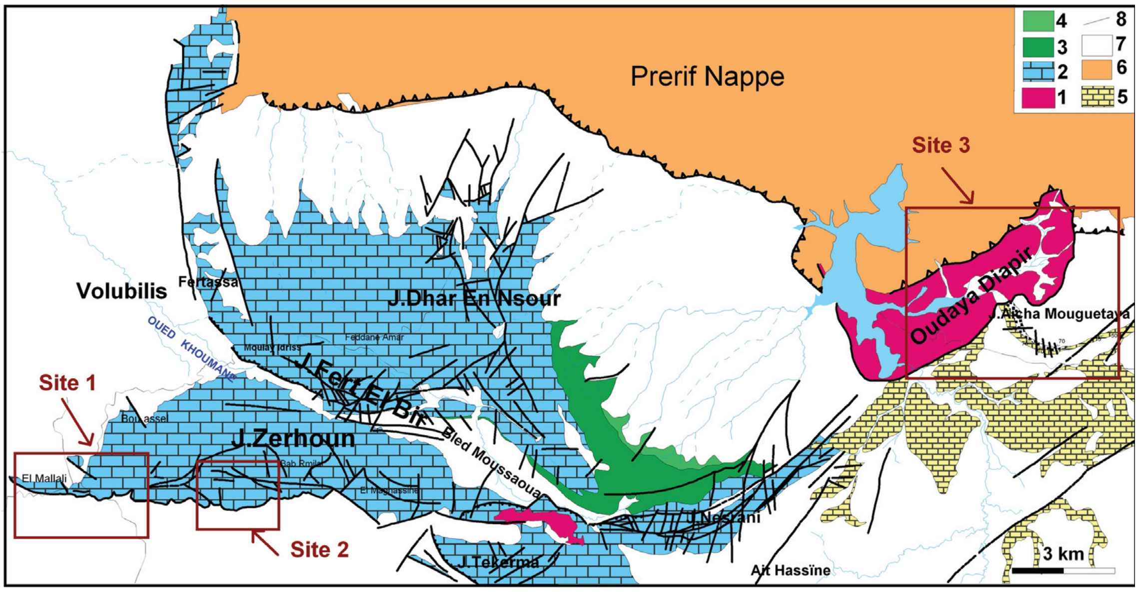
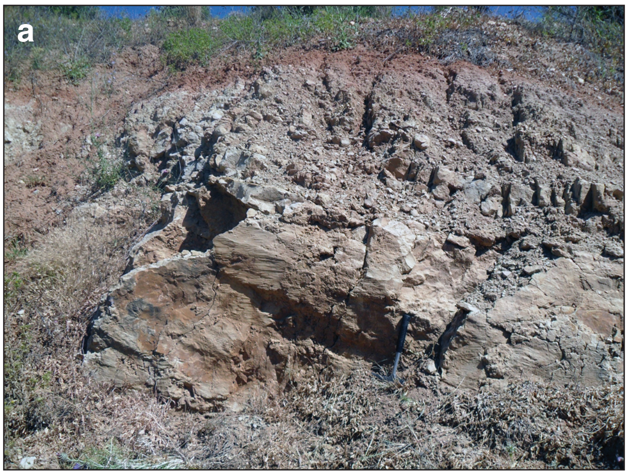
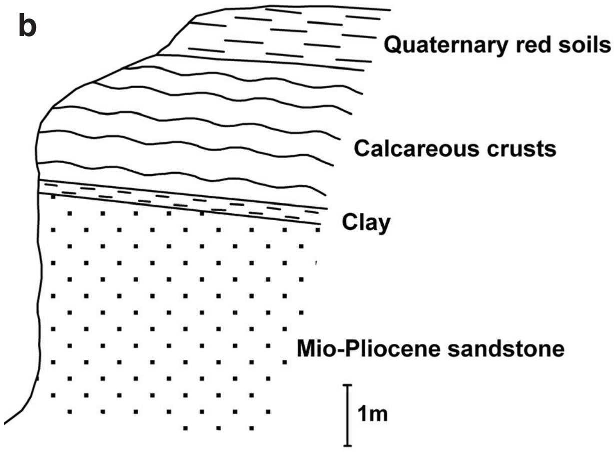


Fig. 2. Structural map of the Eastern Arc of the Southern Rifian Ridges. 1 – Triassic, 2 – Jurassic, 3 – Cretaceous, 4 – Paleocene, 5 – Pliocene, 6 – Prerif nappe, 7 – Quaternary, 8 – faults.





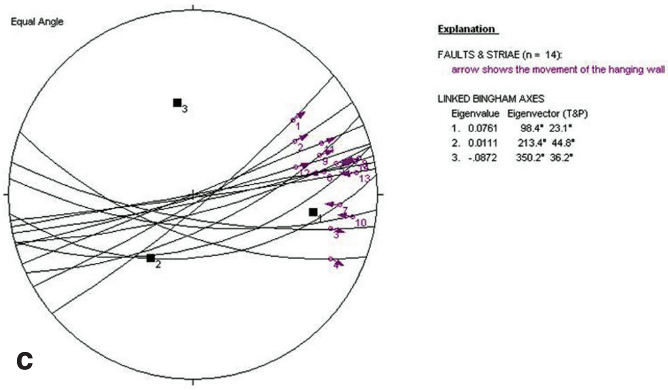


Fig. 3. a – mirror front of the fault at the western end of J. Zerhoune; **b** – log series flush; **c** – stereogram on the fault.

that during this earthquake, the southern front ridges of pre-Rif were reactivated at the ridge Zerhoune of north Meknes and the ridge Zalagh close to the city of Fez. Our research, based on the analysis of different microtectonics fractures, observed in the site, searching their geometric relationships and their relationship to the known regional stress field of the region (cf. Aït Brahim, 1983; Haddaoui, 2000; Faugères, 1978) and detailed observations made along the mirrors of this fault clearly visible in the sandstone facies, has brought new details for earlier considerations.

At the outcrop, the stratigraphic sequence includes sandstone, overlain by calcareous crusts and Quaternary red soils. This frontal fault, considered as a surface rupture and marking the boundary between the Saïss basin and Jebel Zerhoune, affects the stratified sandstone, being attributed to the Mio-Pliocene (Fig. 3b). This subvertical mirror of this fault shows horizontal sliding streaks, benches and stylolitic streaks (between 5 and 30°; Fig. 3a). However, the calcareous crusts and Quaternary soils appear to be intact and bear little evidence of friction, suggesting that this event was sealed by Quaternary deposits. Different markers are observed in the mirror indicating sinistral strike-slip movement. The microtectonic measurements permit to determine a NNE–SSW shortening direction (Fig. 3c). Not far from this site, in another outcrop, the same sandstone series, intercalated with red clay layers, are affected by apparent normal faults. The set of measurements on these faults indicate a NW–SE extensional direction (Fig. 4).

In the second site at the Sidi Ali town (Fig. 2 site 2), we observed an N-S fault along the road between Jurassic sandstone and heterogeneous breccia which determine the limit of the Sais Neogene basin. In previous works, N–S faults were considered as normal faults compatible with N–S shortening phases (Faugeres, 1978; Haddaoui, 2000). We had been modelling these structures and we remark that this N–S direction is exceptional and requires

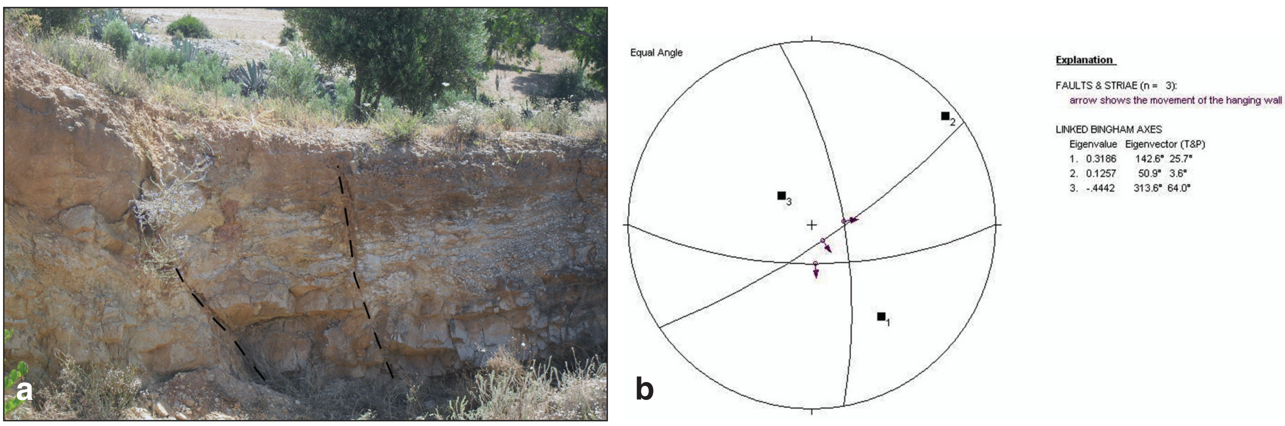


Fig. 4. a – normal faults at the northern edge of Saïss; **b** – stereogram on these faults.

much more attention. In the field, we observed that many markers (sigmoïds, striae, etc; Photo 1) indicate that these faults correspond essentially to reverse faults orthogonal to the E–W major frontal fault. So, we consider that this direction is a minor oblique ramp which develops N–S axis folds during the sub NE–SW shortening phases of Miocene and Plio-Quaternary stages.

Photo 1. Reverse fault trending N-S at the Jebel Zerhoune.

Jebel Aïcha Mouguettaya

Located about 30 km west of Fez, the Jebel Aïcha Mouguettaya forms a ridge oriented approximately E–W to WNW–ESE, striking geographical boundary between the Rif and Saïss (Fig. 2 site 3).

In this massif, the series shows the stratigraphic base to the top of the grey marls of Tortonian. A river--lake formation consists of calcarenites with interbedded conglomeratic, and beige to pink limestone beds 50 m thick, being attributed to Upper Pliocene. North of this massive, the post-nappe marl is unconformably based on red clay gypsiferous Triassic sequence. Southward, the vertically dipping lacustrine limestones, forming the crest of Jebel Aïcha Mouguettaya, display gradual transition to white marl, interbedded with conglomeratic bands in the Quaternary.

Structures

The Pliocene lacustrine limestones of Aïcha Mouguettaya Mts. have different geometries of both sides of the highway linking Fez and Nzala Beni Ammar (Fig. 5). In the immediate contact with the Oudaya Triassic diapir, these limestones are verticalized and sometimes even reversed. They are affected by many sub-N-S trending faults, interpreted as the dextral shears (Ait Brahim, 1983; Ahmamou and Chalouan, 1988). On the southern side of the road, these limestones are affected by very open folds with N60 to N75 oriented axis and become tabular towards Saïss.

In their works in the region, Ait Brahim et al. (1983) and Ahmammou and Chalouan (1988) were observed especially in the events that involved apparent dextral shift of these limestones, forming the crest of the massif. They considered the overprint by the strike-slip faults (Ait Brahim et al., 1983), or the normal faults developed during Pliocene extensional phases (Ahmammou and Chalouan, 1988). These authors, giving much importance to these faults in relation to the regional geodynamic setting in the Late Pliocene and Quaternary, have more or less underestimated the presence of a characteristic diapiric structure in the region that would cause the origin of brittle structures in the region.

Fracturing

The Plio-Quaternary palustrine-lacustrine formations of Saïss, located on the northern edge of the basin at the peak of Jebel Aïha Mouguettaya, are verticalized and affected by vertical submeridian events (Photo 2). These accidents are interpreted by Ahmamou et al. (1988) as synsedimentary normal faults due to an extensive phase trending WNW–ESE in the Upper Pliocene. Previously,

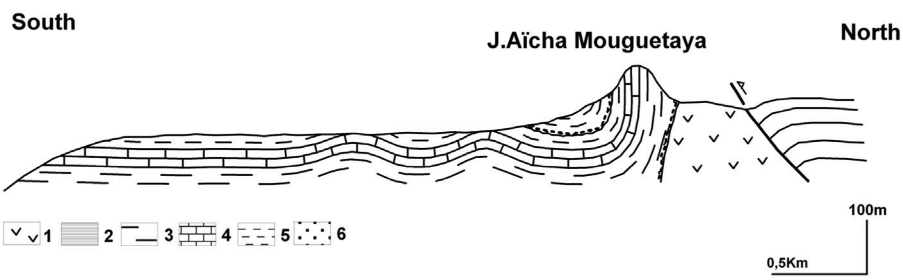


Fig. 5. Geological section of Jebel Aïcha Mouguettaya (location in Fig. 2a). 1 – Triassic gypsiferous red clay, 2 – Prerif nappe, 3 – Tortonian grey marls, 4 – Lacustrine limestones, 5; White marl, 6 – Conglomerates.

Photo 2. The crest of Jebel Aïcha Mouguetaya.

Photo 4. Oudaya salt diapir.

Aït Brahim et al. (1983) have considered these fractures as the dextral strike slip faults related to a sub-meridian compression phase.

Our work in this area allowed us to document the vertical faults oriented N155 to N–S as well as a network of fractures in the limestones. North of the ridge in Miocene marl, we observed fractures of the same direction as those affecting limestone. The south subhorizontal lacustrine limestones are affected by vertical fractures oriented N30 with striated mirrors indicating the strikeslip (Photo 3). Although the sense of shearing in these mirrors we were not been able to determine with certainty, some offset strata indicate sinistral shearing.

Photo 3. Vertical faults with horizontal striae. South of Jebel Aïcha Mouguetaya.

Triassic salt dome

The Jebel Aïcha Mouguettaya is limited to the west by the fault of the Nzala Oudaya, oriented N50-70, being one of the main structural features of the region. This fault took advantage of the Triassic salt diapir (Fig. 2 and Photo 4), constituting the recent important salt deposits overlapping to the SE and S the lake limestone of the Jebel Aïcha Mouguettaya. The presence of this overlap allowed Ahmammou and Chalouan (1988) to assume a shorter regional NW-SE trending deformation phase, being later compared to Pliocene extensional phases.

Discussion and conclusion

Our observations aimed to contribute for better understand of the transition zone between the ridges of South Rif and Saïss Basin. They allowed clarification on earlier interpretations. Indeed, the E–W fault considered by Moratti et al. (2003) as a recent surface rupture appears to be the oldest fault, which was during the Plio-Quaternary compression phases responsible for the reactivation of structures, bordering the basin and the verticalization of the Plio-Quaternary formations of the region (Ait Brahim, 1983; Ahmamou and Chalouan, 1988; Haddaoui, 2000; Sani et al., 2007). The structural analysis done on the mirror of this fault showed that the calcareous crusts and Quaternary formations bear no trace of friction. Similarly, the axes of principal stresses determined from microtectonic measurements on the mirrors of the fault (slip striae, benches and tearing stylolites) determined a regional NNE-SSW shortening direction, being consistent with known regional upper Miocene-Pliocene phase.

At Jebel Aïcha Mouguettaya, fractures affecting the Plio--Quaternary limestones have been interpreted in different manners (Aït Brahim, 1983; Ahmammou and Chalouan, 1988). Our research permitted to observe vertical faults affecting both vertical and sub-tabular limestone formations. The spatial distribution of these faults as radial fractures in the surrounding of diapiric structure of Oudaya, suggests that these faults are contemporaneous with the establishment of this salt Triassic core. Although, the direct relationship between these fractures and the halokinetic movements of Triassic salts is difficult to demonstrate (Zizi, 2002), we note that these fractures are mainly concentrated near the diapir and decrease progressively towards the Saïss basin. Similarly, the recovery and even the overthrow of the series near the diapir argues for a local salt tectonics probably in a regional compressional context.

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Meliata type locality revisited: Evidence for the need of reinvestigation of the Meliata Unit and redefinition of the Meliata Mélange

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The Meliata Mélange and the origin of the different blocks in a cherty matrix (radiolarites, cherty limestones, cherty marls, argillaceous marls) are crucial not only for the interpretation of the geodynamic history of the south--eastern part of the Western Carpathians. Similar mélange complexes do exist in the southern Northern Calcareous Alps and in the Dinarides, Albanides and Hellenides. The Meliata Mélange, and especially its type locality at the Muráň river in the small village Meliata (Slovak Karst Mts.), stands as a synonym for the suture of the Meliata Ocean. According to the widely accepted paleogeographic reconstructions, the Meliata Ocean, sometimes also named Meliata-Hallstatt Ocean, should strike originally from the Northern Calcareous Alps to the Western Carpathians. In this classical model, the Northern Calcareous Alps and the Western Carpathians form its northern shelf, whereas the Transdanubian Range and the Bükk Mts. should have formed its southern margin. On the contrary in our model, which is based on investigations of different mélanges in the Alpine/Carpathian/Dinaride realm, the "Meliata Ocean" does not represent an independent ocean, but the northernmost part of the single Neotethys Ocean. This started to open in the Anisian and was partly closed in the late Middle Jurassic times. During this orogenic phase, which formed the Neotethyan Belt, several types of ophiolitic and radiolaritic mélanges were created. One of them is the Meliata Mélange. However, the understanding and interpretation of the Meliata Mélange differ in the literature and no clear definition of the Meliata Mélange was presented until now. Consequently, an exact definition of a succession or unit should start at the type locality located tectonically south-west and above the Gemeric Superunit, which has the "Meliata Mélange" remnants preserved from both sides. This fact has led some authors to the opinions about two branches of the Meliata Ocean surrounding the Gemeric Superunit, whereas others inferred that the northern occurrences do not represent a true suture, but they were transported to its recent position tectonically by thrusting (obduction). By this, an exact definition of the Meliata Mélange will not only lead to a better understanding of the geology of the southeastern Western Carpathians, it will also help for a better understanding and reconstruction of the geodynamic processes in the whole Neotethys realm.

For that reason we have started with a reinvestigation of the type-locality, particularly the Late Middle Jurassic matrix between the olistostromes and slide blocks of the upper part of the succession recognized in earlier investigations. The lower part of the type section was interpreted as a continuous Anisian to Carnian sequence originally. A sample from the basal part of the section, below the Ladinian cherty limestones and radiolarites and above the Anisian limestones, yielded the Callovian to Early Oxfordian age indicated by the microfacies resembling the silicified Bositra limestone with radiolarians. In the upper part of the Meliata type section, several grey limestone and dolomite fragments resting in a late Middle Jurassic sedimentary matrix occur. Besides Carnian limestones, also the Norian grey limestones occur that represent components derived from the typical grey Hallstatt facies. The different carbonate blocks in the Jurassic matrix show also different thermal overprint based on the Conodont Colour Alteration Index measurements, indicating transported metamorphism. Ophiolite components and slides are missing in the Meliata type section, but occur in the mélange areas in the nearby surroundings of the village. In fact, the Meliata Mélange represents originally a deep-water basin fill in front of advancing ophiolite and sedimentary cover nappes, which was later deformed by incorporation in the nappe stack. As a result, a typical mélange was formed.

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Paleozoic amalgamation of Central Europe – interactive modelling with GPlates software

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The Paleozoic history of Europe is still ambiguous for scientists. Despite of advanced progress in the geological, geochemical and geophysical research, a lot of discrepancies are present. The number of terranes, both of Gondwana and Baltica origin, which participated in amalgamation of Europe, is still unclear, similarly as their boundaries and evolution. In our model we reconstructed the trajectories of terranes for Paleozoic times. A special consideration was given to the region of Central Europe. As an input, we used the datasets developed by Golonka (e.g. Golonka, 2007, 2009), as well as the result of recent regional research (e.g. Pharaoh, 1999; Banka et al., 2002; Winchester, 2002; Oczlon, 2006) to determine the origin, boundaries and the age of accretion of each terrane. Our model is emplaced on the background of global plate tectonic model, which is based on previous work of Golonka (e.g. Golonka, 2007, 2009). The GIS software (ArcGIS, QGIS) was used to create new polygons, which represent second-order tectonic features of Europe. We divided Armorican Terrane Assemblage into following units: Moldanubian, Saxothuringicum, Teplá-Barrandien, Drosedorf and Góry Sowie. The more eastern part of the Central Europe is represented by the Brunovistulicum Terrane and Małopolska Block (with Holy Cross Block included) and the southernmost region is covered by two large polygons: first represents proto-Alps and Italian terranes and second the Aegean and Pannonian zone of Europe. Also the Moesia and the Rhodopes Units were incorporated into our model (Fig. 1). The borders of terranes were generally based on Terrane Map of Europe (Oczlon, 2006) and maps published by Pharaoh (Pharaoh, 1999; Banka et al., 2002). Into the model of the tectonic evolution of Europe we used GPlates software developed by the EarthByte Group in Sydney, which gives an opportunity to work interactively with different data sets (e.g. geophysical, geological, raster data, vector graphics and many others). As a result we produced an animation of the plate tectonic setting for Paleozoic. To validate the obtained model, a basic test of the velocity distribution was conducted. The presented model is not complete, and will be a subject of further revision and refinements.

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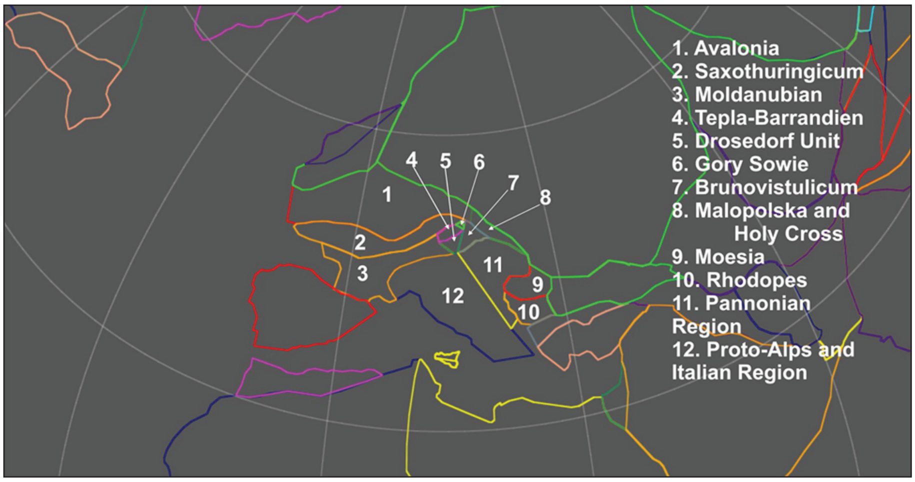

Fig. 1. Model of Paleozoic amalgamation of the Central Europe.

The Kuh-e-Gachab triangle zone in the Central Basin of the Iran Plateau in the Semnan area, central Iran

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During the continent–continent convergence of the Arabia and Eurasia plates, after the Late Eocene inversion of the back-arc rift, the area of the Iran Plateau underwent broad subsidence resulting in the formation of the Central Basin (Morley et al., 2009). New 2D seismic data made by NIOC as well as field investigations in the NW–SW-trending arm of the Central Basin suggest that during the main stage of shortening (Middle–Late? Miocene to Pliocene) the strain concentrations resulted in the development of the thin-skinned Kuh-e-Gachab, Kuh-e-Gugerd and Garmsar structures. These structures are built of Oligocene–Miocene/Pliocene? rocks belonging to the Lower Red, Qom and Upper Red formations. Seismic data suggest that one of the structures comprises the south-verging Kuh-e--Gachab anticline cored by a complex array of thrusts and bounded by the north-dipping Kuh-e-Gachab thrust. The geometric arrangement of these thrusts forms a triangle zone within the Qom Formation dominated by limestones with higher density than the overlying deposits of the Upper Red Formation. An active-roof duplex comprising at least four duplicated south-directed thrust sheets formed above a blind thrust rooted in the Lower Red Formation. The duplex predated or was synchronous with the process of tectonic wedging, which resulted in the development of a backthrust rooted in the Qom Formation. During later layer-parallel shortening involving the triangle zone as a buttress transfer of shortening to the surface, ramping from a detachment horizon within the evaporates of the Upper Red Formation could be initiated. With continued shortening could be formed the out-of-sequence Kuh-e--Gachab thrust propagating through the younger deposits of the Upper Red Formation up to the surface, followed by the Kuh-e-Gachab anticline as a fault-bend fold. According to this interpretation, formation of the triangle zone could predate folding and thrusting in the Upper Red Formation. During the deformation process, two salt evaporate levels played a significant role as detachment horizons. The main detachment horizon was rooted within the Lower Red Formation, whereas the second detachment horizon was localized along the evaporates belonging to the Upper Red Formation strata. Internal geometry of the Kuh-e-Gachab anticline varies considerably along--strike. The size of the triangle zone decreases to the east. Variations in the style of deformation between the size-reduced triangle zone in the western part of the Kuh--e-Gachab structure contrast with smaller shortening

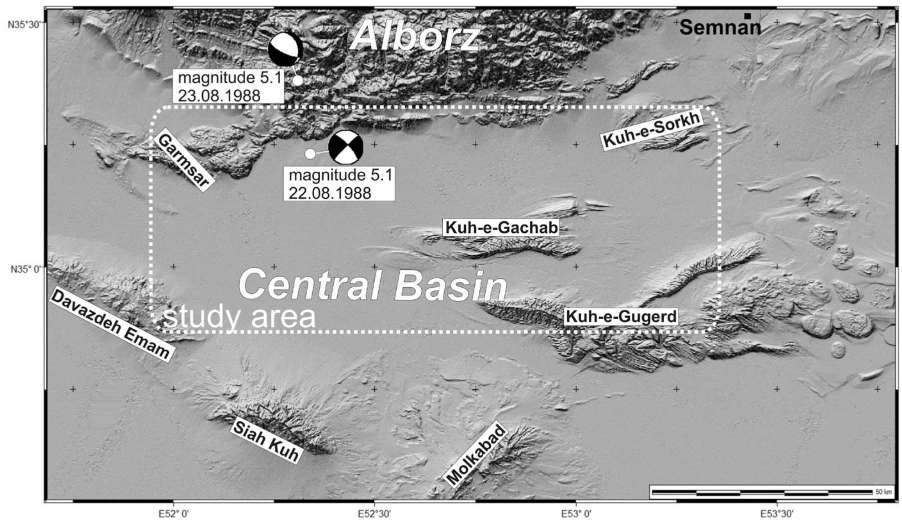

Fig. 1. Location of the thin-skinned Garmsar, Kuh-e-Gachab and Kuh--e-Gugerd structures with CMT focal mechanisms in the north-eastern arm of the Central Basin draped over a shaded-relief SRTM image. Focal mechanisms are taken from the Harvard CMT database.

in the eastern part. Variations of the thin-skinned structural style suggest that thrusting prevailing in the western part was controlled by the occurrence of a thinner detachment layer comprising evaporates contrary to the eastern part, where a few dozens of salt diapirs occur within the Kuh-e--Gugerd structure, suggesting increasing thickness of the mobile detachment horizon. Contractional deformations are still active south of the Alborz Mountains, which is confirmed by the present-day seismicity observed e.g. in the Garmsar structure where focal mechanisms show sinistral movement and oblique thrusting. Contraction is also suggested by GPS data displaying that present-day shortening in the Central Basin south of the Alborz fold--and-thrust belt is ~3 mm/year (Vernant et al., 2004).

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Appearance and characteristics of the Modra Massif sedimentary cover (Malé Karpaty Mts.)

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Sediments of the Tatric cover of the Modra Massif appear in the form of a narrow stripe surrounding the massif from SW to N, to NE direction. They consist of Upper Permian Devín Formation deposited on the Upper Paleozoic Tatric metasediments and followed by Lower Triassic Lúžňa Formation and the Middle Triassic carbonate complex. The whole sedimentary cover is weakly metamorphosed with predominant dip direction of beds towards the NW. The fracture zones have mostly N–S direction with the eastern dip. From the tectonic viewpoint, the cover units of the Modra Massif were folded into a system of dipping or horizontal folds with the SE vergency, laterally sinking in the SW direction. The folds have round anticline closures filled with basement rocks, and tight to pinching out synclines from which the Middle Triassic carbonates were pushed out.

Position of the Grybów nappe in the Polish Outer Carpathians

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Key words: Oligocene, Grybów nappe, duplex, tectonic windows, Western Carpathians

In the Polish sector of the Magura nappe eleven tectonic windows were recognized. These windows belong to the Grybów nappe of the Fore-Magura group of units. This group of units, occupied the intermediate position between the Silesian and Magura nappes and contains transitional lithofacies, which linked the Silesian and Magura Basins (Książkiewicz, 1977; Oszczypko-Clowes and Oszczypko, 2004, 2011). The Grybów nappe has been found also, beneath the Magura nappe, in several boreholes. The most southern occurrences of this unit are limited by following boreholes: Oravska-Polhora 1 (Orava, Slovakia), Obidowa IG-1, Czarny Potok 1 near Krynica. In the following tectonic windows (Mszana Dolna, Szczawa, Grybów, Ropa and Świątkowa Wielka) in Poland we found the Oligocene strata belonging to the Sub-Grybów Beds, Grybów Marl Formation (GMF) and Krosno Beds. All these strata occur above the Sub-Menilite Globigerina Marls. The lower part of the Grybów succession, belonging to the Sub-Grybów Beds, is dominated by non-calcareous grey and greenish mudstones and shales, with packets of the black and brown Menilite-type shales. The most typical deposits of the tectonic windows belong to the GMF. This formation is composed of the dark grey, black and dark brown muddy marls. In the lower part of the formation the marls with intercalations of thin- to medium-bedded turbidite sandstones are present, while the upper part is dominated by thick-massive marl and thick-bedded Cergowa-type sandstones. Subordinately, this formation contains lenses or beds of the ferruginous dolomitic limestones. In the Szczawa, Grybów and Ropa tectonic windows the thickness of the formation is up 200 m, while in the Swiątkowa Wielka and Smilno tectonic windows (Nemčok et al., 1990) the thickness oscillated around 100 m. The lower boundary of the formation is transitional, while the upper boundary is represented by a horizon of hornstones. The upper part of the succession is occupied by shaly facies of the Krosno Beds at least 100 m thick. The Grybów succession correlates well with the succession of the Smilno tectonic window in Eastern Slovakia (Nemčok, 1990; Kováčik et al., 2011). The Rupelian sequences of the Grybów succession were deposited during the TA4 supercycle, resulting in a gradual rise of the relative sea level. The overthrusting of the Magura nappe over the Grybów succession was probably realized under the submarine condition (Oszczypko-Clowes and Oszczypko, 2004) and caused the appearance of an over pressure and development of zone of the tectono-sedimentary breccias along the contact between the Magura, Grybów and the Dukla nappes. The successive Magura nappe overthrusting during the Middle Miocene against the Grybów and Dukla nappes was formed as a classical contraction inter-thrust duplex between the Magura and Dukla nappes (Mastella and Rubinkiewicz, 1998). The post nappe collapse of the Magura nappe was accompanied by the development of the normal transversal faults.

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AMS Fabric differences in relation to ramp within Ordovician rocks, Barrandian, Czech Republic

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The focus of this paper is the study of the anisotropy of magnetic susceptibility (AMS) in relation to a ramp fault. Field data and specimens were processed for AMS measuring and were archived. The principal directions of magnetic susceptibilities were measured by kappabridge. Magnetic fabrics in the majority of the Ordovician sediments are controlled mainly by paramagnetic minerals (Černý, 2010).

Ordovician sedimentary rocks are situated in central Bohemia specifically in the Prague Synform. The synform is situated between the cities of Prague and Pilsen. In-between was a locality with outcrop of an important ramp fault which is situated in the Zahořany Formation. The hanging-wall block as well as footwall were sampled in order to analyze the relationship of the principal directions of AMS to bedding and the ramp fault. The collected and evaluated samples from the hanging wall show a maximal susceptibility direction parallel to the dip of the bedding plane (Fig. 1). Results from the hanging wall were obtained from the samples which were collected in an extensional zone and maximum susceptibility direction may be interpreted as the direction of tectonic transport, e.g. in NW–SE direction, while data from the foot wall show a maximal susceptibility direction parallel to bedding strike (Fig. 1). Results from the foot wall were obtained from the samples which were collected in a compressional zone and therefore maximum susceptibility direction is perpendicular to the tectonic direction transport. As this ramp fault is situated in the Zahořany Fm., the main detachment must be situated in some lower formation. Melichar (2003) previously described a potential detachment horizon in the Ordovician rocks as either the Bohdalec or the Králův Dvůr formations but not any other detachment under the Zahořany Fm. In terms of clay particles amount, the best horizon for detachment is the Šárka Formation. If we consider amount of aleuritic particles in clay rocks, the best candidates are Libeň or Dobrotivá Formation and in case of disintegration the layer with best potential is the Letná Formation. This means that there were four possible candidates for a detachment horizon. Further studies will be focused on finding of main detachment bellow Zahořany Formation especially.

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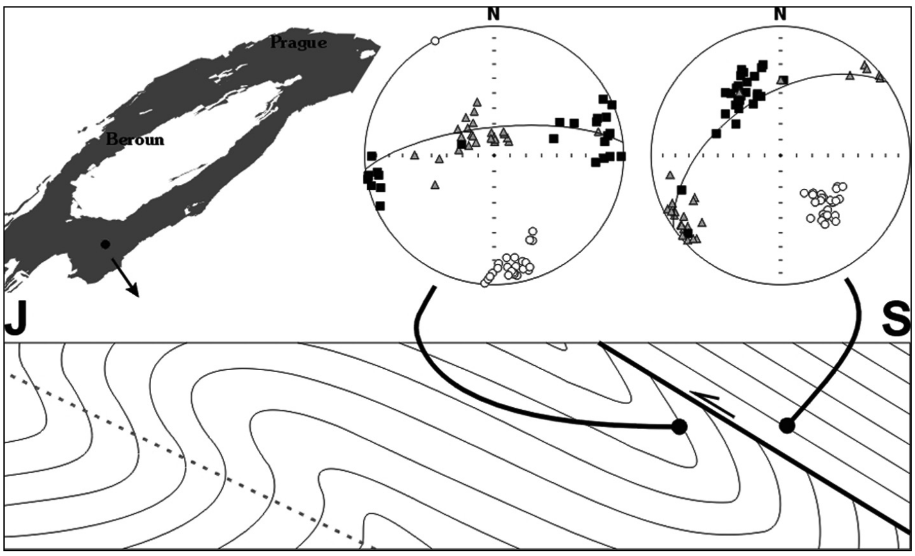

Fig. 1. AMS fabrics in the hanging and foot walls of the ramp fault, 1 km to NW from Skřípel village, for explanation see text.

Eo-Alpine metamorphism and the "mid-Miocene thermal event" in the Branisko Mts. (Western Carpathians, Slovakia) as revealed by multi-system low-temperature thermochronology

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A number of fundamental questions regarding the Carpathian orogenesis, such as timing and grade of metamorphism, thermal histories of crystalline and sedimentary rocks, or the timing and nature of exhumation processes, remain open or controversial due to a lack of empirical data and the sparse geological record. In this study we apply a combination of zircon (U-Th)/He (ZHe), apatite fission track (AFT) and apatite (U-Th)/He (AHe) dating methods to constrain the metamorphic and exhumation history of the Tatric part of the Branisko Mts. in the Western Carpathians.

Latest Cretaceous-Eocene ZHe ages from the basement samples prove that the basement was heated to temperatures between ~180 and 250 °C and did experience a very low-grade to low-grade Alpine metamorphic overprint. The ZHe ages are interpreted as cooling ages recording the exhumation of the Branisko Mts. basement related to the extensional collapse of the Carpathian orogenic wedge after the mid-Cretaceous (Eo-Alpine) collision and thrusting. Miocene AFT and AHe ages found in the basement and in the Paleogene sediments conclusively demonstrate that the Branisko Mts. experienced a "mid-Miocene thermal event". This event had a regional character and was related to magmatic and/or burial heating. According to AFT, AHe and thermal modelling results, the sediments of the Central Carpathian Paleogene Basin and the basement were heated to ~120–130 °C and ~110–190 °C, respectively, during "mid-Miocene thermal event". Final exhumation of the Branisko Mts. occurred in the Early-Late Miocene according to the thermal modelling. This conclusion is in good agreement with the sedimentary record in the adjacent Eastern Slovakian Basin and fits well with the general exhumation pattern of crystalline bodies in the Western Carpathians with well-defined spatial AFT age patterns. However, the exhumation is not directly corroborated by the evidence from the geological record. Detecting the mid-Miocene thermal event in the Western Carpathians by AFT and AHe systems has proved to be a viable tool for reconstructing the original extent of Neogene sediments with application to paleogeographical reconstructions. Further details of this study can be found in Danišík et al. (2012).

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The genesis of the Kurišková U-Mo ore deposit

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Regarding the *regional geology,* the U-Mo ores of Kurišková deposit, which is a well-known uranium deposit in Slovakia, are placed within the Huty Volcanogenic Complex of the Lower Permian age. It belongs to the Petrova hora Formation and tectonically corresponds to the Permian in the North-Gemeric zone of the Western Carpathians.

Lithologically, the Huty Volcanogenic Complex (HVC) is built up by the volcanic rocks of bimodal basalt-rhyolite association, intercalated with sandstones, mudstones and claystones. Compositionally, the basic volcanic rocks represent the primitive undifferentiated subalkaline basalts and basaltic andesites. They are a product of effusive and explosive eruptions, linked to the geodynamic setting of a convergent plate margin.

The *chemistry of acid volcanics* shows dacitic and rhyolitic peraluminous composition of a high potassium magma differentiation series. Both extrusive and explosive types were identified in the HVC. Based on the sedimentary facies reconstruction, it is supposed that the sandstone and siltstone sheets alternating with mudstones and claystones represent sediments of seasonally flooded shallow lakes. The paleoenvironmental conditions of this sedimentary association are assumed to be those of a continental fluvial plain facies. There is a transition to estuaries and shallow marine facies of continental shelf in the upper part of HVC (as evidenced by the presence of phosphate nodules and evaporites).

The thermal history of *metamorphic overprint* was reconstructed on the basis of clay mineralogy, using X-ray powder diffraction methods. It reveals peak condition of 350 °C ($2M_1$ illite/muscovite) of epizonal regional metamorphism, followed by exhumation to conditions of ~200 °C (1M illite, mixed-layered illite-smectite). The temperature decrease and resetting of previous higher thermal conditions have occurred during tectonic uplift of buried HVC along with the hydrothermal alteration by permeating hot water (≤200 °C).

Concerning *the space relationship of U-Mo mineralization and host rock,* the main ore forming minerals are uraninite, coffinite and molybdenite. They occur in various metasedimentary and metavolcanic rock types of HVC, especially on the contact with the surface of basaltic body. Mineralization is disseminated along sedimentary structures and tectonically driven fractures in both main rock types. In many cases, contemporaneous deformation of uranium mineralization, together with the straight deposition of a new uranium ores is present. Some of the molybdenite-rich subvertical faults are likely to be the remnants of the original primary structures transporting mineralized waters into the deposit space.

Geochemistry of U-Mo deposit shows special ratio of $Th/U << 1$ which is a significant deviation from the average Th/U 2–3 for rhyolite rocks as proposed by Nash et al. (2010). Other important geochemical data show strong correlation between U, P ($r > 0.9$) and Pb and only weak correlation with Mo ($r \leq 0.6$). This suggests common geochemical history of U-P-Pb and separation of U-Mo during deposit forming processes.

Ages of U-Mo deposit: The geochronological dating, using Th-Pb electron microprobe method applied robustly to uraninite crystals, provided ages of the main ore forming processes within interval of 200–160 Ma. Surprisingly, this corresponds to the Triassic/Jurassic boundary, which coincides with significant climate change from arid to humid conditions. Consequent uranium remobilization and ore maturation is dated to 150–50 Ma and 40–10 Ma. However, these modification processes were active only within limited scale.

Origin of the Kurišková U-Mo ore deposit: The deposit consists of three ore bodies of a tabular shape. The main ore body is spatially closely linked to mylonitized metabasalt on the contact with sediments. This situation suggests a role of mechanical and geochemical barrier as a key factor for U-Mo precipitation in tectonic and lithological structures.

The presented genetic model operates with a series of step--by-step leaching and precipitation processes which resulted to the present-day appearance of the deposit. About 200 Ma ago, percolating ground waters had invaded into the uppermost parts of buried HTC and started to leach U-Mo out of rhyolitic rocks of the upper Grúň Rhyolite Complex. In the deeper parts of the rock complex, the uranium bearing waters interacted with evaporite and phosphorite bearing beds. Such interaction integrated the U-P-Pb-Mo-S geochemical streams, changed water composition ($pH < 4–5$; $Eh > 0$), thus enabling transport of $UO_2(H_2PO_4)_2^0$ or $UO_2HPO_4^0$ complexes. As water stream proceeded through subvertical fault aqueduct, continual reduction responded to molybdenite precipitation and separation of Mo-S/U-P-Pb streams. The main stage of the ore precipitation is related to alteration of infiltrated metamorphosed rocks synchronically with continual deformation of HVC. The reduction and increasing pH during alteration destabilized the dissolved U-Mo complexes and initiated the uraninite – coffinite precipitation.

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Migration of paleo- and recent fluids in the Podlesí granite, Krušné hory Mts., Czech Republic: Fractures, fluid inclusion planes, open microcracks

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Mesoscopic fractures, fluid inclusion planes and open microcracks were studied in rocks of the Podlesí granite stock to characterize the fractured aquifer and its associated fossil and recent fluids. The Podlesí granite stock is located in the western part of the Krušné hory Mts. in northwestern Bohemia. It represents the most fractionated part of the late Variscan Nejdek-Eibenstock pluton in the Saxothuringian zone of the Variscan orogen in Central Europe (Breiter, 2002). The granitic body intruded into the Ordovician phyllites and the biotite granite of the "younger intrusive complex". The Podlesí granite stock consists mainly of albite-protolithionite-topaz granite (stock granite). In the uppermost part, the stock granite is penetrated by several flat-lying dykes of albite-zinnwaldite-topaz granite (dyke granite).

The combination of well logging methods for borehole PTP-3 enabled the study of the orientation and distribution of various geological phenomena, such as the depth, dip, and strike of fractures, rock boundaries etc. (Maros et al., 2002). The fracture frequency, which was found to be 3.04 fractures per meter in the borehole, is very low. Altogether 877 open or closed fractures were identified in the PTP-3 borehole to the depth of 348 m. The fractures are predominantly oblique to subhorizontal with NW–SE strike with and dip to the NE, or of NNE–SSW strike and dipping both to the NW and SE. Steep fractures strike mainly NW–SE and NE–SW. Moreover, two theoretical paleostress orientations were determined with the main stress orientations to the NE–SW and NW–SE (Maros et al., 2002).

A part of the core of stock and biotite granite was oriented using geophysical methods and ImaGeo mobile corescanner to geographical axis. The microstructural phenomena were studied in horizontal and vertical sections.

Fluid inclusion planes (FIP) result from the healing of former opened cracks and therefore appear to be fossilized fluid pathways (Lespinasse, 1999). FIP are non-penetrative cracks interpreted as extensional cracks, which formed subparallel to the average strike of σ_1 (Segall, 1984). Fluid inclusions in FIP are clearly secondary in relation to the host mineral.

FIP of oriented samples of the PTP-3 borehole have mostly intragranular character. They were reliably identified only in quartz and topaz. The lengths of the FIP range from 0.1 mm to 3.2 mm. The number of FIP in quartz is estimated to be 140 FIP/cm^2. Most of FIP are steep, FIP of N–S strikes predominate, however orthogonally striking steep FIP seem to be distinct: NNE–SSW and WNW–ESE. Subhorizontal and moderately dipping FIP seem to be less frequent. Only about 10 % of FIP dips at angles lower than 60°. Two generations of water-rich fluid inclusions were found in FIP: (1) vapour-rich (V > L) fluid inclusions with homogenization temperatures from 350 to 430 °C, and (2) liquid-vapour inclusions with homogenization temperatures between 140 and 270 °C. The salinity of fluid inclusions did not exceed 10 wt.% NaCl equiv. (Dobeš, 2005).

Microcracks, i.e. intercrystalline cracks, grain boundary cracks, and intracrystalline cracks in quartz, topaz, feldspar and mica can characterize the microporosity network of infiltration of fluids in the non-fractured volume of granitic body (Schild et al., 2001). Preliminary study of microcracks in quartz and topaz showed that microcracks had both intragranular, and intergranular character. The length of microcracks range from 0.1 mm to 4.2 mm, the number of microcracks is about 70 MC/cm^2. The strike of microcracks is variable, but orthogonally striking N–S and E–W microcracks seem to predominate. The range of dip angle ranged mostly between 70 and 90°.

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Revised stress field evolution of the northern and south-western Pannonian basin from the Mesozoic to Quaternary

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Fault-slip data and stress field analysis represent tools that have been applied since the mid-eighties in the Pannonian Basin, following the pioneer work of Bergerat et al. (1984). Since then a great number of data have been accumulated. In this contribution I present the state-of-the art of this data set and touch some geodynamic conclusions.

Jurassic of the Transdanubian Range (TR) was marked by NNE–SSW extension (D1 phase), which was connected to the opening of the Alpine Tethys (195–142 Ma). N–S to ENE–WSW compression or strike-slip stress field dominated the northern part of the TR, and determined the clastic sedimentation during the early Cretaceous (D2 phase, 142–108 Ma). The TR was folded, imbricated during several episodes of roughly NW–SE compression during the prolonged Albian-Coniacian D3 phase (110 to 87 Ma). This contractional deformation was related to nappe emplacement of the TR as the highest nappe in the Alpine edifice. The Senonian D4 stress field is still enigmatic and probably represents a NE–SW extension. The next D5 phase, an ENE–WSW compression and perpendicular extension has uncertain age (65?–46? Ma), but reactivated E–W sinistral faults in the TR and probably also in the wider area.

The D6 mid-Eocene to early Oligocene stress field had transpressional character with WNW–ESE compression. Syn-sedimentary deformation is connected to the formation of the Paleogene basins. The newly recognized mid-Oligocene D7 phase is connected to the major subsidence in the North Hungarian Paleogene Basin. It is also the time span when Periadriatic magmatism was active along the newly formed Periadriatic-mid-Hungarian shear zone. The Early Miocene (23–19 Ma) could be the classical time of extrusion tectonics of the Alcapa unit during the D8 phase.

The D9 rifting phase of the Pannonian Basin was punctuated by vertical-axis rotations, long time recognized by Márton and Fodor (1995). The first rotation was probably preceded by an early ~N–S extensional event (19–18.5 Ma). This temporal relationship may suggest extensional character for rotational deformation. Major syn-rift extension resulted in the exhumation of mid-crustal rock units in the Tauern window and along the western and southern boundary of the Pannonian basin (Rechnitz window, the Pohorje massif and several metamorphic complexes in the Sava zone Usztasewski et al., 2010). ~E–W extension continued during the late Mid-Miocene (ca. 14–12 Ma). This D10 phase and resulted in major basin subsidence in the NE Pannonian Basin. Extensional direction might have changed from ENE–WSW to ESE–WNW from west to east. Transpressional to strike-slip type stress field dominated the western Pannonian Basin and in the Easternmost Alps, and resulted in variable inversion of some basins. Compression axis of this short D11 phase (12?–11? Ma) changed from N–S to ENE–WSW from west to east. Extensional deformation was re-established in the Late Miocene and locally also in the Early Pliocene (D12 phase). E–W to SE–NW extension represents a deformation superimposed on the regional thermal post-rift subsidence. The D13 neotectonic phase of the Pannonian basin is characterized by temporal and spatial transition from extensional to compressional stress field. The earliest inversion structures occurred at ~8 Ma (Uhrin et al., 2009), but transtension seems to persist up to 4 Ma in the central, up to recent times in the eastern basin segment.

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New occurrence of Záskalie Breccia in Orava part of Pieniny Klippen Belt: Preliminary results

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The Záskalie Breccia represents synorogenic sediments of Campanian to Maastrichtian age in the Pieniny Klippen Belt (PKB). Their presence in the Orava part of PKB was until now restricted to only two outcrops (right cut bank of the Orava river near Záskalie; bank of the Orava river on the opposite side of the Kňažia village). New occurrences of the Záskalie Breccia can be added to the list of these localities in the number of two outcrops. They are situated in the northern part of the village of Beňová Lehota, on the banks of the Lehotský stream. First outcrop consists of monomict breccia with clasts of light grey marls and marlstones, which on the southern part shift to unbrecciated spotty grey limestones. Another outcrop represents approximately 100 metres long section with dip orientation 60° to the NWW. The section starts in the red marlstones, which later alternate with polymict conglomerates to breccias, followed by the grey marly limestones, monomict breccia and once again marly limestones. The succession then continues with red marlstones which later pass into the light grey fine-grained sandstones with bioglyphs. The last bed is represented by the light grey limestones characteristic with the light ochreous to white patina. The bioglyphs indicate that the section is in reverse position. In addition, 5 metres below the section, the outcrop in claystones to sandstones emerges. Coarsening of the clasts is towards the north (upwards to the marlstone beds). These flysch-like beds were also determined to be in reverse position, which indicates that they possibly represent a continuation of the profile. In previous studies, there were various opinions on the origin and stratigraphy of the Záskalie Breccia. Polymict conglomerates, present in the middle of the succession in Marschalko et al. (1979), led to suggestions about the genesis of the Záskalie Beds. They considered it either synsedimentary, or, more preferred, they considered the conglomerates as a huge olistolith generated tectonically and later redeposited by gravitational sliding. As a lateral equivalent of the Záskalie Breccia in the eastern part of PKB, the Gregorianka Breccias were described by Nemčok et al. (1989). The microfacies analysis of clasts and matrix show that the Gregorianka Breccia is younger than Upper Cretaceous and the authors assume the beds as Paleogene in age. Findings of clasts (olistoliths) of larger size (3–5 meters), together with microclastic material, may signify deposition by gravitational transport. During field works in the Orava region, the olistoliths of such size were also found around mentioned sections of the Záskalie Breccia. This may indicate that the breccias are of tectonic origin, resulting from the shortening of the sedimentation space of the PKB during the Laramian phase, when PKB collided with the Central Western Carpathians and the sedimentary sequences were thrusted. If such origin will be proved, it will be one of the rare sedimentary evidences of the Laramian composition in the PKB. Therefore further structural, lithological and biostratigraphical analysis of new outcrops and surrounding beds may bring data which will help to elucidate the genesis of Záskalie Breccia and provide a more accurate view on the evolution of the sedimentary area of the Pieniny Klippen Belt in the Upper Cretaceous.

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Tectonics of the axial zone of the Podhale synclinorium in Spiš (Slovakia)

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The Podhale synclinorium extends from Orava in the west to Spiš in the east. It is an asymmetric structure built of flysch-like deposits belonging to the Central Carpathian Palaeogene Basin. Several longitudinal tectonic zones were distinguished in the Podhale synclinorium, including the axial zone in its central part (Pepol, 1972; Mastella, 1975).

The aim of the research was to describe the geological setting of the eastern part of the axial zone, recognize its geometry, and reconstruct the structural evolution by the structural analysis. The field-study was conducted directly in the axial zone and adjacent areas. The lower Zakopane Beds (Huty Fm. sensu Gross et al., 1984) and Chochołów Beds (Zuberec Fm.; op cit.) reaching a total thickness of 1 195 m were mapped in the area.

The W–E-trending axial zone is characterized by the high variety of bedding orientations and the occurrence of numerous folds. The width of the axial zone changes from 1.3 km in the west to 2.25 km in the east of the study area. The axis orientation was estimated, based on bedding orientation in both limbs of the synclinorium as 89/2 in the western part and 272/2 in the eastern part. Generalized axis orientation indicates the existence of a small depression in the study area, which is also confirmed by the orientation of mesofold axes.

Upright, gentle, parallel folds were mainly observed in the study area. The fold axes are W–E-oriented, shallow--dipping eastwards in the western part and shallow-dipping westwards in the eastern part.

The axial zone is cut by oblique NNW–SSE and SW–NE faults and parallel W–E faults. The orientation of oblique faults is similar to the orientation of the diagonal joint system.

The joint pattern in the study area is typical of the entire Podhale synclinorium (Boretti-Onyszkiewicz, 1968a, b; Mastella, 1972; Ludwiniak, 2010) and consists of a diagonal joint system (DR and DL sets), as well as longitudinal (L, L', L") and transversal (T) joint sets.

The axial zone developed as a result of folding in the inner hinge during the formation of the Podhale synclinorium, under N–S compression. Oblique faults probably arose in two stages, as the strike-slip, *en-echelon* faults, rejuvenated as normal faults during the uplift of the Podhale flysch. Longitudinal faults developed under N–S extension are the youngest.

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Basement of the Carpathian foredeep at Pilzno (SE Poland) in seismic data

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The basement of the Miocene Carpathian foredeep basin near the town of Pilzno is represented by the Permo--Mesozoic sedimentary cover of the post-Variscan platform. 3D seismic data acquired in this area make possible a reliable interpretation to be done down to the base of the Jurassic carbonate platform. Deeper reflectors are rather chaotic and difficult for interpretation. The Upper Jurassic carbonate sequence is covered by Cretaceous sediments, both dipping to the SE at low angles. The combined thickness of these two units varies from ca 700 to 1 100 m, with reduced values occurring in the NW part of the area, where a structural high appears below the Jurassic sedimentary strata.

Three seismic facies can be identified within the Jurassic carbonate sequence. From the bottom to top these are: (1) lowermost (Lower Oxfordian) strata parallel to the top of the underlying basement, (2) onlapping facies, presumably related to a lower sea level, (3) uppermost sequence with downlap and toplap base and top contacts, respectively. These facies changes may have been due to a syndepositional activity of the structural high.

The Mesozoic succession is dissected by several NW–SE-striking, mostly normal, SW-throwing faults, defining a system of horsts and grabens. Antithetic faults occur both in their hangingwalls and footwalls. Throws on the major faults reach up to 100 m. Most of the faults reach the base of overlying Miocene sediments at their tops and they do not continue upwards into the fill of the Carpathian foredeep.

In the southern part of the area, where Cretaceous to Paleogene flysch successions of the Outer Carpathians and folded Miocene sediments of the Carpathian foredeep margin are thrust upon undisturbed foredeep strata, the seismic features are of low quality, which precludes their reliable structural interpretation. In this area the reflectors in the foredeep's basement are deflected into an anticline which can be interpreted as a potential hydrocarbon trap. However, in the present author's interpretation, this feature is an artefact (pull up effect) caused by a salt pillow localized right above the "antiform". The salt increases the velocity of seismic waves in relation to that in the surrounding rocks. The presence of this feature allows us to trace the lateral extent of a tectonically thickened salt horizon. The seismic interpretation carried by the author has not confirmed the occurrence of reefs, which are common in adjacent areas within the Jurassic carbonate sequence.

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Residence of elements in minerals of a single granite sample (Říčany granite, Variscan Central Bohemian Plutonic Complex)

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A single large (~30 kg) sample of coarse grained, weakly porphyritic biotite (–muscovite) Říčany granite (Central Bohemian Plutonic Complex) was studied in terms of petrography and mineral chemistry, combining electron-microprobe, *in situ* LA ICP-MS and ICP-MS analyses of dissolved mineral separates. This information was used to assess the distribution of individual elements among the main-rock forming minerals and accessories, with general consequences for petrogenesis of the granite and availability of selected geochemical species during the hypergene processes.

The commonly used approaches to modal analysis (point counting, image analysis of a stained polished rock slab, XRD, Granite Mesonorm and least-squares method) were first tested on the major elements, Rb, Sr and Ba, all hosted by the main rock-forming minerals. The best estimate yielded the constrained least-squares method, as implemented in the *GCDkit* (www.gdckit.org). Following the subtraction of the elements' inventory stored by the main rock-forming minerals, the modal percentages of accessories were obtained by least-squares fit using selected trace elements.

The final balance and relative contributions of individual phases was visualized by the "balloon plot" (see examples in Fig. 1). Among major elements, Si is shared almost equally by Qtz, Kfs, and Pl, most Al is bound in feldspars (Pl > Kfs), Pl is the main sink for Ca and Na, and Kfs for K. Bulk of the mafic cations Ti, Fe and Mg resides in Bt. Rutile takes 20 wt.% of TiO_2 and Ap 86 % of the P_2O_5.

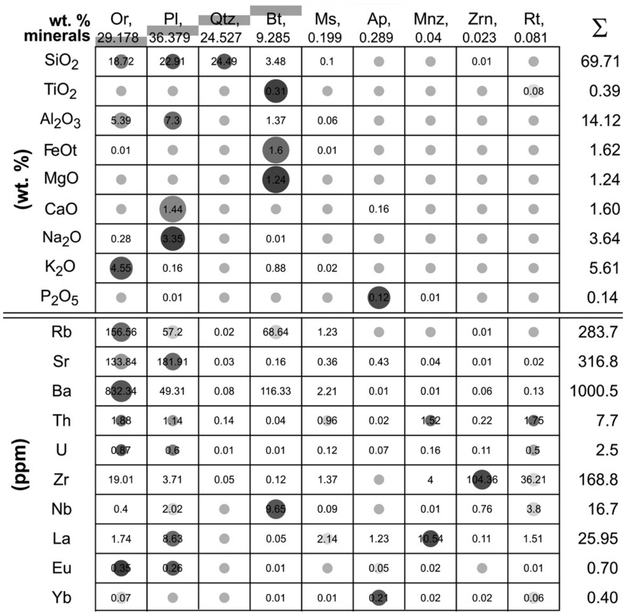

Fig. 1. The "balloon plot" (of R-language package *gplots*) giving the balance of selected elements in the studied Říčany granite sample (concentration in the mineral × its modal abundance). The relative contributions of individual phases are expressed by the size of circles; top row gives the "best" modal analysis obtained by the least-squares technique.

Over a half of the Rb is hosted by Kfs and a quarter by Bt; Sr is distributed mostly between the feldspars but the Kfs represents a key host for Ba. Most Be is concentrated in Pl and Pb is hosted by feldspars (Kfs > Pl). The four accessories, Ap, Mnz, Zrn and Rt incorporate more than half of the LREE and over three-quarters of HREE, Y, Zr and Hf. They also represent important reservoirs for Th, U, Ti, Ni, Co, Nb and Ta. Some 60 % of the Nb and Ta budget are stored in Bt, probably as submicroscopic inclusions. The feldspars seem to incorporate most of U. For Th, almost equally significant are Kfs, Mnz and Rt and, less so, Pl and Ms. Minerals such as Zrn and Ap play only marginal role in hosting the radioactive elements. On the other hand, important seems the newly recognized, REE-, Th and U-rich zircon-like ABO_4 phase, the complete chemistry and modal abundances of which could not have been determined, though.

In Říčany, 83 % of the whole-rock Zr and Hf and *c.* 10–30 % of HREE, U, Th, Nb, Ta, Ti, Cd, Co and Ni are contained in resistant accessory phases Zrn and Rt. Thus the pressure bomb or sample fusion – and not merely a combined acid attack – are vital were these elements to be determined quantitatively.

A great deal of essential structural components (P, Zr, LREE) used in Ap, Zrn and Mnz saturation thermometry is incorporated into other minerals and this leads to overestimation of the liquidus temperatures. In the present case, the saturation temperatures for Zrn are *c.* 40 °C (5.1 %) and for Mnz *c.* 70 °C (9.6 %) higher. This effect is negligible for Ap, and there the more important become analytical errors as the isotherms of the saturation model rapidly converge for felsic compositions.

The study demonstrates that for modal analyses of coarse--grained or porphyritic granites, the most appropriate are chemistry--based approaches, especially those taking into account the true mineral chemistries (e.g., linear programming and constrained least squares). They represent a large volume of the sample and thus (i) smooth out any local variations caused e.g. by the small-scale crystal accumulation, (ii) account for the presence of phenocrysts, and (iii) eliminate the effects of fabric.

The current research confirms the notion that the accessory phases play a key role in controlling the behaviour of many trace elements during the differentiation of felsic granitic systems by processes such as partial melting or fractional crystallization. Especially the REE seem of little value in petrogenetic modelling of felsic igneous suites, unless the role of accessories is properly assessed and saturation models for apatite, zircon, monazite and rutile are carefully considered.

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Inverse ductile thinning and fold-induced doming in the West Carpathian Cretaceous collisional wedge

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Continental core complexes are generally interpreted as a result of extensional doming due to gravity driven up-flow of lower crust. However, the Vepor Dome is characterized by the lack of inverted density profile and relatively low metamorphic field gradient which precludes activation of Rayleigh-Taylor instability. Instead, the crustal structure of the Vepor Unit is marked by the presence of dense and weak metapelites in the deeper part of the crust and the presence of light and more competent quartz-feldspatic gneisses and granitoids within the upper crust. This structure is believed to be inherited from Variscan nappe tectonics. We show that the Cretaceous tectonic evolution of the Vepor Dome is controlled by the dynamics of two mechanically strong continental blocks represented by the overthrusting supra-crustal Gemer Unit from the south and the underthrusting Fatric basement from the north. Based on structural, metamorphic and geochronological data, the following tectonic scenario is proposed: (1) The Early Cretaceous northward propagating crustal thickening caused by an internal deformation of the Gemer Unit together with upper crustal folding within the Vepor Unit led to the progressive development of an orogenic front parallel pressure gradient. The instantaneous response of the lower crustal and low viscosity metapelites led to the development of a lateral lower crustal flow accompanied by a prograde Barrovian type metamorphism called here inverse ductile thinning. (2) As the southward underthrusting of the Fatric basement propagated to greater depths, these generally top-driven processes switched to bottom-driven. Consequently, an exhumation of lower crust occurred via a polyharmonic folding associated with doming and vertical extrusion. This process was accompanied by the upper crustal detachment faulting and eastward unroofing of the Vepor dome.

Paleostress analysis of NE part of the Brno Massif: Another piece of puzzle

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The Brno Massif is a composite unit built up mainly by igneous rocks of Cadomian age, which belongs to the Brunovistulian Unit, situated on the eastern margin of the Bohemian Massif. The Brno Massif consists of two granodiorite parts separated by the Metabasite zone, composed of metamorphic rocks (mainly green schists). In the west, the Brunovistulicum borders with the Moldanubian Unit, which is thrust over it along so-called Moldanubian thrust. This area was tectonically affected during Variscan orogeny, inducing the Moravo-Silezian shear zone with dextral kinematics in SSW–NNE direction. Nevertheless, some observations are in contrast with this dominant top-to-the NNE sense of movement.

In 1983 and 1991, the first discrepancy with general dextral movements within the Brno Massif was published by Hrouda et al. and Hrouda. Based on petrophysical data, the sinistral strike-slip movements was predicted in the Metabasite zone. This predication was subsequently confirmed by porphyroclast systems with sinistral shear sense, observed by Hanžl (1996).

Another example of untypical kinematics was described by Roupec (1992) in a limestone quarry near Lelekovice village, where tectonic contact of the Metabasite zone rocks and the Devonian limestones crops out. The limestone bears NW-dipping stretching lineation with top-to-the SE (sinistral) movement. This kinematics indicates NW–SE orientation of the main principal stress σ_1 (maximal compression).

Equivalent tectonic movement was presented by Bábek et al. (1995) on asymmetric structures surrounding the Visean limestone pebbles in calcareous sandstones quarries near Černá Hora village. Furthermore, Melichar et al. (1999) described intensively deformed granodiorite with incorporated slices of Devonian limestone in an outcrop near the Valchov village. The older kinematics of this restrained limestone was top-to-the SE, whereas younger one indicated top-to-the NNE sense of movements.

New method of paleostress analysis (Kernstocková and Melichar, 2011; Melichar and Kernstocková, 2011) was used to determine stress state in the north-eastern part of the Brno Massif. Data from several outcrops along the Svitava river was processed by a computer programme MARK 2010 (Kernstocková, 2011). There occurred predominantly reverse or strike-slip faults, which were filled or altered with older chlorite, epidote and younger hematite or calcite. The main principal stress σ_1 (maximal compression) was oriented in SE quadrant of equal-area plots, and principal stress σ_3 (relative extension) was oriented in SW quadrant of equal-area plots. These results are compatible with the above mentioned anomalous movements.

All this evidence probably suggest some old Variscan tectonic events. Lower limit of the age determination is induced by limestone biostratigraphy which is even post--Givetian if Visean (post V2a). On the other hand, these events must be older than the Moldanubian thrust which is indicated by the Valchov outcrop. The succession of mineral alteration indicates cooling process corresponding probably with the orogeny evolution. Unfortunately, interpretation of these results is not clear enough. Some pieces of eastern margin of Bohemian Massif puzzle are still missing.

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The large Variscan strike-slip fault between Kozičín and Řitka villages, Barrandian, Bohemian Massif

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The Clay and the Závist faults were described as two different structures. Both these faults are steeply dipping and striking in SW–NE direction. As both faults have reverse dip--slip component but opposite dip direction, it seemed evident that they are really two different faults.

The Clay fault was recognized in mines of the Příbram and Bohutín ore districts and named by ancient miners. The dip varies from 70° to NW in the SW part at the Kozičín surroundings to nearly vertical in the NE part at the Pičín area (Havlíček, 1973). Havlíček (1981) classified this structure as an overturned synsedimentary normal fault. He deduced the Cambrian age of the fault base on his geological map, where the Lower Paleozoic basalt dike cross-cuts the fault surface. The SW end of the fault is marked by the downthrown SE block with the Lower Paleozoic sediments ("Rožmitál Islet"), which is rimmed by the tonalitic intrusion (Blatná type).

The Závist fault was described by Kettner (1911). The main SW part of the fault steeply dips to the SE in the Řitka surroundings. Near Kamýk in Prague, the fault surface splits into two branches. The first one turns to the WSW–ENE direction and dips slightly to the SSE making typical thrust, the second one continues to the NE, e.g. in the same direction as the main part, and after 2.5 km turns in the same way as the first branch.

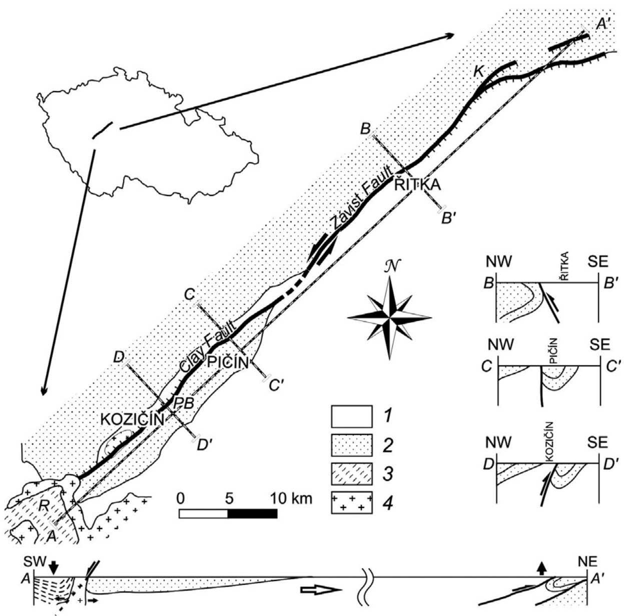

Fig. 1. Schematic map and cross-sections of the Clay fault and Závist fault. 1 – Proterozoic; 2 – Lower Paleozoic; 3 – Rožmitál Islet; 4 – Tonalite; R – Rožmitál town; PB – Příbram town; K – Kamýk.

Havlíček´s idea assuming Cambrian age of the Clay fault was tested with new geophysical data, showing the basaltic dike cut by this fault (Šešulka et al., 2011) and therefore the Clay fault should be younger. We can associate origin of the fault with intrusion of the Blatná tonalite, age of which is 346 ± 10 Ma (Holub et al., 1997). The Lower Carboniferous age of the Závist fault was accepted by all authors without any doubt, as the Lower Paleozoic sediments are overthrusted by Proterozoic rocks along this fault.

Both of the studied faults are terminated by the compensation structures, which indicate their sense of movement. The extensional post-sedimentary pull-apart depression of the Rožmitál Islet and intrusion of the Blatná tonalite at the SW end of the Clay fault indicate sinistral strike-slip movement, which is accompanied by the dip-slip component indicating uplift of the NW bock. Small thrusts at the NE end of the Závist fault indicate the same sinistral sense associated with upthrown SE block. This means, that both faults have the same sense of movement, the other dip-slip components can be explained by the influence of vertical movements, produced by considered compensational structures.

Based on these arguments, it is evident that both faults are only parts of one sinistral strike-slip fault originated during the Lower Carboniferous. The fault length is over 60 km. It starts near Rožmitál town, then runs through Kozičín, Pičín and Řitka villages and ends in the SE margin of Prague.

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Analysis of 3D structures in GIS

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Geographic Information System (GIS) is a very useful and proven tool in the construction of geological maps produced by geological mapping. Others specialized maps such as uncovered or tectonic map are derived from geological units in the map and from database storing data collected during this process of geological mapping.

For geologists the set of structural data measured in the field is a way how to see under the mapped surface. Structural data are stored in the GIS database. It contains coordinates of stations, type and orientation of tectonic features represented by dip and dip direction. Other information relating the lithology could be included.

Common software for orientation analysis of tectonic features works out of the GIS environment. Showing only the angle relationships and missing spatial context form limits of this method. One can not distinguish if points in the plot lie near each other forming a belt of shear zone or if there is no mutual interconnection.

Prototypes of tools, that were developed for the ArcGIS Desktop (ESRI) software, frequently used in geological mapping, are presented. These tools allow us to analyse structural data with respect to their position in the geological map. All tools are grouped into a toolbox "Orientation analysis", that can be added to the map application and allow the user to plot selected data into diagrams, construct contour diagrams, count spatial averages and construct appropriate maps. The selection is made by spatial query (e.g. select structures that lie in the particular geological unit or near a significant fault) and/or by an attribute selection such as type of structure.

The processing result provides the data of vectorial type. It enables us to select these data in the plot and link them back to the map. All information from the attribute table are preserved which allows us to symbolize them as desired.

Combination of GIS tools and the tools of orientation analysis presented above can bring a considerable profit in tectonic and geological maps construction.

Tools are tested using data from the Strážek Moldanubicum and Svratka crystalline unit region in the Rožná surrounding.

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Genesis of the Gemeric granites in the light of isotope geochemistry: Separated facts from myth

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The basement of the Gemeric Superunit is composed of Early Palaeozoic (Cambrian to Late Carboniferous) rocks, mostly low-grade flyschoid metasediments and metavolcanics, with remnants of an ophiolite complex metamorphosed under high-grade conditions. This volcano-sedimentary sequence was intruded by small granite apophyses derived from a huge underlying post--orogenic granite body 50 km long and 15 km wide, known from geophysics in the Upper Permian. Granitic rocks of the Gemeric unit are commonly referred as Gemeric granites. Several petrographic types of granite are distinguished. A coarse-grained and/or porphyritic biotite granite variety occurs in the deeper part, whereas the medium-grained muscovite-biotite granite and fine-grained two-mica granite, often greisenized, are found in the upper part of body. Geochemically, the Gemeric granites are unique in comparison to the other Western Carpathians Hercynian granitic rocks. Their overall characteristics place them among specialized tin-bearing granites. They have elevated SiO_2 values (73–78 wt.%), a strongly peraluminous character (Shand's index – A/CNK = 1.2–1.6), high concentrations of F, B, Rb, Li, Cs, Sn, Mo, Be and low concentrations of Sr, Ba, Zr and V (Uher and Broska, 1996; Petrík and Kohút, 1997; Broska and Uher, 2001, and citations therein).

The genesis and source of the Gemeric granites were discussed many times (e.g. Cambel and Petrík, 1982; Kráľ, 1994; Petrík and Kohút, 1997; Kohút et al., 1999, 2001; Gaab et al., 2005; Jiang et al., 2008; Magna et al., 2010). Cambel and Petrík (1982) postulated their S-type affinity and origin from mature crustal material. According to Kráľ (1994) the Gemeric granites were generated from one source with high Rb/Sr and wide I_{Sr} ratios 0.707–0.732; representing disturbed Rb-Sr system, which was reopened during the Alpine time (250–145 Ma). Petrík and Kohút (1997) supposed dehydration melting of a quartz- and muscovite-rich precursor from matured, recycled sedimentary supracrustal rocks, such as quartz--muscovite pelitic schist as a source of Gemeric granites. Negative $\varepsilon_{Nd(i)} = -4.6$ and elevated stable isotopes values $\delta^{18}O_{(VSMOW)} = 10.0 \sim 10.4$ ‰, $\delta^{34}S_{(CDT)} = 4.48$ ‰, indicate a mature continental metasedimentary feldspar and muscovite-rich protolith according Kohút et al. (1999, 2001; Kohút and Recio, 2002). Lead isotopic data from Gaab et al. (2005) e.g. high $^{206}Pb/^{204}Pb$ ratios (above 18.6) and similarly high $^{207}Pb/^{204}Pb$ ratios (above 15.7) suggest for melting of metasedimentary protolith, being typical for collision granites. However, fluids played a major role in the development of the Gemeric apophyses according Gaab et al. (l. c.) as WR–Pb–Pb data suggest for reopening of system between 250–231 Ma. Tourmaline $\delta^{11}B_{(TO\text{-}1)}$ values varying between –10.3 and –14.2 ‰ are partly overlying with those from their host rocks (–11.4 ~ 17.1 ‰). These tourmalines likely formed from crustal magmatic–hydrothermal fluids related to the Hnilec granites and/or from the late stage metamorphic–hydrothermal fluids (Jiang et al., 2008). The modest variability with restricted range of $\delta^{7}Li_{(L\text{-}SVEC)} = -0.4 \sim +1.2$ values common in pelites, points to a metapelitic parentage (Magna et al., 2010) for the Gemeric granites. Presented data suggest for their evolved crustal origin in general.

However, check of primary Sr isotopic data reveals, that not all I_{Sr} are extremely radiogenic. Similarly, new Nd isotopic results with $\varepsilon_{Nd(i)} = -0.3 \sim -4.0$ and $T^{Nd}_{DM} = 1.30 \sim 1.01$ Ga indicate that these data are analogous to common I/S-type granitoid of the Tatric Unit. Hafnium isotopes (Kohút, 2011) measured close to zircon SHRIMP spots denoted as $\varepsilon_{Hf(t)}$ form distinct intervals with following values: –5.35 ~ –0.75 (–2.47 ± 1.6; mean ± standard deviation). Hafnium model ages (T^{Hf}_{DM}) of the studied zircons provided following age spectra: 1 258 ~ 1 004 Ma (1 098 ± 87 Ma). These characteristics are comparable to identical ones from common I/S-type granitic rocks from the Tatric and Veporic superunits of the Western Carpathians. Taking in account the results from all isotopic systems (Sr, Nd, Pb, Hf, O, S, Be, Li) it is suggested that the Gemeric granites were melted from crustal sources of reworked Pan-African basement remnants, that experienced sea--floor weathering, were permeated by volcanic (boron) emanations and finally were modified by ore bearing fluids.

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Geochemical and geochronological arguments for heterogeneous nature and complex development of Variscan lower continental crust: Náměšť Granulite Massif (Bohemian Massif, Czech Republic)

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Felsic kyanite–garnet–ternary feldspar granulites bearing volumetrically minor, but petrogenetically important, "orogenic peridotite" fragments (garnet or spinel peridotite, pyroxenite and associated eclogite), represent a rock assemblage typical of the high-grade orogenic root of the European Variscan Belt (Gföhl Unit in the Moldanubian Zone). Understanding the tectonic and metamorphic history of these lower crustal complexes is crucial for correct interpretation of the Variscan continental collision.

In our study, whole-rock geochemical analyses were obtained for all three main lithologies of the Náměšť Granulite Massif (NGM) in the eastern part of the Gföhl Unit, namely (i) felsic Ky–Grt granulite, (ii) Spl- and Grt-bearing peridotite and (iii) Grt amphibolite enveloping the NGM. The remarkably uniform geochemical signature of the Náměšť felsic granulite displays the same compositional characteristics as other granulite massifs throughout the Moldanubian Zone. The NGM metabasite envelope corresponds to E-MORB or Within Plate Tholeiite resembling occurrences of Late Cambrian to Early Ordovician age at the eastern margin of the Bohemian Massif. The Mohelno peridotite is interpreted as a harzburgite of asthenospheric origin, only later refertilized.

The precise *in situ* (SHRIMP) U–Pb zircon dating of the felsic granulite yielded two distinct peaks in metamorphic ages, at ~353 and ~339 Ma, interpreted as timing the HP metamorphic peak and partial melting during the early stages of uplift, respectively. The Early Devonian protolith ages (~400 Ma), obtained for the Náměšť granulite, differ from ~450 Ma protoliths for other granulite bodies from the Moldanubian Zone and Saxon Granulite Massif.

The current work shows that the three studied lithologies could not have originated in a single geodynamic environment. The felsic granulites represent a subducted Early Devonian continental crust, while the tholeiitic metabasites were probably generated during Cambro–Ordovician rifting. Based on these characteristics and contrasting P–T data we adopt here a model of lower crustal relamination of the low-density continental crust below autochthonous dense mafic root of the Moldanubian Continent. The difference in HP metamorphic ages between the Náměšť granulite (~353 Ma) and the more westerly granulite massifs (~340 Ma) is interpreted in terms of diachronous emplacement and different time scale of thermal maturation of western and eastern portions of the relaminated crust. Our work also shows that the mantle was refertilized before its incorporation into the crust, a feature typical of asthenospheric mantle below slow spreading rifts. Therefore, it is very likely that the Late Devonian history recorded in the mantle fragment (constrained by the Sm–Nd age of ~370 Ma: Medaris et al., 2006) reflects heterogeneous nature of the local subcontinental mantle lithosphere related to the Devonian rifting (most likely in the back-arc position with respect to the Saxothuringian subduction) unrelated to the surrounding felsic granulites. The place of incorporation of the mantle fragment to felsic granulite is impossible to determine, but the Late Devonian age coincides well with the onset of the magmatic-arc related plutonic activity in the Teplá–Barrandian Unit (Štěnovice and Čistá plutons, as well as protolith to orthogneisses in the roof pendants of the Central Bohemian Plutonic Complex; Žák et al., 2011). In conclusion, the Mohelno peridotite represents an autochthonous heterogeneous lithospheric mantle fragment that was sampled by felsic (granulite) crust during relamination process. This mechanism can explain significant variations and P–T conditions of mantle material enclosed nowadays in individual granulite massifs of the Bohemian Massif.

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Tectono-sedimentary features of the southern margin of the Orava–Nowy Targ basin (Poland-Slovakia cross-border): Their possible relationship with the Late Cenozoic Western Carpathians evolution

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The Orava–Nowy Targ (O–NT) basin could be treated as a crucial block in the puzzle of the understanding of the Cenozoic history of the Western Carpathians area. This basin is one of few records of the tectono-sedimentary history that postdates the uplift and erosion of older structural units such as the Magura Unit, Pieniny Klippen Belt, Central Carpathian Paleogene and the Tatra block. Moreover, its sedimentological profile reflects geological events in the Podhale and Orava regions from the Middle Miocene until now.

The O–NT basin originated from the Middle Miocene as a tectonic depression overlying different Central and Outer Carpathians units. The subsidence trend is observed until present times, however tectonic inversion can also be found at the basin margins. The basin is considered as a pull--apart structure. Although some geophysical investigations have been done, the tectonic style of the basin is still not confirmed in details known.

During the sedimentary history, the O–NT basin was filled with thick series (more than 1.3 km in the central part) of diversified clastic deposits, from silts to gravels as well as with phytogenic deposits such as brown coals. The provenance of clastic deposits is considered to be mainly Magura and Podhale flysch units and less the Pieniny Klippen Belt and the Tatra Mts. The alteration grade of an autochthonic and detritic brown coal shows that the organic matter exposed now at the surface was buried at a depth of over 1 km. Moreover, the pyroclastic layers that are widespread in the basin can be used for dating and correlation.

Despite many years of basic geological, geomorphological and geophysical investigations the knowledge about the structure and evolution of the basin is still unsatisfactory. In last few years, good opportunity to expand studies on the basin infilling appeared due to strong erosion of Czarny Dunajec and Oravica rivers. In these rivers cuttings, long sections of unweathered Neogene deposits and their contact with the O–NT basin basement have been exposed.

Recent preliminary investigations revealed some aspects of basin evolution in the southern part of the O–NT basin. Fine clastic deposits were observed in the outcrop of Oravica river near Čimhová at the basin boundary with the Central Carpathian Paleogene flysch. Such deposits indicate the lake and alluvial plain environments with general direction of material transport to S–SW. Relatively high-degree coalification of brown coal suggests thick overburden. It seems that at the time of sedimentation there were no nearby high-relief areas and the O–NT basin spread more to the south. After long time of sedimentation there was an episode of uplifting and erosion of the basin rocks, probably related with an uplifting of Skorušina foothills. Deposits at the Oravica outcrop show no evidence of tectonic activity at the time of sedimentation. Thick coarse clastic layers are exposed at the Bystry and Cichy streams and the Domański Wierch hill. The clasts lithology points to the nearby source area but not from the Tatra block. A synsedimentary tectonic activity east to this area is probable and should be distinguished from the tectonic activity related with the Domański Wierch uplift.

For future studies it is essential to acquire additional data on the structural evolution of the O–NT basin based on sedimentological and geochemical studies. Because the basin infill is mostly clastic, it shows what rocks were weathered and eroded in the region during the time of sedimentation. Size of clasts could indicate distance from source rocks as well as the intensity of weathering. Freshwater lake and river sediments show dynamics of environment thus allowing to interpret the terrain paleomorphology. Diagenesis of wide-spread brown coals and sediment compaction, supplemented by apatite fission-track method indicate depth/temperature of burial and can suggest time and conditions of uplifting of basin infill.

Fault rocks of the Jelešňa fault zone (Central Carpathian Paleogene Basin, SE Orava, Slovakia)

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The study is focused on mesoscopic fault zones which form the Jelešňa fault zone. This app. 5.5 km long, NNW–SSE-trending zone cuts flysch-like rocks of the Subtatric Group (Gross et al., 1984) and extends from the Magura Witowska Mt. to the Hladovka village (Ludwiniak and Rybak-Ostrowska, 2010). The general course of the zone is rectilinear along this section and its northern part coincides with the lineament recognized by Struska (2009, Fig. 2 ibid.). The Jelešňa fault zone is predominantly recorded by apparent deviations of bedding orientation from the regional trend. In the close vicinity of the mesofaults, the bedding strikes are frequently subparallel to them; the bedding planes are steep, sometimes vertical or even overturned. The mesofaults observed in the outcrops are mostly parallel or subparallel to the course of the Jelešňa fault zone. Other mesofaults are sub-perpendicular or oblique to the general direction of this fault zone.

Field observations point that the Jelešňa fault zone does not seem to have affected the Neogene deposits of the Orava–Nowy Targ Basin that discordantly overlies the Paleogene rocks in the northern part of the study area. Along the northern prolongation of the Jelešňa zone, the offset segments of the gravilineament are located, being distinguished by Pomianowski (2003, Fig. 10 ibid.) within the southern margin of the Orava–Nowy Targ Basin. This offset probably corresponds to an oblique/transverse fault cutting the Orava–Nowy Targ Basin basement. It is described by Pomianowski (2003) as a dextral fault, although assessment of the character and magnitude of fault displacement requires further studies.

The mesoscopic fault zones have been investigated along natural outcrops whose lengths vary from 1 to several metres. Faults cut sandstones, siltstones and shales. The fault zones contain slices of fault rocks sub-divided by packages of undeformed host rocks. The fault rocks are breccias and cataclasites (according to Killick, 2003). The cataclasites are composed of fine-grained clayey matrix and macroscopically visible variably-sized porphyroclasts. Foliation in these rocks has a random fabric. The particular fault rocks differ in composition that corresponds to the rock from which they have been derived.

The mineralogical composition of the fault rocks was investigated with XRD techniques, with particular focus on clay mineralogy. The results indicate that the rocks are typically composed of smectites, illite, kaolinite, chlorites, quartz and minor amounts of calcite and feldspars. There are some areas characterized by the higher illite, kaolinite and chlorite contents. Variations in the clay mineralogy can be interpreted in terms of paleoenvironmental conditions. The increase in (kaolinite + illite) may correspond to tectonic events and/or climatic changes (Martinez Ruiz et al., 2001). Higher contents of feldspars and lower contents of calcite are observed with decreasing content of smectites. This suggests relatively short-distance transport of these minerals.

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Magnetic and geochemical constrains on alteration processes: An example from the Krudum granite body (KGB), western Bohemia

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The Krudum granite body (KGB) represents a reversely zoned pluton with the oldest, least fractionated biotite granite in the centre, surrounded to the NW by younger topaz-bearing, two-mica granite. The youngest, topaz–albite granite forms the outermost shell. From geochemical point of view, all these rock types are subaluminous to strongly peraluminous (leuco-) granites (A/CNK = 1.0–1.5), which form a compositional continuum.

The Vysoký Kámen Stock in the SE part of the KGB is formed by topaz–albite leucogranite and – together with alkali-feldspar syenite – it represents apical parts of a highly fractionated granite body, which crystallized from residual magmas oversaturated in respect to alkalis and fluorine (René, 1998; Breiter et al., 1999; Jarchovský, 2006).

The alteration of topaz-bearing granites was connected with a strong influx of volatile-rich fluids and opening of the geochemical system in general. In order to bring new insights into such a complex alteration process, we have conducted a detailed comparative study of rock physical properties on variously altered samples taken from the Vysoký Kámen Stock. The modelling included the evolution of rock physical properties (porosity, density), rock magnetic properties (magnetic susceptibility, magnetic minerals abundances, anisotropy of magnetic susceptibility) and whole-rock chemical composition (mobility of elements).

Two alteration processes related to chemically different fluids could be recognized at the Vysoký Kámen Stock, feldspathization and greisenization. The greisenization was caused by near-critical low-salinity aqueous fluids with low amounts of CO_2, CH_4, and N_2 (≤ 10 mol. % in total) at ~350–400 °C and 300–530 bar (Dolníček et al., 2012). The influx of these fluids led to enrichment in Sn, W, Al, Na, K, F, Rb, Cs, Sr, Nb and LREE. The other characteristic fluid-related feature is the occurrence of tetrad effect in chondrite-normalized REE patterns. Compared to leucogranite and alkali-feldspar syenite from the Vysoký Kámen Stock, the greisenized samples are also enriched in Fe, Mn, Co and Zn, i.e. elements triggering paramagnetism of minerals. During *feldspathization,* the fluid leached mainly Fe and Mn from the decomposed Li-micas (protolithionite and zinnwaldite) and produced muscovite in rock microstructure and quartz-hematite veins.

The magnetic susceptibility in the whole KGB is very low (median = 66.9^{-06} [SI]). The leucogranite and alkali-feldspar syenite from the Vysoký Kámen Stock shows even lower values of magnetic susceptibility (from -5^{-06} to 7^{-06} [SI]). Feldspathization did not change the magnetic susceptibility significantly, while the greisenization increased susceptibility up to 300^{-06} [SI]. The thermomagnetic curves have hyperbolic shapes characteristic of paramagnetic phases in paramagnetic samples including greisenized ones. With decreasing magnetic susceptibility, the thermomagnetic curves show mainly diamagnetic character. In contrast to evolution of the scalar magnitudes, the anisotropy of magnetic susceptibility keeps the consistent subhorizontal magnetic foliation with NE–SW trending horizontal lineations.

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Tectonics of the Trangoška syncline – preliminary results

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The Trangoška syncline (Kettner, 1927) belongs to the Tatricum crystalline unit of the Central Western Carpathians. It consists of autochthonous Mesozoic rocks, which have been preserved in a form of more-or-less upright, tight syncline. The direction of the syncline axis is roughly E–W. The sedimentary record started in Early Triassic with basal clastic rocks such as quartzite, arkose and "Werfenian" shale. These rocks are covered by limestone and dolomite. The Cave of the Dead Bats was formed in the Triassic limestone and/or dolomite during Tertiary by water flowing through the interlayer spaces and faults created earlier. Thanks to complex 3D pattern of its corridors, the cave is a perfect place for taking readings of linear and planar structures by geological compass.

The readings document the two slightly different systems of bedding planes (Fig. 1a), which are plotted in diagrams by their poles. The poles form two intersecting belts; the first one in NNW–SSE direction and the second one in NNE–SSW. These belts correspond to two systems of the fold axes in ENE–WSW and ESE–WNW directions, which were recognized by Nemčok (1989, see Fig. 1b). These data demonstrate the existence of at least two phases of folding and a fact that the whole Trangoška structure is a bit more complicated than a straight, upright, tight W–E syncline.

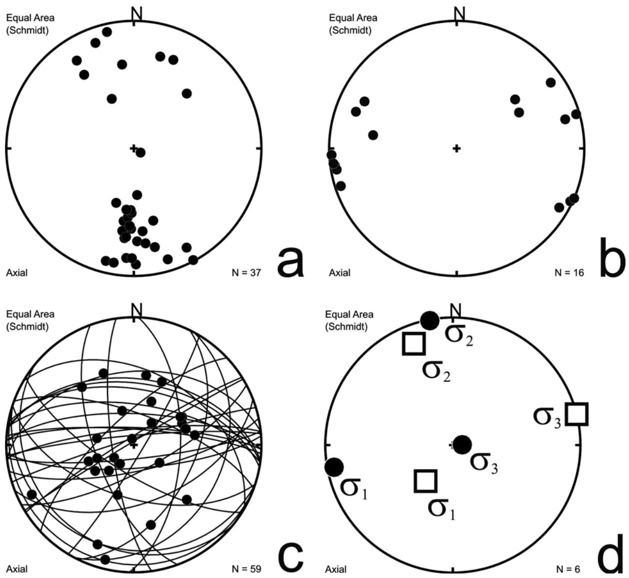

Fig. 1. Orientation of structural elements in the Trangoška syncline shown in Lambert equal-area projection, lower hemisphere. a – bedding; b – fold axes; c – fault surfaces and striae; d – principal stress directions.

The fault system consists of several fault sets. The dominant faults are parallel to bedding of the carbonates. Other faults are transversal, being either sub-horizontal or steep. Striae are usually close to dip line, thus, the majority of faults seems to be dip-slips (Fig. 1c). Two different striations on one fault surface indicate the activity of at least two subsequent stress fields, which formed and/or reactivated faults.

Described variable fault orientation was suitable for paleostress analysis, for which we used software Mark2006 by Kernstocková and Melichar (2011). Two different stress states were recognized. The dominant stress field is characterized by sub-vertical σ_3 (88/84) and subhorizontal σ_1 and σ_2 (259/6 and 349/1, see Fig. 1d – full circles). This field represents a reverse faulting regime with respect to Anderson's theory (e.g., characteristic by its shallow depth and the absence of subsequent rotation). Principal directions of subordinate stress fields include σ_1 = 217/61, σ_2 = 338/16 and σ_3 = 76/23 (Fig. 1d – squares). Oblique orientation of all principal stresses may indicate older age of these faults.

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Landforms and structural expression of the Muráň fault in the Levočské vrchy Mts. (Western Carpathians)

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The Muráň fault (MUF) trace is clearly visible only in the middle segment of the fault, where it creates distinct tectonic contact between contrasting Mesozoic sequences and the Veporic crystalline basement unit. The fault trace in lithologically monotonous Paleogene flysch terrane of the Levočské vrchy Mts. is difficult to determine for the lack of geological criteria. In geological maps, it uses to be only intuitively drawn as a directional continuation of confirmed middle fault segment. Nevertheless, the MUF trace is evident at the surface morphology along its whole length, even in the Central Carpathian Paleogene Basin (CCPB), in the Levočské vrchy Mts. (Fig. 1). It represents one of the most spectacular photolineaments in the visible spectrum as well as in Radar (ERS-2) images. To evaluate the nature of the geomorphological MUF-related phenomena, derived DEM maps were compiled. In directional continuation of the MUF trace to the CCPB, there is a system of parallel morpholineations genetically related to joint sets or faults with moderate normal block separation. They allowed increased rate of selective erosion within the MUF zone and affected also drainage network. The most prominent NE–SW morpholineations following the MUF strike represent positive morphostructure, the main mountain ridge line, which is followed by the water springs. It suggests that this structure is related to discontinuities open for the groundwater migration. As the youngest structures seem to be arc-shaped morpholineations. The huge circular structure is located just at the northern tip of the MUF trace, with the centre in the Plaveč village. Other ones are situated at the eastern wall of the fault, interpreted as boundary dislocations rimming gravitationally slided blocks. They could be genetically related to dynamics of the MUF zone. Field research focussed to analysis of structural phenomena related to fault trace was carried out. Only two fault-slip related paleostress events were resolved, the WNW–ENE extension and the NNE–SSW extension in the study area. Both events are recorded by populations of meso-scale slickensides and tension gashes, which correspond well with the map-scale fault network of the area. To confirm occurrence of the fault damage zone at the surface geological architecture, two geophysical profiles with electric resistivity profiling method (ER) across the expected MUF trace were done as well. The ER profiles show ca. 100 m wide anomalous zone of strongly decreased resistivity just at the expected MUF line course. The character of resistivity curves is typical for the damage zone of dislocations. Finally, it can be concluded that the MUF influences landforms, what refers to its neotectonic reactivation. Field structural data show extensional character of the MUF zone affecting the surface of the CCPB in the Levočské vrchy Mts. and no strike-slip or reverse-slip records were observed. Present--day activity of the studied Muráň fault segment is not probable, because the cluster of earthquake epicentres do not follow Muráň fault trace, but the Ružbachy fault, as well as the longitudinal river valley profiles analysis does not show any Quaternary reactivation of faults in the vicinity of MUF trace, at the eastern wall of the fault.

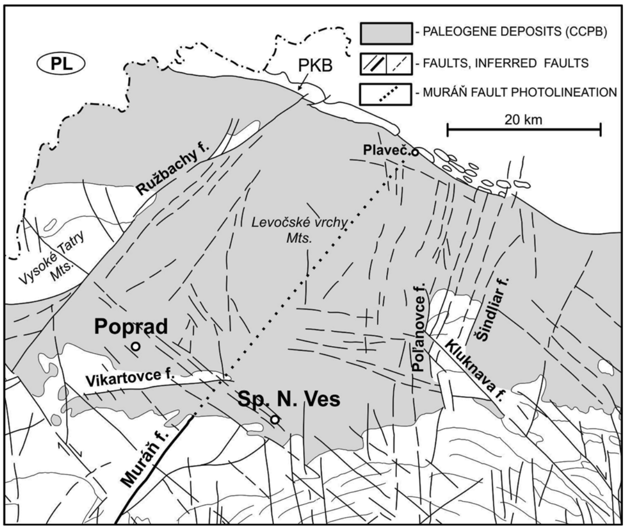

Fig. 1. Map-scale faults network of the area with indicated Muráň fault trace in the Central Carpathian Paleogene Basin.

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Paleomagnetic indication for possible CCW rotation of the Bohemian Massif with respect of the rest of stable Europe during Miocene

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The paper presents paleomagnetic results from the Bohemian Cretaceous basin (four localities, 48 independently oriented samples), from the Austrian part of the Molasse-Zone (Eggenburg area: six localities, 71 independently oriented samples), from the North Bohemian basin (Bilina open pit, 44, Bogatynia, 34 independently oriented samples) and the South Bohemian basin (one locality, eight independently oriented samples). The studied rocks from the first group are of Turonian-age, from the second and third of Early Miocene age, from the last, of Badenian age. Except one locality in the Eggenburg area, the samples are coming from clastic sediments, deposited in different environments (fully marine in the Turonian and fluviatile, deltaic, shallow lake during Miocene). We obtained the best results for the Turonian sediments, which exhibit an about 26° CCW rotation with respect to the expected stable European declination for this age. From the Eggenburg area four localities yielded statistically good paleomagnetic directions, but one of them is not acceptable for tectonic interpretation, since it was collected from a slump. The overall mean direction for the three localities exhibits CCW rotation, but the direction is poorly constrained statistically.

Of the several horizons sampled from the huge open pits of Bilina and Bogatynia, only eight had statistically well-defined paleomagnetic directions. The declination of the combined result from the two pits departs from the expected stable European declination by about 17° in the CCW sense. The single Badenian locality from the South Bohemian basin also shows westerly declination.

As the expected paleomagnetic direction in a stable European co-ordinate system for the Bohemian massif has practically the same inclination and similar declinations for the time represented by the above localities, an overall paleomagnetic direction was calculated for the whole data set, based on 18 locality/site mean directions. This has practically the same declination/inclination before and after applying corrections for local bedding tilts and the declination departs about 25° to the west from the European reference direction.

The above results will be discussed in the light of previous paleomagnetic data from the Bohemian Massif.

Paleomagnetism of the Late Cretaceous red marls from the Pieniny Klippen Belt: Tectonic implications

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We present paleomagnetic results from 14 geographically distributed localities in Late Cretaceous red marls along the Pieniny Klippen Belt (PKB), from Košariská, in the West and Skrabské, in the East. The localities were sampled either by the Polish–Hungarian or Slovak–Hungarian team. Most of the laboratory measurements and evaluations of samples from 12 localities were made in Budapest, but several samples/specimens were also processed in Warsaw, as a kind of inter-laboratory control. It proved the remarkable consistency of results obtained in different laboratories. One of the remaining two groups was entirely analysed in Warsaw, the other in Bratislava. As the main carrier of the remanent magnetization was hematite, the samples were thermally demagnetized stepwise up to 680 °C or sometimes even to 720 °C. Analysis of the demagnetization curves usually revealed an overprint component which had to be removed in order to obtain tectonically useful paleomagnetic signal (characteristic magnetization). This removal took place at minimum 350 °C, but more often at 450 °C or higher temperatures.

Fold/tilt test carried out on locality level, wherever it was applicable, proved that the characteristic magnetization was of post-folding age for two and of pre-folding age for five localities. Including the localities with monoclinal bedding dips (total of 11 localities) an overall-mean paleomagnetic direction was calculated before and after restoring the position of the strata to horizontal level. This test proved the pre-folding age of the magnetization and suggested an about 50° CCW rotation of the PKB, as a whole relative to the present North. This is in harmony with earlier measured tectonic rotations on the Central and Outer Western Carpathian flysch of Oligocene age (Márton et al., 1999, 2009).

As the 11 locality mean paleomagnetic directions exhibit somewhat smeared distribution in declinations, a paleomagnetic oroclinal test was also carried out which proved to be negative. However, moderate correlation is observed between the general trend of the PKB and the paleomagnetic declinations when four localities with monoclinal steep dip or overturned strata are omitted. Thus, we can not exclude the possibility that the present shape of the PKB is partly due to oroclinal bending. In the context of the above cited Oligocene paleomagnetic results from the Central and Outer Western Carpathians, the age of the possible bending is constrained as of pre-Oligocene.

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Fault-related dawsonite veins from the Fore-Dukla thrust sheet (Outer Carpathians, Poland)

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Dawsonite ($NaAlCO_3(OH)_2$) veins have been investigated in the Tertiary flysch rocks of the Silesian nappe in the eastern part of the Polish Outer Carpathians. The veins have been observed in minor thrusts and faults associated with thrust zones in the Fore-Dukla thrust sheet (Opolski, 1930; Świdziński, 1958). The aim of the study is to present the characteristics of the dawsonite veins, establish the origin of dawsonite and draw conclusions on the process of vein formation. The origin of dawsonite was investigated using petrographic, microstructural and geochemical analyses.

Vein samples were taken from natural outcrops along the Jabłonka and Solinka streams. They were found in the Hierglyphic, Menilite, and Transition beds. Dawsonite veins occur on fault surfaces as single objects or in the form of a multilayered structure, and are arranged parallel to each other. In few places the dawsonite veins form thin fibrous covers on calcite. The observed dawsonite is fibrous, white in colour and with a silky gloss. All dawsonite fibres are subparallel to the vein boundaries. Cross-sections normal to the fibres show slightly curved or straight fibres in undeformed veins, or deformed dawsonite fibres and folded dawsonite veins.

X-ray diffraction study clearly identified the presence of dawsonite with small admixture of calcite and quartz. In the majority of the samples the dawsonite content is about 95 %.

Isotopic analysis of dawsonite shows high variability in the $\delta^{18}O$ values, from –7.06 to +4.15 ‰, and low variability in the $\delta^{13}C$ values, from –6.77 to –4.40 ‰. The $\delta^{18}O$ values reflect complex sources and/or processes responsible for the stable oxygen isotope ratios. In turn, the uniform range of $\delta^{13}C$ values suggests the same source of carbon: mantle-magmatic CO_2. Such $\delta^{13}C$ values are observed in the majority of Carpathian CO_2-rich mineral waters.

Deformed and folded dawsonite veins point to the early origin of dawsonite, prior to thrusting in the study area. The $\delta^{18}O$ composition shows that dawsonite could have crystallized from waters with isotopic characteristics of marine waters and provides further support for the early vein formation.

Veins with lack of deformation of the dawsonite fibres and the specific $\delta^{18}O$ composition allow to conclude that this generation of dawsonite was a late authigenic mineral and crystallized after thrusting of sediments in the study area.

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Polyphase structural and metamorphic evolution of Variscan superstructure, Teplá-Barrandian unit, Bohemian Massif

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The Teplá-Barrandian Unit (TBU) represents the largest relict of orogenic superstructure within Variscan Bohemian Massif characterized by common occurrence of well--preserved pre-Variscan and early-Variscan fabrics. It is mostly composed of medium to low-grade Neoproterozoic metasediments unconformably overlain by Paleozoic unmetamorphosed sequences and therefore it offers an excellent opportunity to study not only superposition of individual structures, but also their P-T evolution using thermodynamic modelling.

We present here the preliminary data collected along the Střela river profile, which exposes a continuous crustal section across the western margin of the TBU. We identified three distinct deformation stages and related fabrics, each characterized by systematic spatial variations of P-T conditions and structural styles.

The eastern part of the studied area is dominated by sub-horizontal metamorphic foliation (S_1) originated via complete transposition of original bedding and showing normal metamorphic zonation from very-low grade in upper part to at least garnet zone in structurally lower part. From the east to the west, the S_1 foliation is progressively reworked by north-south trending steep S_2 slaty cleavage formed by large-scale upright folding and transposition. The metamorphic conditions increase together with the degree of reworking from chlorite zone in the east to kyanite zone in the west. The structural style as well as prograde character of metamorphic evolution shows that major thickening of TBU occurred during D_2 deformation.

In contrast, the western part of the studied area is characterized by the dominance of S_2 fabrics, which are progressively transposed by tight to isoclinal folds F_3 accompanied with SE dipping axial plane cleavage S_3 towards contact with Mariánske Lázně complex (MLC). The S_3 cleavage is associated with significant vertical shortening and retrogression of S_2 metamorphic assemblages in sillimanite stability field. We interpret the S_3 fabrics as a result of activity of a large-scale detachment zone responsible for unroofing of the MLC.

The western part of the Pieniny Klippen Belt: An example of inclined transpression zone

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The Pieniny Klippen Belt (PKB) represents the recent surface contact between the Outer Western Carpathians (OWC) – Neoalpine accretionary wedge and the Central Western Carpathians (CWC) – the Paleoalpine nappe pile. During the Miocene collision of the European Platform and the CWC, the lithotectonic units of the OWC, PKB as well as the CWC have been integrated into the bivergent structure. The different tectonic position of PKB in this structure has been determined. In the northern part of the PKB (Varín-Orava segment), the rock sequences of the PKB and adjacent portion of the OWC were thrusted to the south. The elements of the CWC are strongly affected by the south vergent tectonics. The axis of the bivergent structure is situated externally from the recent position in this part of the PKB. Different situation is in the westernmost part of the PKB (Podbranč-Drietoma segment). The rocks sequences of the PKB, OWC and the part of the CWC units are altogether thrusted to the north. The axis of the bivergent structure here is situated internally from the recent position of the PKB.

The recorded structural data represent complex fold-and-thrust system with top to the S–SE as well as top to the N–NW thrusting related to reverse, normal and strike-slip displacements. The conspicuous feature of the deformation in the PKB units is a heterogeneous assemblage of recumbent, upright and high curvilinear folds. The resulting geometry and mutual relationship of the fault and fold structures indicate their origin under the inclined/triclinic transpression conditions. The process of inclined transpression can be defined in terms of simultaneous contraction with strike-slip and dip-slip shearing in an obliquely convergent thrust wedge. Origin and deformation of the PKB is a result of sinistral inclined transpression during the Early Miocene with continual attenuation of tectonic activity.

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3D recent geodynamics monitoring of the Western Carpathians

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The Slovak Republic covers a major part of the Western Carpathians. This region is well known by the occurrence of natural hazards like slope deformations (especially landslides), erosion, soil (loess) collapsibility, earthquakes, active faults and floods. Detection of very slow movements (displacements) along active faults needs a specific measurement or monitoring techniques. The TM-71 extensometer is a device capable to detect micro-displacements in three dimensions. It works on the principle of moire´s pattern (optical interference) which records displacement as a fringe pattern on superposed optical grids that are mechanically connected to opposite crack faces. Data are obtained in three Cartesian coordinates (x – across joint/crack enabling to measure compression or extension of a joint/crack width, y – horizontal (shear) displacement along crack and z – vertical (shear) displacement calculated from recorded interference patterns). This measuring device is very accurate (displacement up to ±0.01 mm, rotation up to ±0.01 $\pi/200$) and has been broadly and successfully applied in Slovakia since 2000. On the other hand, the first gauge has been monitoring since 1973 in the Malá Fatra Mts. Recent monitoring network of the TM-71 extensometers covers 28 devices installed at 25 locations (caves, tunnels, quarries). First three sites have been created in the frame of the COST Action 625 international project between 2000 and 2002. Installations at Vyhne and Banská Hodruša mining tunnels were covered by the international project CADSES INTERREG IIIB SISMA (2005–2006). Majority of the TM-71 crack-gauges was installed in collaboration with Czech partners from the Institute of Rock Structure and Mechanics (Academy of Sciences of Czech Republic, Prague) along active faults inside selected caves distributed all over the Slovak territory between 2004–2008 and 2010–2011. Western located devices (Malé Karpaty Mts.) are operated by Czech partners in the frame of EU TecNet project. Other monitoring sites are covered by national project entitled “Partial monitoring system of geological factors of Slovakia – Tectonic and seismic activity” which is managed by the ŠGÚDŠ and funded by the Ministry of the Environment of the Slovak Republic.

Long-term monitoring results from some TM-71 sites (Branisko highway tunnel – 2000, Demänová cave of Liberty – 2001, Ipeľ investigation tunnel – 2002, Banská Hodruša and Vyhne mining tunnels – 2005, Driny Cave – 2005) revealed the recent tectonic activity. Registered micro-displacements are in good coincidence with the recent stress axes determined by the structural, geodetical and geophysical methods.

Origin of curved traces of the regional thrusts and fault-related folds in the Polish Outer Carpathians in the light of analogue modelling

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Upper Jurassic to Lower Miocene rocks of the Polish Outer Carpathians (POC) were deformed into the pile of nappes, which are named, from S to N, the Magura, the Fore-Magura–Dukla Group, the Silesian, the Subsilesian and the Skole pile of nappes (Książkiewicz, 1977). In traditionally opinion, the POC belt was formed from hinterland to foreland during Oligocene and Miocene. In the thrust belts the most folds are generated by the thrust fault movement at depth (e.g. Groshong, 2007). The typical thrusts has the ramp-flat geometry (e.g. McClay, 1992; Groshong, 2007). There are three types of ramps according to their orientation with respect to the transport direction as follows: frontal ramps which are approximately perpendicular to the transport direction; lateral ramps approximately parallel and oblique ramps at an intermediate angle. The ramp-flat geometry is also characteristic for the thrust in the POC. Curvature of the contractional structures in map-view is one of the main features of the typical mountain belts. In the Western Outer Carpathians the major thrusts are also generally not linear. The traces of single, small thrusts are mostly convexly curved. The traces of large, south-dipping thrusts or regional fold axes have curvilinear or wavy outline. For example, the trace of the Brzanka-Liwocz-Podzamcze anticline axis in the Silesian nappe, in the eastern part of the POC shows the step-like outline.

In our experiments, we investigated the role of fault linkage in the process of thrust fault growth. All experiments were performed at the Laboratory of Analogue Modelling, in the Institute of Geological Sciences, Polish Academy of Sciences. During experiments the isolated single thrusts linked along-strike into a large, segmented thrust with a single, continuous fault trace. When these segments, small thrusts were aligned along more or less longitudinal line or slightly convex arc, the trace of such larger segmented thrust was mostly slightly convex towards the direction of tectonic transport. When the location of such segments was more chaotic, then the trace of the final thrust had the curvilinear or wavy outline. The shape of this outline depended on the kind of transfer faults (being lateral or oblique thrust) which connected the small thrust faults.

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Paleostress analysis in the Mokrá quarries (Moravosilezian Zone, Czech Republic): Two methods, one result

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Extensive research on paleostress analysis based on both, fault-slip data and calcite twinning, recently yielded software tools, based on theoretical framework built up during past several decades, to effectively reconstruct the stress-states: TwinCalc for calcite twining (Rez and Melichar, 2010) and MARK for fault-slip data (Kernstocková, 2011).

Calcite *e*-twinning has been used for stress inversion purposes since the 1950s, because it is the main deformation mechanism at low temperatures, low confining pressures and low finite strains (<400 °C, 8 %; e.g. De Bresser and Spiers, 1997). An *e*-plane twins only if the shear stress τ_i along the glide vector **g** exceeds τ_c, which has been proven independent from normal stress, strain rate and temperature and its magnitude is approximately 10 MPa (e.g. De Bresser and Spiers, 1997). The most common stress inversion technique based on calcite twinning is the Lacombe and Laurent method (e.g. Laurent et al., 1981), which is based on applying 500–1 000 randomly generated reduced stress tensors [**T**] on data and selecting the best-fit one using a penalization function f_L. Recently, Rez and Melichar (2010) suggested improvements of this method: a total search instead of a random one and use of a different penalization function (f_R), which provides sharper maxima and hence has a better resolution. Using both functions for cross-checking the results is of course strongly recommended.

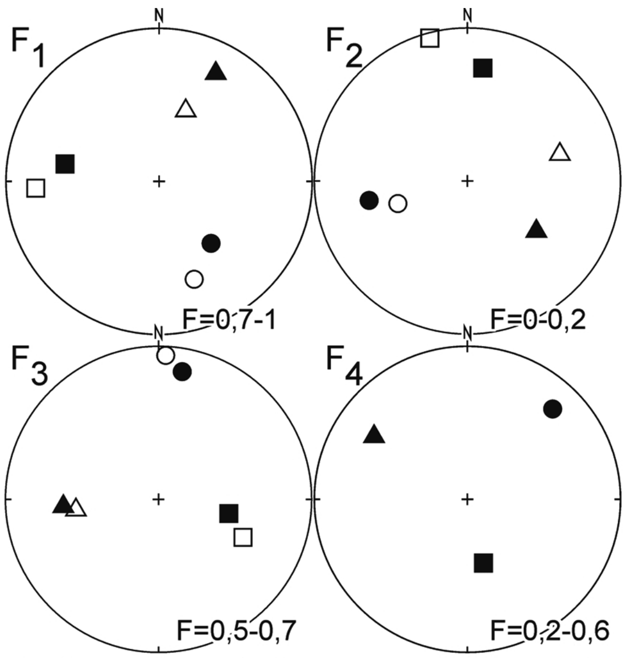

Fig. 1. Equal-area plots of stress phases recognized in the Mokrá quarries: black symbols using calcite twinning, white symbols using fault-slip data.

Stress inversion of fault-slip data underwent dramatic evolution during past several years (e.g. Kernstocková, 2011; Yamaji, 2000). Both most recent methods are based on multiple inversion of fault--slip data, which can be performed directly on heterogeneous data sets, thus eliminating data pre-sorting often introducing subjective view of the analysing geologist (even though the process should be supervised and the results thought about, otherwise one can get numerically correct solutions without any geological sense; e.g. Kernstocková and Melichar, 2010). The data is divided into fourths, each yielding a reduced stress tensor. Spurious solutions arising from fourths of faults of mixed up phases can be easily eliminated by "contouring" the results in 9D σ-space, because the solutions related to homogeneous phases tend to cluster. Each cluster represents a possible stress phase and can be used to separate data into homogeneous sets.

Four samples of calcite veins from the Mokrá quarries yielded several stress tensors (two samples four and two samples three stress tensors). 9D vectors of calculated stress tensors (for detail see Melichar and Kernstocková, 2010) cluster in 9D σ-space and thus define four stress states F_1–F_4 (black symbols in Fig. 1). The relative timing of these phases is uncertain, because despite of the asymmetry of Rose channels (crossings of twin lamellae), suggesting relative timing, no systematic relationship between phases has been found. Three deformation phases found by MARK 2010 using fault-slip data (white symbols in Fig. 1) nicely correspond to the ones found by TwinCalc. Direct evidence of relative timing was unfortunately not found, however, relationships of corresponding faults in the map scale suggest, that the F_2 phase is younger than F_3.

Despite this lack of time-relation data, excellent correlation of stress states estimated using two different techniques, based on fault-slip data and calcite twinning, validates the results and once again confirms calcite twinning as a useful stress inversion tool.

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The thermotectonic evolution of the Apuseni Mountains (Romania) based on structural and geothermochronological data

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The Apuseni Mountains in Romania take a central position in the Alpine Carpathian Dinaride system between the Pannonian basin in the West and the Transylvanian basin in the East. Following the final Mid-Cretaceous obduction of the East Vardar ophiolite a NW-vergent nappe stack formed, which involves from bottom to top: Tisza- (Bihor and Codru) and Dacia-derived (Biharia) units, overlain by the South Apuseni or Transylvanian ophiolite belt (see Schmid et al., 2008). This study tries to provide new and additional information on the complex structural and metamorphic evolution of these units, from the onset of obduction during Jurassic times, to the (final?) exhumation processes observed during the Eocene (according to Merten, 2011). Based on observed stretching lineation, kinematic indicators such as porphyroclasts, shearbands, etc., were analysed to establish a relative chronological order of deformation and tectonic transport. Two major tectonic events can be differentiated through structural mapping: the first one, represented by penetrative top to the NE structures in the Biharia unit, relates to the thrusting of Tisza over Dacia during the mid-Cretaceous ("Austrian Phase" in local nomenclature). These top to the NE oriented structures are overprinted at internal nappe contacts and at the contacts to Codru and Bihor units by a top to the NW event during the Turonian, which relates to the NW directed backthrusting of Dacia units over Tisza (see Fig. 1). Microstructural studies provide additional data on the relative succession of events and the relevant synkinematic temperatures. A thermochronological study, based on the integration of newly aquired Rb-Sr, Sm-Nd, Ar-Ar and fission track ages with existing data allowed to assign the structures to the tectonic events, as well as to refine the tectonic history of the involved units. The position of the Transsylvanian ophiolites tectonically overlying the Biharia unit, as well as distinct thermochronological data define the need of a Late Jurassic-Earliest Cretaceous exhumation event preceding the earlier mentioned events, but this cannot be directly constrained by structural data so far. Later events, such as the "Laramian Phase" and Palaeogene tectonics caused mainly brittle structures and their thermal imprint is rather scarce.

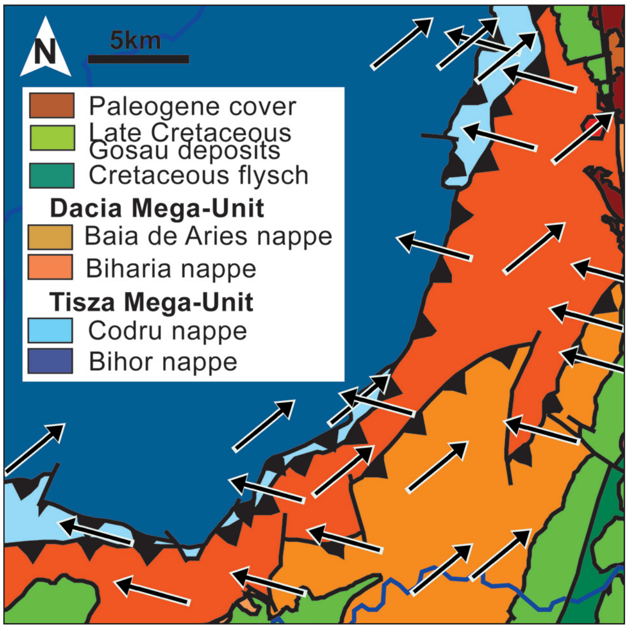

Fig. 1. Arrows show orientation of porphyroclasts. More internal parts of the nappes show the top to the NE orientation of the mid--Cretaceous "Austrian Phase" deformation, while the nappe contacts are overprinted by NW oriented Turonian deformation.

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Subsequent exhumation, burial and exhumation of the Tatra Mountains constrained by the low temperature thermochronology

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The Tatra Mountains form the highest peaks of the Carpathian mountain range in southern Poland and northern Slovakia. They are composed of a crystalline Variscan granite core and folded Mesozoic sedimentary cover, and are surrounded by slightly deformed sediments of the Central Carpathian Paleogene Basin (CCPB). In the north they are overlapped by transgressive Eocene conglomerates and carbonate deposits of the Podhale syncline – part of the CCPB. In the south they are separated from Eocene-Oligocene flysch strata of the Liptov Basin by the Sub-Tatra fault. The geometry and kinematics of the Sub-Tatra fault are still under debate. The deformation history of the Tatra block can be divided into the Late Cretaceous "Alpine" collision, a Paleogene burial under the CCPB forearc sediments and a Neogene exhumation and uplift. The amount of the pre-Eocene exhumation and timing of the Neogene emergence of the Tatra Mountains and its mechanisms are still poorly constrained.

Through the project IP7 of Thermo-Europe supported by the EUROCORES programme TOPO-EUROPE of the European Science Foundation we are performing the low temperature thermochronometry of apatite and zircon (AFT, AHe, ZHe) from the granite samples of the Tatra Mountains. We have sampled along sub-horizontal N–S profile through the High Tatras (including sub-vertical profile in the Czarny Staw area) as well as the E–W profile along the Sub-Tatra fault.

Apatite He ages from all samples (n = 14) are remarkably uniform with the average 14.5 ± 1.5 Ma. AFT ages range from 15 to 17 Ma in the north and 14 to 20 Ma in the south and along the Sub-Tatra fault. The AFT lengths are unimodal with a mean track length of 13–14 μm. The AHe and AFT data indicate a pulse of rapid, uniform exhumation of at least 3 km between ~18 and ~14 Ma, with exhumation of less than 2 km in the last ~10 Ma. Zircon He ages vary from 40 to 45 Ma in the north and core of the massif, to 21 ± 3 in the south close to the Sub-Tatra fault. This difference might reflect northward tilting or fault related folding of the High Tatras that caused exhumation of about 3 to 4 km along Sub-Tatra fault prior to more uniform exhumation revealed by AFT and AHe ages.

We conclude that the most significant episode of exhumation in the Tatra Mountains is non-rotational and is coeval with Miocene tectonic activity, expressed in folding and thrusting in the Outer Carpathians. After cessation of thrusting at the front of the orogen at ~11–12 Ma there has been no significant inversion of the Tatra Mountains. ZHe ages record post-Alpine exhumation prior to Eocene transgression of the CCPB on eroded and most probably strongly faulted Tatra block. The original thickness of Mesozoic nappes is estimated to be 5–7 km.

Recent tectonic movements recorded in the Bohemian Massif

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During the last 10 years, regular and long-term 3-D monitoring of the fault displacement has started in many parts of the Bohemian Massif and other parts of Europe (see www.tecnet.cz). Monitoring is organized preferentially under Earth's surface, inside the caves and galleries. It can reduce or eliminate displacement induced by climatic variation. From our long-term monitoring of displacement, it has been possible to recognize periods of increased geodynamic activity (Stemberk et al., 2010). The suitability of this monitoring technique for the observation of geodynamic activity was confirmed by other geophysical methods (Košťák et al., 2011).

Principal results of the monitoring of tectonic faults will be presented:

– The results exemplify successful monitoring of present tectonic micro-deformations on faults, which most experts considered impractical until recently.

– Results had evidenced deep tectonic processes of continental extent which culminated in particular earthquakes. Examples have been found in an extensive territory of Europe (Bohemian Massif; Western Carpathians, Rhine fault, Mediterranean – Central Apennines, Gulf of Corinth, and SW Bulgaria – Turkey).

– Recent records from a series of caves instrumented with 3D crack gauges TM71 displayed similarities in development which occurred irrespective of the position of caves in the structure of Bohemian Massif. A conclusion was drawn that registered displacements are very likely connected with significant changes in the recent configuration of tectonic stress field.

– Periods of relative tectonic stability, as well as of increased tectonic activity were identified. Records concern underground objects (caves, galleries, tunnels) or superficial objects (rock massifs, fault slopes, engineering structures).

– Results indicate interference of aseismic tectonic impulses into slope deformation processes in an extent more effective than anticipated before.

A complex tectonic monitoring network based on our original instrumentation was gradually put into operation in Bohemian Massif, now being implemented into the international geophysical monitoring system (TecNet as a part of the EPOS project). Moreover, monitoring bases were successfully established in a series of European, as well as non-European countries.

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An attempt at chronostratigraphic and maximum burial dating of bentonites within the Cretaceous/Paleogene sequence in the Outer Carpathians (Poland)

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In burial diagenetic settings, the mixed-layer illite-smectite (I/S) in non-contaminated bentonite is a product of progressive diagenesis. The grade of transformation from smectite to illite correlates with paleotemperature attained at maximum burial depth. In this context, the I/S is useful for dating of maximum burial. However, there are factors which can modify this simple relationship like, for instance, the local source of potassium and duration of burial.

Bentonitized tuffites occur at numerous sites within the sedimentary sequence in the Polish segment of the Outer Carpathians (Cieszkowski et al., 2006 and references therein). However, it follows from previous studies from this region, that only strata which underwent paleotemperatures >100 °C, may contain bentonites with diagenetic I/S convenient for K-Ar dating of maximum burial. Therefore, in present studies, sampling was restricted to regions where maximum paleotemperatures in claystones exceed 100 °C.

Bentonite samples were collected at 18 sites, mostly hitherto unreported ones. The sampled strata are from Cenomanian/Turonian up to Oligocene in age. Ten sites are located in the Magura nappe, 2 sites in the Dukla nappe and 6 sites in the Silesian nappe. The sampled bentonite layers are 1 cm to 1 m thick. At two sites, sampling was performed in hemipelagic sequences whereas at the remaining sites mudstone and claystone intercalations within turbidites were sampled.

Clay fraction (<0.2 micrometer) was analysed by X-ray diffraction (XRD) in all samples of betonites and adjoining claystones. The degree of smectite to illite transformation was determined and maximum paleotemperatures were calculated using grade of the transformation in claystones. Based on the results of XRD analysis, most of bentonite samples were excluded from further studies due to strong contamination by detrital illite. Therefore, K-Ar dating of I/S for maximum burial was carried out for three clay fractions (<0.02, 0.02–0.05 and 0.05–0.2) for only 8 samples of bentonites. The K-Ar dates for particular fractions for these particular samples show strong differentiation, except one Cretaceous sample from the Magura nappe. Only 3 bentonite samples do show maximum burial age younger than their stratigraphic age. These ages range from 22 to 48 Ma for the Eocene bentonite, 41–56 Ma for the Paleocene bentonite, and 43–44 Ma for the Cenomanian/Turonian bentonite, respectively. For determination of chronostratigraphic age of bentonites, U–Pb dating of zircons was performed using SHRIMP method for grains, separated from the oldest and youngest samples. The ages of analysed grains are significantly older than stratigraphic age of the host strata. The grains show mostly Paleozoic ages indicating contamination of bentonites. These results show that obtained maximum burial K-Ar ages of bentonites in both samples are too old. Summing up, bentonites within turbidite and hemipelagic sequences of the Outer Carpathians are: (i) mostly contaminated and, therefore, (ii) largely useless for K-Ar dating of I/S and U-Pb zircon dating.

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Quaternary exhumation of Western Carpathians: A record from Orava–Nowy Targ Intramontane Basin, Polish Galicia and Slovakia

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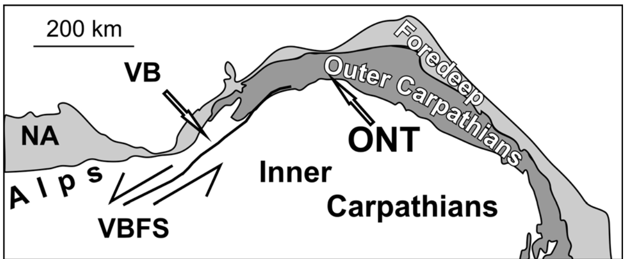
This paper discusses the results of studies of gravels comprised within Neogene and Quaternary fill of the Orava–Nowy Targ Intramontane Basin (ONT). The ONT is an important structure of the Western Carpathians. First, the ONT is the only basin, except the Vienna Basin, which straddles across the junction of the Inner and Outer Carpathians (Fig. 1). Therefore, the infill of the ONT records the behaviour of tectonic units of the Western Carpathians during regional collapse, which was the last stage of structural development of the Carpathians. Second, the ONT is located at the NE termination of the Mur-Žilina fault zone of prominent seismic activity (Lenhardt et al., 2007). The NE segment of the zone corresponds to the Vienna Basin Fault System, which had been locus of sinistral strike-slip since 17 Ma until 9–8 Ma, and again since the Middle Pleistocene times (Fodor, 1995; Decker et al., 2005). The activity of this fault zone has been essential for structural development of the Western Outer Carpathians and Carpathian Foredeep (Márton et al., 2011).



NA - North-Alpine Molasse Basin
ONT - Orava-Nowy Targ Intramontane Basin
VB - Vienna Basin
VBFS - Vienna Basin Fault System

Fig. 1. Position of the ONT within the Carpathian-Alpine orogenic system.

The infill of the ONT comprises two tiers showing contrasting lithology. The Neogene tier is largely composed of claystones and siltstones, whereas the Quaternary tier is dominated by gravels. The two sequences are separated by an erosional surface underlain by a regolith. Deposition of the Neogene sequence took place during subsidence of the basin. No prominent relief existed in the area of present-day mountains actually surrounding the basin at that time. The regolith started to form at the onset of basin inversion. Still, no prominent relief existed in the present-day mountains. The onset of deposition of Quaternary gravels in the basin corresponds to acceleration of uplift of the surrounding mountains, which has been continuing until now. The Pieniny Klippen Belt has been subjected to erosion, at least locally, since the deposition of the basal part of the Neogene sequence filling of the Orava–Nowy Targ Basin until present times. In contrast, the Paleogene cover of the Tatra Mts. was removed only during Quaternary.

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The relation between geological structure and slope orientation as a context of landslide development: An example from Lubań and Gorc ridge (Gorce, Polish Outer Carpathians)

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Structural geology has recently become a key topic in landslide research. However, the link between tectonics and slope orientation in landslide development is not deeply recognized. The aim of our research is to find out relation between bedding and slope orientation as a context of occurrence and distribution of landslides.

Area of the research covers parts of Gorce Mountains (Polish Carpathians), along the Lubań and Gorce ridge which include 129.5 km^2. Study area is placed in the southern part of Magura nappe (Polish Outer Carpathians) and includes two main tectonic unit: Krynicka Unit and Bystrzycka (Sądecka) Unit (Paul, 1980).

This region is built of sandstone–shale flysch deposits of turbidite origin. Mechanical characteristic of flysch rocks and very complex tectonics contribute to development of mass movements (Kleczkowski, 1955; Mastella, 1975; Bober, 1984; Wójcik, 1997; Margielewski, 2004). On the area of the research altogether 494 landslides were mapped. Landslides cover 15 % of this region. Distinguished landslides include all type of mass movements (Dikau et al., 1996; Margielewski, 2009).

Proposed method is comparison of several raster maps of different parameters: map of bed strike, map of bed dip, map of slope and map of aspect. To create continuous map of bedding we built 3D geological model using all available data such as geological unit boundary, location of faults and strike/dip measurements and DTED2 (Digital Terrain Elevation Model Level2). Maps of slope and aspects are based on DTED2. Using simple map algebra we are able to calculate the relation between beddings and slopes parameters. Final bedding vs. slope map were compared to map of distribution of landslide. Our methodology allows to define witch kind of slope is more predictable for developing of the mass movements.

Acknowledgement. The location of landslides has been mapped during realization the SOPO project in the Ochotnica Dolna commune.

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Nature, tectonic setting and likely origin of the Paleoproterozoic (~2.1 Ga) Světlík orthogneisses (southern Bohemia)

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The growing database of *in situ* zircon data from the core of the Variscan orogen in the Bohemian Massif indicates a major role for recycling of a component c. 2.1 Ga old, corresponding to a magmatic event widespread in the northern part of Gondwana and related terranes (e.g., Eburnean basement of the West African Craton or Icartian Gneiss of the North Armorican Massif, France).

This component appears as inheritance in metaigneous rocks of the Moldanubian Zone, including the HP felsic granulites (e.g. Friedl et al., 2004), as well as in some Variscan plutonites, e.g., in the Central Bohemian Plutonic Complex (Janoušek et al., 2010). Eburnean ages form also a common part of the zircon age spectra in metasediments of the Moldanubian (Kröner et al., 1988) as well as Teplá–Barrandian zones (Drost et al., 2004; Strnad and Mihaljevič, 2005).

However, the outcrops of the Eburnean basement are extremely rare, being confined to allochthonous tectonic slices at the base of the Varied Group. The only region where they have been found and dated, is the surrounding of Muckov and Rájov in southern Bohemia (Wendt et al., 1993). The aim of the current work is to document the petrology and geochemical variability of these Paleoproterozoic orthogneisses known collectively as "Světlík orthogneiss". Granite members of the suite are studied for the first time.

The new SHRIMP dating of a Bt–Amp quartz dioritic gneiss from Rájov yielded an average $^{207}Pb/^{206}Pb$ age of 2 088.6 ± 4.3 Ma, which is in good agreement with previous zircon datings by Kröner et al. (1988) and Wendt et al. (1993): 2 048 ± 12 (conventional U–Pb age, U. I.), 2 060 ± 12 Ma, 2 104 ± 1 Ma and 2 061 ± 6 Ma (Pb–Pb evaporation). Any inherited components are lacking.

The petrological and geochemical studies have shown that the protoliths to amphibolite-grade orthogneisses were rather sodic, meta- to subaluminous quartz diorites–granites (SiO_2 ~ 60–74 wt.%). The NMORB-normalized spiderplots are characterized by a strong enrichment of LILE over HFSE, and conspicuous Nb–Ti anomalies, typical of magmas derived at active continental margins. Alternatively, such signatures may originate during continental collision, by anatexis of the older (arc-derived) crust. The chondrite-normalized REE patterns are steep, showing strong LREE/ HREE enrichments (LaN/YbN = 2.3–57) and variable magnitude of Eu anomaly (Eu/Eu* = 0.3–1.7).

The two-stage depleted mantle Nd model ages range from 1.8 to 3.4 Ga and show a crude positive correlation with differentiation indexes, such as SiO_2. This provides a strong evidence for two magmatic sources, one with composition close to the Paleoproterozoic depleted mantle, and the other mature crustal, most likely Archaean, as indicated by Nd model ages near 3 Ga.

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Decoupling of deformation in the Skole nappe near Strzyżów (Outer Carpathians, SE Poland)

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The Skole nappe is the most external, completely detached nappe occurring in the Outer Carpathians fold-and-thrust belt. Analyses of the field and 2D seismic reflection data made by the Polish Oil and Gas Company showed that during NE–SW shortening a series of longitudinal NW–SE-trending folds was formed, e.g. Strzyżów syncline and Babica anticline comprising the Inoceramian Beds and the Menilite and Krosno formations (Nescieruk et al., 1995). The Inoceramian Beds (Upper Cretaceous–Paleocene) are represented by the thick-bedded turbiditic sandstones with intercalations of grey shales and marls (Kotlarczyk, 1978). Menilite Beds consist of black and brown shales and cherts with intercalations of sandstones. The Krosno Formation (Oligocene–Miocene), which is the youngest lithostratigraphic unit in the area, is dominated by medium- to thin-bedded, calcareous sandstones and grey shales (Jucha and Kotlarczyk, 1961).

Analysis of seismic data suggests that a dual internal structure may be distinguished within one of the most significant folds, i.e. the 15 km wide Strzyżów syncline. The structure is subdivided by a detachment horizon occurring at the depth of about 300 m below the surface. Above this depth there occurs an upper level, consisting of the Krosno and Menilite formations and below is the lower level comprising the Inoceramian Beds. The upper level is dominated by box folds that are several hundred meters wide, whereas the lower level comprises duplicated thrust sheets of rocks and fault-bend folds. Detachment folds with the box shape geometry, occurring in the upper level, suggest that the layer-parallel shortening prevailed during folding. The presence of duplexes in the lower level of the Skole nappe indicates the possible occurrence of simple shearing.

The dual internal structure of the Skole nappe near Strzyżów may be interpreted as being controlled by differences in mechanical stratigraphy. Location of the detachment folds was favoured in the upper level, where the weak thin-bedded sandstones and shales were present during the development of the sheet thrusting in the stronger rock units. Seismic data suggest that the major boundary, along which the style of deformation changes, corresponds to a detachment level rooted in the Menilite Formation.

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Multiple detachment levels in the Silesian nappe near Jasło, Polish Outer Carpathians

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The Silesian nappe near Jasło includes a series of W–E to NW–SE-trending map-scale folds composed of Valanginian/Hauterivian?–Oligocene rocks (Neścieruk et al., 1995). The Silesian nappe between Nowy Żmigród and Frysztak towns comprises the Glinik, Niepla, and Moderówka synclines, and the Lubla, Brzanka–Liwocz, Potok, Żołków, Łajsce–Kopytowo, Iwonicz Zdrój, and Folusz–Dukla anticlines (Neścieruk et al., 1995). Their wavelengths range from 1.5 to 15 km. New 2D seismic data suggest that most of the outcropping folds can be interpreted as symmetric detachment folds. However, anticlines that are bounded from the north by thrusts have an asymmetric geometry. The folds comprise narrower northern forelimbs and wider southern backlimbs. The lithostratigraphic units of the Silesian nappe include the Lower Krosno Beds, Menilite Beds, Hieroglyphic Beds, Ciężkowice Beds, Variegated Beds, Lower and Upper Istebné Beds, Godula Beds, Lgota Beds, and Upper Cieszyn Beds, comprising a fairly uniform lithology of thick- and medium-bedded sandstones and shales (Neścieruk et al., 1995; Oszczypko, 2004).

Seismic data, field investigations, digital elevation models and satellite images have been interpreted to suggest the occurrence of multiple detachment horizons in the Silesian nappe. About 10 significant detachment levels have been identified within the nappe close to the depth of 6 km. However, it cannot be excluded that the thrust sheets contain more discrete detachment horizons, difficult to identify on seismic profiles. Six of the recognized décollement levels can be interpreted as existing along the entire length of the nappe, measured between the Magura and Skole nappes. The average thickness of the thrust sheets estimated at dozens to several hundred meters was calculated between two parallel flats, belonging to the floor and roof detachments, respectively. On seismic profiles below 1 km depth, the rocks display an array of thrusts forming a series of active-roof duplexes comprising north-directed thrust sheets and fault-bend folds. A similar possibility of the occurrence of such multiple detachment levels was, for example, displayed by Mastella (1988) in the Mszana Dolna tectonic window within the Magura nappe. It seems that this is an important mechanism of strain transfer during the process of thrusting in the Outer Carpathians fold-and-thrust belt.

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Flow fabrics and dynamic porosity in Pleistocene dacite lava flows from Three Sisters volcanoes (Cascades, OR, USA)

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The statistics show that pyroclastic flows derived from the flow frontal collapse of highly viscous "block lavas" formed by andesite to dacite caused the most (70 %) of all volcano-related casualties in 1900–1982 (Blong, 1984). These flows can advance on large distances, because the blocky cover of the advancing flow effectively insulates the interior of the flows, which remains molten and mobile (Harris et al., 2002). Their insidious threat to surrounding populations is that these flows show abrupt transition from ductile flow to gravitational failure of the front, which exposes their overpressured interior and triggers devastating pyroclastic flows (e.g. Sigurdsson et al., 2000). Textural evidence in exposed parts of such collapsed flows revealed that the lava is affected by cavities that form due to the ductile tearing of the magma at high strain rates (Smith et al., 2001). In order to constrain critical conditions that can trigger frontal collapse of such flows, two Pleistocene dacite flows on the eastern slope of Middle Sister Volcano in Cascades (OR, USA) were studied by means of field survey and microstructural analysis. The basal slope of both flows is approximately 30°. Both flows were sampled along 230, resp. 360 m long glacial erosion scarps trending in ENE direction. Both flows reveal blocky upper parts and fabrics inclined downslope or upslope along the axis of the flow with magnetic lineations either parallel or perpendicular to the flow axis. Both flows reveal up to 10 cm long lenticular to sigmoidal shaped pores distributed along distinct layers 5–15 cm thick. These cracks frequently dip against the slope of the flow and show 15–50° angular difference with the macroscopic flow induced fabric in the lava. Cavities with diffuse edges and low aspect ratio mark the "pressure shadows" – edges of lithic fragments that are also locally distributed in layers parallel with the flow fabrics. Our preliminary interpretation of the field and AMS (anisotropy of magnetic susceptibility) fabric data suggest that the described porosity represents a result of mechanical failure of the dacite glass and/or failure induced by dilatancy of the groundmass rich in plagioclase lath shaped crystals. The progression of this brittle-ductile failure can disrupt the lava into distinct angular to spherical fragments that start to roll in the surrounding and still viscous lava. Further microstructural work will aim to constrain the timing, conditions and growth rate of the dynamic porosity in different parts of the flows. These parameters should be in the future incorporated into numerical models simulating stability of lava flows for mitigation of associated volcanic hazards.

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The Ailao Shan–Red River Shear Zone, NW Vietnam: A long-lived continental fault zone in SE Asia

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In SE Asia, the Ailao Shan–Red River Shear Zone (ASRR), stretching from Tibet to Vietnam, is located in the SW part of the South China Block. Its Vietnamese sector, exposed in the Day Nui Con Voi Massif (DNCV), occurs to the north of the Song Ma suture which developed during the Indosinian events in the Triassic. Our studies show that in the DNCV, the high-grade paragneisses and micaschists were intruded by granites, leucogranites and pegmatites in the Late Jurassic to Miocene times and repeatedly deformed. An integration of tectonic data and isotopic datings of some selected igneous rocks, the structural position of which was carefully identified, has revealed 4 tectonothermal episodes at 152–135 Ma, 80–70 Ma, 60–40 Ma, and 30–25 Ma intervals. During these episodes, the DNCV rocks were ductilely deformed by dextral wrenching, sinistral wrenching accompanied by vertical folds, dextral transpression associated with subhorizontal folds, and sinistral transtension accompanied by steep to low-angle normal faulting. These observations suggest multiple rejuvenation of the shear zone with changing kinematics. Although timing of an early dextral event is still unconstrained, it must have occurred under amphibolite facies conditions, prior to the intrusion of coarse-grained leucogranites at ~80–70 Ma. The felsic igneous rocks contain enclaves of country rocks with preserved pre-existing mylonitic fabric. Late Cretaceous magmatism affected rocks which were already sheared not less than twice. Detailed observations of the cross-cutting contacts, mesofabric and microfabric in mafic and felsic rocks revealed in several places that amphibolites became striped due to leucosomatic segregations and sheared at high temperature conditions. Migmatization went on at least partly in the dextral strike-slip regime. Leucocratic melts that were produced at 60–40 Ma were coeval with the last episode of high temperature metamorphism recorded by the DNVC rocks. The 60–40 Ma leucocratic rocks were then often zonally mylonitized in the strike--slip regime, with kinematic criteria indicating dextral over sinistral displacement overprints. Important information also comes from migmatitic amphibolites with pegmatitic granite neosome offsets oblique or normal to the foliation planes. The neosome bodies became subsequently sheared to gneisses and folded together with metabasites. Asymmetric, bivergent folds were formed in a transpressional regime. The contractional folding was accompanied by the reverse-type to vertical shearing located in or parallel to the short limbs of the folds. Such shearing led eventually to subvertical stretching and boudinage of the pegmatite veins. The transpressional deformation occurred under greenschist facies conditions as shown by chlorite tails or rims around hornblende porphyroclasts. Our observations show that the DNCV recorded complex and protracted tectonothermal evolution. In the Vietnamese part of the ASRR, rocks were high-grade metamorphosed, migmatized and sheared dextrally already by Late Cretaceous times at the latest. Accordingly, the ASRR is a polygenic feature in the South China Block, with protoliths of different ages and various records of multiple deformations throughout the Mesozoic and Cenozoic. Its polyphase tectonic history is evidently more complex than previously assumed and has likely reflected accommodation of dynamic interactions between crustal blocks in SE Asia since Carboniferous times. A crustal-scale response to India-Asia collision in the Tertiary seems to be only a part of this history.

Neotectonics of the Carpathians: Lessons learned from tectonic geomorphology

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Neotectonic studies in the Carpathians have focused mainly on the effects of large-scale domal uplifts and open folding above marginal zones of thrust and imbricated map-scale folds, deformation of fluvial terraces related to reactivated pre-Quaternary faults, morphometric indicators of young tectonic activity, and rarely to the structural characteristics of young faulting. Neotectonic faults tend to be associated with the margins of the Orava–Nowy Targ Basin at the boundary between the Inner and Western Carpathians, as well as some regions within the Outer Carpathians. Quaternary grabens within the Orava–Nowy Targ Basin, oriented E–W, reveal throws of up to 120 m. Reactivation of the northern boundary fault of the Pieniny Klippen Belt was shown to have occurred as late as in the Holsteinian. Minor vertical block movements of oscillatory character (0.5–1 mm/yr) were detected along faults cutting the Pieniny Klippen Belt. In the Pliocene and Quaternary the Polish Carpathians witnessed differential vertical and some remnant horizontal movements, resulting in the formation of elevated and subsided areas. Valleys of the Outer Carpathians bear 5 to 9 terrace steps of Quaternary age. Most of Pleistocene terraces are strath or complex-response terraces; the Weichselian and Holocene steps are usually cut-and-fill landforms, except those located in the neotectonically elevated structures, characterized by the presence of young straths. Longitudinal profiles of individual strath terraces frequently show divergence, convergence, upwarping, downwarping, or tilting that can be indicative of young tectonic control. Examples based on detailed examination of deformed straths and fluvial covers in selected segments of the main Outer Carpathian rivers appear to indicate Quaternary reactivation of both normal and thrust faults in the bedrock. The latter are mostly confined to the eastern portion of the Outer Carpathians. In the western portion of the Outer West Carpathians, middle and late Pleistocene reactivation of early Neogene thrust surfaces was documented in the Beskid Żywiecki Mts. Differentiated mobility of reactivated as normal Miocene strike-slip faults (oriented N–S to NNW–SSE and NNE–SSW) in the medial portion of the Dunajec River drainage basin appears to be indicated by the results of long-profile analyses of deformed straths, usually of early and middle Pleistocene age. A small normal, seismogenic fault on the NW margin of the Nowy Sącz Basin probably originated in Eemian or early Weichselian times. Quaternary uplift of the marginal part of the Beskid Niski Mts. (W–E to WNW–ESE), in the mid-eastern portion of the Outer Carpathians of Poland, was estimated at 100–150 m, including no more than 40 m of uplift after the Elsterian stage. Analyses of different morphometric indices (abnormal river bed gradients, hypsometric integrals, valley floor width-valley height ratios, stream-length gradient indices, and others) point to the presence of several longitudinal zones, subparallel to the structural grain of the area and showing recent uplift due to buckling of frontal parts of imbricated slices.

Tectono-sedimentary breccias in the Upper Cretaceous–Lower Paleogene formations from the eastern part of the Pieniny Klippen Belt (Western Carpathians)

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The studied section of the Pieniny Klippen Belt is, apart from tectonic klippens, characterized by the presence of sedimentary-type klippens – olistoliths situated in the Upper Cretaceous and Paleogene flysch sediments (Jarmuta and Proč fms.) of the Oravic Subpieniny and Šariš units, respectively. These tectono-sedimentary breccias are known as the Gregorianka and Milpoš breccias (Nemčok et al., 1989; Plašienka and Mikuš, 2010) and represent synorogenic deposits formed in response to superficial thrusting processes. The Gregorianka breccias form tabular to lenticular bodies in the upper parts of the Maastrichtian Jarmuta Fm. of the Subpieniny unit. They contain mostly monomictic material derived from the structurally highest Pieniny unit of the Pieniny Klippen Belt. In contrast, the Paleocene – Lower Eocene Milpoš Breccia from the structurally lowermost Šariš Unit contains variegated material derived mainly from the overlying Subpieniny unit and probably also from the Pieniny unit, including some recycled "exotic" material. They also carry blocks – olistoliths derived from these units which range up to the size of megaolistolites. These can be considered as already partly disintegrated fronts of the overriding Subpieniny nappe that were transformed to bodies of tectono-sedimentary breccias and transported gravitationally as mass-flows into the frontal Proč flysch basin. Consequently, the Gregorianka and Milpoš breccias represent important sedimentary records of the tectonic thrust processes in the Oravic Superunit of the Pieniny Klippen Belt. The main aim of this contribution is sedimentological, biostratigraphical and lithologic-petrographic analysis of the breccia material and interpretation of their origin and significance for dating of the thrusting events within the Pieniny Klippen Belt.

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Tectonic constraints of travertine occurrence in the Podhale Flysch (Inner Carpathians)

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The occurrence of travertines in the Podhale Flysch has been documented a long time ago (Halicki and Lilpop, 1932). Only a few appearances of these rocks were noted in later reports. During fieldwork in the entire Podhale area, the authors have documented about 50 localities with travertines. Their number is variable due to the erosion of the existing exposures and the creation of new ones. According to pollen analysis, these rocks have developed from the Early Holocene times until present.

Travertines are formed when the environment contains Ca^{+2} ions mostly with HCO_3^- anions and minimal quantities of CO_3^{-2} anions. Precipitation of travertines is induced by disturbances in the system, resulting from turbulent flow and/or decrease of partial pressure. In turn, Ca^{+2} ions appear as the result of leaching of calcium carbonate by thermal waters from the flysch rocks or their basement.

The Podhale Basin is filled with flysch shales and sandstones, mainly of Oligocene age, lying on the Nummulitic Eocene. The thickness of the entire complex is estimated at 4÷2.5 km. The contact of the Podhale Flysch with the Tatra Mts. is sedimentary, whereas with the Pieniny Klippen Belt – tectonic in nature. Steep bedding dips gradually become gentlier near the Pieniny Mts. Dip values significantly increase again in the zone of the peri--Pieniny flexure. Further to the south, an uplifted zone of gently dipping beds with occurs, followed by the axial zone. The southern limb of the basin is isoclinal with a narrow belt of tectonic deformations near the Tatra Mts. These parallel tectonic zones are cut by large transversal Białka and Biały Dunajec fault zones (Mastella, 1975). The structure of the Podhale Basin was formed in the course of block movements in the basement from the Late Oligocene to Middle Miocene times.

Travertines precipitate near fissure springs linked with small faults and breccia zones or seepages occurring in their elongations. From tectonic viewpoint, exposures with travertines occur in two belts concordant with the Białka and Biały Dunajec faults. The belt of travertine occurrences is less distinct in the zone of beds with gentle dips in the eastern part of the basin, continuing in the axial zone in the western part of Podhale.

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Sandstones elevations in Lubin-Polkowice-Sieroszowice ore deposits- result of tectonic or deposition?

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The Lubin-Polkowice-Sieroszowice ore deposit located on Fore-Sudetic Monocline is one of the largest polymetallic ores in the world. Dominant ore minerals are copper sulfide. The origin of mineralization is very complicated and ambiguous. At present most researchers consider it to be of post-sedimentation origin. Every year 500,000 tonnes of copper, 1,000 tonnes of silver, 0.5 ton of gold, nickel and lead are mined from this deposit. This ore appears in sedimentary rock mainly in sandstones, shales, limestones and dolomites of the Permian period. Deployment zone of mineralization changes locally covering different parts of profile. They belong to Rotliegend and Zechstein. Rotliegend rocks arisen on land contrast with Zechstein's sea rocks. Thickness of Rotliegends rocks in deposit area is 200–300 m. These rocks are red and brown sandstones, conglomerates and mudrocks of fluvial origin. The dominant colour of rock in the upper part of profile is white, that is why it is called Weissliegend. Ore occurrence is localized in upper part of Weissliegend and lower part of Zechstein. In the deposit area the top of Weissliegendes displays remnant paleomorphological features, among which are evidenced several elevations of which crests are elongated in NW–SE direction. Elevations are a few kilometers long, several dozens length, to several hundred metres width and more than 30 metres height. The average length between crests is more than several hundred metres up to 2 kilometres. In elevations area the inclination of top of Weissliegendes is more than 25° when local inclination is near 2–5°. An interrelationship between elevations and the assemblage of sedimentary facies of copper-bearing series and underlying lower Weissliegendes is pointed out. The Weissliegendes, which belong to the ore-bearing series, show higher variability of facies within the elevations than outside of them. The elevations are typified by relatively greater thicknesses of the Weissliegendes, and also by considerably greater thicknesses of the entire zone of copper mineralization. Within the elevations the ore-bearing series lack the characteristic copper-shale (Kupferschiefer) deposits. On the wings of elevations there are series of tectonic structures like faults and overlaps. They are mainly on the border between Kupferschiefer shale and Weissliegendes sandstones. The origin of elevations has been a mystery with two proposals of solution. The first proposal is a tectonic theory assuming occurring horsts, tectonic trenches and stair faults (Dubicz and Don, 1977). Argumentation beyond this theory assumes traces of brittle and plastic strain or dislocation often of several meters height. The second proposal is a sedimentation theory. In this theory the most important evidence are facies as large-scale cross--stratified sandstones, washout of upper parts of elevations and no shells layers in them. Tectonic disturbances are treated as the effect of inconstant compaction, related with primary thickness of Kupferschiefer deposits. Differences in Zechstein Limestone facials, shows clearly the existence of elevations in Zechstein seabed. In this approach elevations are early Permian dunes sunk at rapid transgression. Our poster shows a range of evidence to support the sedimentary origin of elevations. The demonstrated sedimentary structures and tectonic disturbances can be interpreted as related with each other.

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Príloha časopisu Mineralia Slovaca, roč. 44, č. 1
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Obsah – Content

Na úvod

Geovestník ako súčasť časopisu Mineralia Slovaca vychádza od roku 1993. Vytvorenie tohto spravodaja pre geológiu, baníctvo, úpravníctvo a životné prostredie bolo motivované snahou o poskytnutie aktuálnych informácií o dianí na poli geovied na Slovensku. Tieto informácie v iných periodikách dlhodobo absentovali a stále absentujú.

Pre špecifickosť informácií publikovaných v Geovestníku, a tiež neobvyklú formu ich prezentovania (napr. reportáže z vedeckých podujatí, vrátane kompletnej zostavy abstraktov prezentácií z týchto podujatí), v ostatných rokoch dochádzalo z pohľadu svetových bibliografických a citačných databáz (napr. SCOPUS, Web of Knowledge, Web of Science) k nejasnostiam, kam časopis Mineralia Slovaca zaradiť a akým spôsobom ho scientometricky hodnotiť. Z tohto dôvodu v súčasnosti jedinou (a vysoko produktívnou) databázou, ktorá časopis v plnom rozsahu registruje, poskytuje jeho články v neskrátenej verzii, rovnako ako poskytuje kvalitný prehľad citovanosti týchto článkov, je Google Scholar.

V snahe o zaradenie časopisu aj do ďalších svetových databáz došlo rozhodnutím Vydavateľskej rady ŠGÚDŠ zo dňa 31. januára 2012 k oddeleniu Geovestníka od časti časopisu s pôvodnými vedeckými článkami. Informačný spravodaj aj napriek tomu nekončí svoju existenciu. Informovať o aktuálnom dianí na poli geovied bude aj naďalej ako príloha časopisu určená len slovenským čitateľom a inštitúciám, tzn. pre zahraničných odberateľov a bibliografické databázy bude časopis distribuovaný len s pôvodnými vedeckými článkami. Význam publikovania v Geovestníku sa napriek tomu neznižuje, lebo všetky informácie budú aj naďalej celosvetovo dostupné na webovej stránke časopisu www.geology.sk/mineralia, aj keď s patričným grafickým odlíšením a informáciou, že ide o prílohu pre slovenskú geovednú verejnosť.

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Zoltán Németh
vedecký redaktor

2012 - Zemplínska Šírava
Slovak Republic
CETEG

10th CETeG 2012 meeting in Slovakia – Tectonic phenomena of the Eastern Slovakia

10. stretnutie CETeG – Tektonické fenomény východného Slovenska

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Abstract: *The article reports about the 10th CETeG meeting held in the Eastern Slovakia on 2.–5. May 2012. The conference was preceded by the whole-day field excursion devoted to lithology and tectonic overprint of Paleozoic sequences of Gemericum and partly Veporicum, as well as Mesozoic sequences in the nappe outlier of Meliaticum (the Bôrka nappe). Two conference days were devoted to tectonic topics of the crystalline basement and Paleozoic/Mesozoic sequences of Variscan and Alpine realms, as well as the tectonics of the Pieniny Klippen Belt and Outer Western Carpathians. At the end of the second day of the conference, the field excursion to Zemplinicum and the Neogene extrusive volcanic body Borsuk in the Zemplínske vrchy Mts. was held. The scientific event terminated with the whole-day post-conference field trip to Pieniny Klippen Belt in the Eastern Slovakia, presented along a cross-section between the Jarabina and Litmanová villages.*

Key words: *CETeG, tectonics, structural geology, tectonometamorphism, Gemericum, Veporicum, Meliaticum, Eastern Slovakia*

The 10th meeting of the Central European Tectonic Studies Groups (CETeG) was held in Eastern Slovakia this year (Fig. 1). It represented the third meeting, held in territory of Slovakia. The previous two CETeG meetings were held in the Borsuk area of the town of Lučenec (2004 – 2nd meeting) and in Upohlav (2008 – 6th meeting). This year's meeting in the locality Medvedia hora at the Zemplínska Šírava water reservoir and the field trips were organized by J. Kobulský, Ľ. Petro, Z. Németh, M. Kováčik, Ľ. Gazdačko and P. Bačo, as well as logistics by K. Žecová and Z. Bačová, all being the employees of the State

10. stretnutie Skupín stredoeurópskych tektonických štúdií (CETeG – Central European Tectonic Studies Groups) sa konalo tohto roku na východe Slovenska (obr. 1). Bolo to v poradí tretie stretnutie uskutočnené na Slovensku. Prvé stretnutie sa konalo v oblasti Lučenca (2004 – 2. stretnutie CETeG) a druhé v Upohlave (2008 – 6. stretnutie). Tohtoročné stretnutie na Medvedej hore v oblasti Zemplínskej Šíravy zorganizovali pracovníci košickej pobočky Štátneho geologického ústavu Dionýza Štúra (ŠGÚDŠ) J. Kobulský, Ľ. Petro, Z. Németh, M. Kováčik, Ľ. Gazdačko a P. Bačo. Vedeckým

Fig. 1. Participants of the 10th CETeG meeting 2012 in front of the conference site in locality Medvedia hora at the Zemplínska Šírava water reservoir in the Eastern Slovakia. In the middle of the upper row: Branislav Žec – Director of ŠGÚDŠ, the low row right: Ľubomír Petro – the Head of ŠGÚDŠ – Regional centre Košice, providing the logistics of the meeting. Photo Z. Németh.

Obr. 1. Účastníci 10. stretnutia CETeG 2012 na Medvedej hore pri Zemplínskej Šírave na východnom Slovensku. V hornom rade v strede: B. Žec – riaditeľ ŠGÚDŠ, v dolnom rade vpravo: Ľ. Petro – vedúci ŠGÚDŠ – Regionálne centrum Košice, zabezpečujúci logistiku podujatia. Foto Z. Németh.

Geological Institute of Dionýz Štúr (ŠGÚDŠ), Regional centre Košice. Scientific guarantee of the conference was Prof. D. Plašienka from the Faculty of Sciences, Comenius University Bratislava. The meeting was attended by 69 specialists from the area of structural geology, tectonics, tectono-metamorphism, but also sedimentology, engineering geology and the software processing of tectonic data and GIS.

The cycle of the CETeG international conferences began in April 2003 at the castle Hrubá Skála in the Czech Republic. Although the so far circulation of conferences was carried out only in the states of so-called Višegrád Four, the conference is attended also by geologists from other European countries, or even overseas. In line with this trend, also the territorial scope of presented geological-tectonic results is extended. The attractiveness of the meeting, in addition to many high quality lectures and posters, is enhanced by the field trips, focused on geological and tectonic peculiarities of the host countries or visited regions.

2. May 2012
Pre-conference field trip to the region of Gemericum

The traditional pre-conference excursion was in this year's meeting focused on the region of the Spiš-Gemer Ore Mts. with the emphasis on lithology and tectonometamorphic overprint of a part of Paleo¬zoic sequences of Gemericum, as well as surrounding units – Meliaticum, and partly Veporicum in the eastern contact zone with Gemericum. In accordance with the description of individual localities (published in following paper), the often multiple tectonic overprint of the Lower Paleozoic sequences was presented in localities Opátka, Gelnica and – during the transport – in locality Smolník, similarly as in the contact of Gemericum with Veporicum (Margecany). The excursion stop in the saddle on the Folkmársky kopec hill above the village of Veľký Folkmar provided the sceneric view towards NNW on tectonic units Gemericum, Meliaticum in the North-Gemeric zone, but also Veporicum and Tatricum in the Branisko Mts. Towards the E the view on Veporicum and its Permian-Triassic-Jurassic cover was extended also on Carboniferous and Permian sequences in the nappe outliers of Hronicum in apical parts of hills built by Veporic lithology. Moreover – the view to the S presented the Silicicum of the Murovaná skala hill. The locality Folkmársky kopec hill allowed the very instructive presentation of the geology and tectonic setting in the Eastern part of the Gemeric region.

The different tectonometamorphic overprint of two types Upper Paleozoic of conglomerates in the North-Gemeric zone – the Carboniferous Rudňany Conglomerates of the Dobšiná Group and the Permian cover Muráň Conglomerates of the Krompachy Group was presented in locality Závadka at the village of Nálepkovo (Fig. 8). Besides the presentation of exhumed lithologies of Meliaticum in the North-Gemeric zone in the Jaklovce area, also those in the Šugovská dolina valley in the South-Gemeric zone were presented. The high--pressure Meliatic sequences are included into the so-called Bôrka nappe. The particular overprints of sequences, presented during the whole-day field trip, were classified using the concept of two Variscan deformation phases (VD_{1-2}) and three Alpine deformation phases (AD_{1-3}), including their sub-phases. The excursion guide-text is available in following paper.

3. May 2012
First conference day

The conference (Fig. 2) was opened by the welcome speech presented by the Director of ŠGÚDŠ Branislav Žec (Fig. 3). Wish of the high quality presentations and the support to this traditional scientific event were expressed also by Zdeněk Venera, the Director of the Czech Geological Survey, who was personally present also at the pre--conference excursion as well as the first two days of the conference.

The scientific program of the first conference day started with the invited lecture of Prof. W. Zuchiewicz (Fig. 4) from AGH University of Science and Technology, Cracow, Poland, presenting the neotectonics of the Outer Carpathians in the frame of tectonic geomorphology. Next lectures were devoted to crystalline basement, Paleozoic and

garantom konferencie bol prof. D. Plašienka z Prírodovedeckej fakulty Univerzity Komenského v Bratislave. Logistiku zabezpečovali okrem Ľ. Petra aj K. Žecová a Z. Bačová zo ŠGÚDŠ – Regionálneho centra v Košiciach. Stretnutia sa zúčastnilo 69 špecialistov zaoberajúcich sa z problematikou štruktúrnej geológie, tektoniky, tektonometamorfózy, ale aj sedimentológie, inžinierskej geológie a softvérového spracovania tektonických dát a GIS.

Cyklus medzinárodných tektonických konferencií CETeG sa začal v apríli 2003 na hrade Hrubá Skála v Českej republike. Aj keď sa konferencie doposiaľ uskutočňovali len v štátoch tzv. Vyšehradskej štvorky, účastníkmi podujatia sú nezriedka geológovia aj z ďalších európskych štátov, či zámoria. V súlade s týmto trendom sa rozširuje aj teritoriálny záber prezentovaných geologicko-tektonických výsledkov. Atraktívnosť stretnutí popri množstve kvalitných prednášok a posterov umocňujú aj hodnotné exkurzie orientované na geologicko-tektonické osobitosti hostiteľských krajín či navštívených regiónov.

2. máj 2012
Predkonferenčná exkurzia do regiónu gemerika

Tradičná predkonferenčná exkurzia bola v prípade tohtoročného stretnutia zameraná na región Spiško-gemerského rudohoria s dôrazom na litológiu a tektonometamorfné pretvorenie časti paleozoických sekvencií gemerika, ale aj priľahlých jednotiek – meliatika a čiastočne veporika vo východnej kontaktnej zóne s gemerikom. V súlade s popisom jednotlivých lokalít (publikovaným v nasledujúcom príspevku) boli prezentované spodnopaleozoické sekvencie a ich často viacnásobný tektonický prepis v lokalitách Opátka, Gelnica a počas presunu Smolník, rovnako ako na kotakte gemerika s veporikom (Margecany). Zastávka v sedle na Folkmarskom kopci nad obcou Veľký Folkmar poskytla v smere na SSZ scenerický výhľad na tektonické jednotky gemerikum a meliatikum v severogemerickej zóne, ale tiež veporikum a tatrikum v pohorí Branisko. V smere na východ sa k nim pridával pohľad na veporikum a jeho permsko-triasovo-jurský obal, a tiež na karbónske a permské sekvencie v príkrovových troskách hronika vo vrcholových častiach kopcov budovaných litológiou veporika. Navyše – smerom na juh pristupoval výhľad na silicikum Murovanej skaly. Lokalita Folkmarský kopec umožnila názorne prezentovať úvod do geologickej a tektonickej stavby východnej časti gemerického regiónu.

Rozdielny tektonometamorfný prepis dvoch typov zlepencov v severogemerickej zóne – karbónskych rudnianskych zlepencov a obalových permských muránskych zlepencov knolského súvrstvia – bol prezentovaný v lokalite Závadka pri Nálepkove (obr. 8). Popri prezentácii exhumovaných litológií meliatika v severogemerickej zóne v oblasti Jakloviec bol v oblasti Šugovskej doliny prezentovaný výskyt vysokotlakových sekvencií meliatika v juhogemerickej zóne (tzv. príkrov Bôrky). Pri vysvetľovaní jednotlivých tektonických prepisov daných sekvencií bola použitá koncepcia dvoch variských deformačných štádií (VD_{1-2}) a troch alpínskych deformačných štádií (AD_{1-3}), vrátane subštádií. Exkurzného sprievodcu publikujeme v nasledujúcom príspevku.

3. máj 2012
Prvý konferenčný deň

Konferenciu (obr. 2) otvoril riaditeľ ŠGÚDŠ Branislav Žec úvodným prejavom (obr. 3). Prianie kvalitných a prínosných prezentácií a podporu tomuto tradičnému vedeckému podujatiu vyslovil následne aj riaditeľ Českej geologickej služby Zdeněk Venera, ktorý bol osobne prítomný na predkonferenčnej exkurzii aj počas prvých dvoch konferenčných dní.

Odborný program prvého konferenčného dňa začal vyzvanou prednáškou prof. W. Zuchievicza (obr. 4) z AGH Univerzity pre vedu a technológiu z Krakova (Poľsko), prezentujúcou neotektoniku Vonkajších Karpát na pozadí tektonickej geomorfológie. Ďalšie prednášky boli venované kryštalinickému fundamentu, paleozoickým


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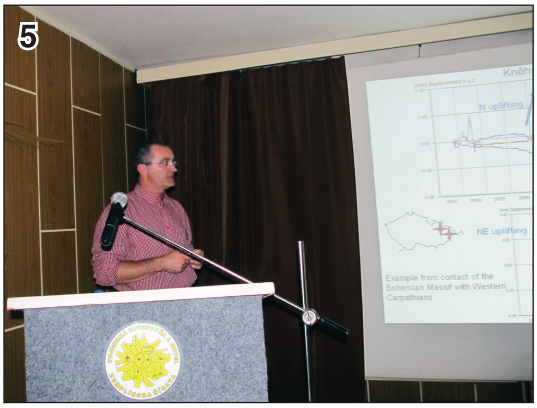
N uplifting
NE uplifting
Example from contact of the Bohemian Massif with Western Carpathians
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Fig. 2. Opening ceremony of the conference. From the left: Z. Németh – ŠGÚDŠ, organizer of the scientific and excursion program of the whole meeting, Z. Bačová – ŠGÚDŠ, logistics, B. Žec – Director of ŠGÚDŠ, Z. Venera – Director of the Czech Geological Survey and Ľ. Petro – ŠGÚDŠ, the chief of the meeting logistics. Photo M. Kohút.

Obr. 2. Otvárací ceremoniál konferenčnej časti stretnutia. Zľava: Z. Németh – ŠGÚDŠ, zostavovateľ vedeckého a exkurzného programu stretnutia CETeG 2012, Z. Bačová – ŠGÚDŠ, logistika, B. Žec – riaditeľ ŠGÚDŠ, Z. Venera – riaditeľ Českej geologickej služby a Ľ. Petro – ŠGÚDŠ, logistické zabezpečenie. Foto M. Kohút.

Fig. 3. In his introductory speech the Director of ŠGÚDŠ B. Žec wished the participants the successful course of the conference and field trips during the CETeG meeting in Slovakia. Photo M. Kohút.

Obr. 3. Riaditeľ ŠGÚDŠ B. Žec v úvodnom prejave poprial účastníkom úspešný priebeh konferencie a exkurzií v rámci tohtoročného stretnutia CETeG na Slovensku. Foto M. Kohút.

Fig. 4. First day of conference started with invited lecture by Prof. W. Zuchiewicz from Poland. Photo Z. Németh.

Obr. 4. Prvý konferenčný deň začal vyzvanou prednáškou prof. W. Zuchievicza z Poľska. Foto Z. Németh.

Fig. 5. The introduction into the second day of the conference represented the invited lecture by J. Stemberk (Czech Republic) about the recent movements on disjunctive structures in the Bohemian Massif. Photo Z. Németh.

Obr. 5. Úvodom do druhého konferenčného dňa bola vyzvaná prednáška J. Stemberka (Česká republika) o recentných pohyboch na disjunktívnych štruktúrach v Českom masíve. Foto Z. Németh.

Fig. 6. Prokop Závada (Czech Republic) – the winner of the Radek Melka price 2012 for the best scientific article of the author younger than 35 years immediately after the announcing the results. Photo Z. Németh.

Obr. 6. Prokop Závada (Česká republika) – víťaz Ceny Radka Melky v roku 2012 za najlepší vedecký článok autora do 35 rokov bezprostredne po vyhlásení výsledkov. Foto Z. Németh.

Fig. 7. Lenka Kociánová (Czech Republic; left) as the winner of the category "The best student poster presented in the CETeG conference in 2012". The price was awarded by Z. Venera (in the middle) and O. Lexa (right). Photo Z. Németh.

Obr. 7. Víťazom kategórie o Najlepší študentský poster prezentovaný na konferencii CETeG sa v roku 2012 stala Lenka Kociánová (Česká republika; vľavo). Výhru odovzdali Z. Venera (v strede) a O. Lexa (vpravo). Foto Z. Németh.

Fig. 8. The lunch break during the pre-congress field trip in the region of Gemericum. Outcrops of the Permian cover Muráň Conglomerates. The Knola Formation of the Krompachy Group, at the Závadka village on the ridge north of the Hnilecká dolina valley. Photo Z. Németh.

Obr. 8. Obedňajšia prestávka počas predkongresovej exkurzie v regióne gemerika. Odkryvy permských obalových muránskych zlepencov knolského súvrstvia krompašskej skupiny pri obci Závadka na hrebeni severne od Hnileckej doliny. Foto Z. Németh.

Fig. 9. Familiarization with the lithology and tectonics of Zemplinicum – Carboniferous rhyolite-rhyodacite volcaniclastics of the Šimonov vrch Formation at the village of Malá Tŕňa. Photo Z. Németh.

Obr. 9. Oboznamovanie sa s litológiou a tektonikou zemplinika – karbónske ryolitovo-ryodacitové vulkanoklastiká súvrstvia Šimonovho vrchu pri obci Malá Tŕňa. Foto Z. Németh.

Fig. 10. Lecture about the forms of Neogene volcanism in the area of Zemplínske vrchy Mts. before the descent to underground spaces in the extrusive body Borsuk. From the right: P. Bačo – lecturing volcanologist, Ľ. Gazdačko and J. Kobulský (ŠGÚDŠ). Photo Z. Németh.

Obr. 10. Prednáška o formách neogénneho vulkanizmu v oblasti Zemplínskych vrchov pred zostupom do podzemných priestorov v extruzívnom telese Borsuk. Sprava: P. Bačo – prezentujúci vulkanológ, Ľ. Gazdačko a J. Kobulský (ŠGÚDŠ). Foto Z. Németh.

Fig. 11. Post-congress field trip in the segment of the Pieniny Klippen Belt between villages Jarabina and Litmanová. D. Plašienka (middle in front of the map) familiarizes the participants with the general tectonic and geodynamic aspects of the Pieniny Klippen Belt. The valley of the Hlboký potok brook – one of the type localities of the Gregoriánka Breccia. Photo Z. Németh.

Obr. 11. Pokongresová exkurzia v segmente bradlového pásma medzi obcami Jarabina a Litmanová. D. Plašienka (v strede pred mapou) oboznamuje účastníkov so základnými tektonickými a geodynamickými aspektmi bradlového pásma. Údolie Hlbokého potoka – jednej z typových lokalít gregoriánskych brekcií. Foto Z. Németh.

Mesozoic sequences of Variscan and Alpine terranes. The morning session chairman was D. Plašienka. The lectures were ordered successively according to the age of studied tectonometamorphic sequences, as well as applied methodology of investigation. In the first lecture of this section V. Kusbach et al. evaluated the heterogeneous nature and the evolution of the Variscan lower continental crust in the area of the Bohemian massif. The nature, probable genesis and tectonic overprint of Paleoproterozoic (~2.1 Ga) Světlík orthogneisses were presented by J. Trubač et al. and the mineralogy of the granite Říčany type (Central Bohemian Plutonic Complex) V. Janoušek et al. The Variscan polyphase structural and metamorphic evolution of the Teplá-Barrandian unit were treated by V. Peřesný et al.

The lectures about the Bohemian Massif were followed by the block of lectures dealing with the Western Carpathians. M. Kohút summed up until knowledge about the genesis and isotopic geochemistry of Gemeric granites. R. Demko et al. presented the genesis of U-Mo mineralization in the locality Kurišková in Permian sequences of Gemericum. Z. Németh et al. presented new proofs about the allochthonity of Meliatic occurrences in the Jaklovce area in the North--Gemeric zone. M. Śmigielski et al. presented new geochronological data about the Neogene exhumation of the Tatry Mts. F. Marko et al. have reconstructed the continuation of the Muráň fault into the area of the Levočské vrchy Mts.

Following block of lectures from regions besides the Western Carpathians (Chairman Z. Németh) started with the lecture by L. Fodor about the stress field parameters in the Pannonian basin from the Mesozoic to Quaternary. M. Reiser at al. drew the attention of listeners on new structural and geochronological data from the Apuseni Mts. in Romania, A. Żelaźniewicz reconstructed the tectonic evolution of the regional Ailao Shan-Red River shear zone in NW Vietnam from a view of geodynamics of lithospheric plates. The end of the first conference day belonged to computer visualization of the Paleozoic drift and amalgamation of lithospheric plates by J. Barmuta and J. Golonka.

The scientific program of the first conference day was enlarged by 21 posters devoted to Bohemian Massif, Western Carpathians and the software processing of the tectonic, sedimentological and GIS data.

4. May 2012
Second conference day, field trip into the area of Zemplinicum and the Neogene volcanic body Borsuk

Second conference day was devoted to Tertiary and Quaternary tectonics, dominantly in the Klippen Belt and the Outer Western Carpathians. The scientific presentations started with invited lecture by J. Stemberk (Fig. 5) from Academy of Sciences of the Czech Republic about the recent displacements on disjunctive structures in the Bohemian Massif, being registered by dilatometers TM71 with possibility of the 3D reconstruction of the registered movements. The results of such monitoring in Slovakia were presented in following lecture by Ľ. Petro et al.

The section about the Klippen Belt and the Outer Western Carpathians (Chairman A. Tokarski) started with the lecture by D. Plašienka about the structural evolution of the Pieniny Klippen Belt, based on new data from its East-Slovakian segment. E. Márton et al. provided new data about the paleomagnetism, registered in the Upper Cretaceous marlstones of the Pieniny Klippen Belt, and added also the tectonic interpretation of results. The tectonics of the western part of the Pieniny Klippen Belt was treated by I. Pešková et al. The origin of the curved traces of the regional thrusts and fault-related folds in the light of the analogue modelling was documented by M. Rauch et al.

This section was enlarged by 11 posters, devoted prevailingly to Outer Western Carpathians.

The field trip in afternoon and evening hours was focussed on the Zemplínske vrchy hills and Neogene volcanic body Borsuk. The excursion was led by J. Kobulský, Ľ. Gazdačko and P. Bačo. The visit of two principal outcrops in the Carboniferous rhyolite--rhyodacite volcaniclastics of the Šimonov vrch Fm. in the Malá Tŕňa area (Fig. 9) and the Upper Permian claystones with intercalations of conglomerates and sandstones of the Černochov Fm. in the Malá Bara area were followed by the excursion in the newly built wine cellars in

a mezozoickým sekvenciám variských a alpínskych teranov. Predsedajúcim dopoludňajšej sekcie bol D. Plašienka. Prednášky boli radené sukcesívne podľa veku študovaných tektonometamorfných sekvencií a podľa aplikovanej metodiky výskumu. V prvej prednáške tejto sekcie V. Kusbach et al. hodnotili heterogénnu povahu a vývoj variskej spodnej kontinentálnej kôry v oblasti Českého masívu. Povahu, pravdepodobnú genézu a tektonické prepracovanie paleoproterozoických (~2.1 Ga) ortorúl typu Světlík prezentovali J. Trubač et al. a mineralógiou granitu typu Říčany (Stredočeský plutonický komplex) V. Janoušek et al.. Variským polyfázovým štruktúrnym a metamorfným vývojom jednotky Teplá-Barrandien sa zaoberali V. Peřesný et al..

Po prednáškach z Českého masívu nasledoval blok prednášok z problematiky Západných Karpát. M. Kohút zrekapituloval doterajšie poznatky o genéze a izotopovej geochémii gemerických granitov. R. Demko et al. prezentovali genézu U-Mo zrudnenia v lokalite Kurišková v perme gemerika. Z. Németh et al. uviedli nové dôkazy o alochtonite výskytov meliatika v oblasti Jakloviec v severogemerickej zóne. M. Śmigielski et al. prezentovali nové geochronologické dáta o neogénnej exhumácii Tatier. F. Marko et al. rekonštruovali pokračovanie muránskeho zlomu do oblasti Levočských vrchov.

Nasledujúci blok prednášok z regiónov mimo Západných Karpát (predsedajúci Z. Németh) začal L. Fodora prednáškou o parametroch napäťového poľa v Panónskom bazéne v období od mezozoika po kvartér. M. Reiser et al. upriamili pozornosť poslucháčov na nové štruktúrne a geochronologické dáta z pohoria Apuseni v Rumunsku, A. Żelaźniewicz rekonštruoval tektonickú evolúciu regionálnej strižnej zóny Ailao Shan v SZ Vietname z pohľadu geodynamiky litosférických platní. Záver prvého dňa prednášok patril počítačovej vizualizácii paleozoického driftu a amalgamácie litosférických platní autorov J. Barmuta a J. Golonka.

Vedecký program prvého konferenčného dňa rozširovalo 21 posterov venovaných Českému masívu, Západným Karpatom a softvérovému spracovaniu tektonických, sedimentologických a GIS dát.

4. máj 2012
Druhý prednáškový deň, exkurzia do oblasti zemplinika a neogénneho vulkanického telesa Borsuk

Druhý prednáškový deň bol venovaný terciérnej a kvartérnej tektonike, bradlovému pásmu a Vonkajším Západným Karpatom. Odborné prezentácie sa začali vyzvanou prednáškou J. Stemberka (obr. 5) z Akadémie vied Českej republiky o recentných pohyboch na disjunktívnych štruktúrach v Českom masíve, zaregistrovaných dilatometrami TM71 s možnosťou trojrozmernej rekonštrukcie charakteru nameraných pohybov. O výsledkoch takéhoto monitoringu na Slovensku zreferovali v nasledujúcej prednáške Ľ. Petro et al..

Sekcia o bradlovom pásme a Vonkajších Západných Karpatoch (predsedajúci A. Tokarski) začala prednáškou D. Plašienku o štruktúrnom vývoji bradlového pásma, opierajúcou sa o nové údaje získané z jeho východoslovenského úseku. E. Márton et al. poskytli nové výsledky z meraní paleomagnetizmu vrchnokriedových slieňovcov bradlového pásma a tiež tektonickú interpretáciu výsledkov. Na tektoniku západnej časti bradlového pásma bola zameraná prednáška I. Peškovej et al.. Vznik zakriveného priebehu regionálnych zlomových a prešmykových štruktúr na základe analógového modelovania zdokumentovali M. Rauch et al..

Danú sekciu obohatilo 11 posterov, venovaných prevažne Vonkajším Západným Karpatom.

V popoludňajších hodinách sa uskutočnila terénna exkurzia v oblasti Zemplínskych vrchov a neogénneho vulkanického telesa Borsuk. Vedúcimi exkurzie boli J. Kobulský, Ľ. Gazdačko a P. Bačo. Po oboznámení sa s dvoma podstatnými odkryvmi (umelými zárezmi) v karbónskych ryolitovo-ryodacitových vulkanoklastikách súvrstvia Šimonovho vrchu v oblasti Malej Tŕne (obr. 9) a vo vrchno-permských ílovcoch s preplástkami zlepencov a pieskovcov černochovského súvrstvia v oblasti Malej Bary sa účastníci presunuli *the Viničky area, penetrating the Neogene extrusive body of Borsuk hill. The individual volcanological phenomena were presented by P. Bačo (Fig. 10).*

The excursion guide-texts about the Zemplinicum and the volcanic body Borsuk are published in a full range behind the guide-text to pre--congress field trip in Gemericum.

The scientific program of the meeting CETeG 2012 culminated by the announcement of the winner of the Radek Melka price for the best scientific article published in 2011 by the author younger than 35 years. The 2012 winner was Prokop Závada (Czech Republic; Fig. 6) for the article: Závada, P., Dědeček, P., Mach, K., Lexa, O., & Potužák, M., 2011: Emplacement dynamics of phonolite magma into maar-diatreme structures – Correlation of field, thermal modeling and AMS analogue modeling data. Journal of Volcanology and Geothermal Research, 201, 1–4, 210–226.

The winner of the category "The best student poster presented in the CETeG conference in 2012" was Lenka Kociánová (Czech Republic) with the poster Analysis of 3D structures in GIS (Fig. 7).

Both prices were given to winners in the untraditional atmosphere of the wine cellar inside the extrusive volcanic body Borsuk. After the ceremony, A. Żelaźniewicz (Poland), on behalf of the participants, addressed thanks for the organizers of the GETeG meeting for the high quality scientific program and the instructive field trips. Followingly L. I. Fodor invited the participants for the next CETeG meeting 2013, being organized in Hungary.

5. May 2012
Field trip along the East-Slovakian segment of the Pieniny Klippen Belt

The field trip was focussed on lithological and tectonic relations in the wider area of the Pieniny Klippen Belt between villages Jarabina and Litmanová. The leaders of the trip were D. Plašienka, R. Vojtko and J. Madzin (Fig. 11). Eight excursion localities are characterized in the contribution by Plašienka et al., published as the second article in this issue of Minerala Slovaca. First part of the field trip – localities in the valley of the Hlboký potok brook – presented the tectonites of so-called Gregoriánka Breccia and the litho-biostratigraphic profile through the Czorsztyn Succession. Subsequently, the participants moved along individual klippes above the quarry at the village of Jarabina into the Jarabina Narrows. The eastern slopes the gorge above the Malý Lipník brook, in combination with the lithology of nearby quarry, allowed the interpretation of the duplex setting of the Subpieniny nappe. The location of the borehole Jar-1 and the relation of the Subpieniny nappe and the Šariš unit were presented in the area of klippes situated west of the Jarabina Narrows. In the area of the ski resort near Litmanová the participants became familiar with the facies of Milpoš carbonate breccia, situated in the environment of turbiditic sandstones and shales of Jarmuta-Proč Formation.

do novovybudovaných vinárenských zariadení vo Viničkách. Súčasťou exkurzie bola aj prehliadka nových pivníc na uskladňovanie vína vyrazených v neogénnom extruzívnom telese Borsuk. Jednotlivé vulkanologické fenomény boli prezentované P. Bačom (obr. 10).

Texty exkurzných sprievodcov po zempliniku a telese Borsuk publikujeme v plnom rozsahu za sprievodcom k predkongresovej gemerickej exkurzii.

Vyvrcholením odborného programu stretnutia CETeG 2012 bolo vyhlásenie víťaza Ceny Radka Melky za najlepší vedecký článok autora do 35 rokov, publikovaný v roku 2011. Víťazom tohtoročnej ceny sa stal Prokop Závada (obr. 6) za článok: Závada, P., Dědeček, P., Mach, K., Lexa, O. & Potužák, M., 2011: Emplacement dynamics of phonolite magma into maar-diatreme structures — Correlation of field, thermal modelling and AMS analogue modelling data. Journal of Volcanology and Geothermal Research, 201, 1 – 4, 210 – 226.

Víťazkou kategórie Najlepší študentský poster prezentovaný na konferencii CETeG sa v roku 2012 stala Lenka Kociánová s posterom Analysis of 3D structures in GIS (obr. 7).

Obidve ceny boli odovzdané výhercom v štýlovom prostredí vínnej pivnice v extruzívnom telese Borsuk vo Viničkách. Po odovzdávaní cien sa A. Żelaźniewicz (Poľsko) v mene účastníkov poďakoval organizátorom podujatia za kvalitný vedecký program a inštruktívne exkurzie. Následne L. I. Fodor pozval účastníkov na ďalšie stretnutie CETeG 2013, ktoré sa uskutoční na budúci rok v Maďarsku.

5. máj 2012
Exkurzia do oblasti východoslovenského úseku Pieninského bradlového pásma

Exkurzia bola zameraná na litologické a tektonické vzťahy širšej oblasti bradlového pásma medzi obcami Jarabina a Litmanová. Vedúcimi exkurzie boli D. Plašienka, R. Vojtko a J. Madzin (obr. 11). Osem exkurzných lokalít je charakterizovaných v príspevku autorov Plašienka et al., publikovanom ako v poradí druhý článok tohto čísla časopisu Mineralia Slovaca. Prvá časť exkurzie – lokality v údolí Hlbokého potoka – prezentovala fáciu tektonitov, tzv. gregoriánske brekcie a lito-biostratigrafický profil cez czorsztynskú sukcesiu. Účastníci následne pretraverzovali pozdĺž jednotlivých vystupujúcich bradiel ponad kameňolom pri obci Jarabina do Jarabinského kaňonu. Východné svahy kaňonu nad tokom Malého Lipníka, v kombinácii s litológiou v neďalekom kameňolome, umožnili interpretáciu duplexnej stavby subpieninského príkrovu. Lokalizácia vrtu Jar-1 a prezentácia vzťahu subpieninského príkrovu a šarišskej jednotky boli prezentované v oblasti bradiel situovaných západne od Jarabinského kaňonu. V oblasti lyžiarskeho areálu pri Litmanovej sa účastníci oboznámili s fáciou karbonatických milpošských brekcií, situovaných v prostredí turbiditných prieskovcov a bridlíc jarmutsko--pročského súvrstvia.

Variscan tectonic setting vs. Alpine overprint in Gemericum (Inner Western Carpathians): Their role in the recent distribution of tectonic units in the eastern part of the territory as expressed in significant localities

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Abstract

Eight localities in the eastern part of Gemericum (Inner Western Carpathians) are presented for explaining the multiple tectonic overprints of Paleozoic and Mesozoic rock sequences.

The south-vergent Variscan collisional closure of the Lower Paleozoic basin caused the origin of the *Rakovec suture zone* with exhumed dismembered ophiolitic suite. The Westphalian age of the collision was supposed by geological criteria, as well as the Westphalian cooling age of clastic mica in the post-collisional Upper Carboniferous (Stephanian) detrital sequence in the North-Gemeric zone.

Two principal Variscan deformation phases are distinguished in the Gemeric domain: VD_1 – the south-vergent Carboniferous exhumation and obduction in the North Gemeric zone (323–275 Ma; origin of the Rakovec geosuture). This phase ended after the pressure release by an extension episode with a less distinct north-vergent sliding/unroofing (275–262 Ma) and the establishing of the Permo-Mesozoic sedimentary basin in the North-Gemeric zone. The following era of dominant south-vergent unroofing (VD_2 phase, 262–216 Ma) resulted in the origin of extended Mesozoic Meliata-Hallstatt basin in the South-Gemeric zone.

The closure of the basin in the South-Gemeric zone (AD_1 phase; Lower Cretaceous; 141–114 Ma) caused the north-vergent imbrication of the Gemeric sequences, overthrusting of Gemericum as a basement nappe on Veporicum, but also a north-vergent transport of superficial nappes including the Meliatic nappe (Bôrka nappe) and Silicic nappe. The transpression kinematics at the beginning of the AD_1 collision prevailed, and the suture zone (Rožňava discontinuity zone) originated. The overthrusting of the basement nappe of Gemericum on Veporicum and the thermal consequences of the thickened crust caused the south-vergent unroofing of the overthrusted Gemeric sequences from Veporicum in the Upper Cretaceous phase AD_2 (107–82 Ma). Due to the recent arc-bending of the contact zone between both megaunits, caused by conjugate shearing in AD_3 phase (76 Ma-recent), the meso- and microstructural evidences of AD_2 unroofing demonstrate apparently opposing vergence – in the western contact zone the unroofing is towards the E and SE, and in the eastern contact zone to the SW. Among the principal conjugate AD_3 shear zones in the eastern part of Gemericum belong the sinistral ENE–WSW trending Transgemeric shear zone and the dextral NW–SE trending Košice–Margecany shear zone, playing the most important role in the recent tectonic setting of this territory.

Key words: tectonics, Variscan, Alpine, Rakovec suture zone, Rožňava discontinuity zone, Opátka, Margecany, Jaklovce, Gelnica, Závadka, Smolník, Šugovská dolina valley, Gemericum, Veporicum, Meliaticum, Silicicum, Western Carpathians

Short review of the geological and tectonic research in the Gemeric domain and its principal results

Long-lasting research in the territory of the Spiš-Gemer Ore Mts., done from the time of the famous Slovak geologist Dionýz Štúr (1868), resulted in the 1980s in establishing of two interpretations of the geological setting of Gemericum.

The results of the first research stream were summarized in the Explanations to the geological map of the Slovak Ore Mts. – Eastern part in the scale 1 : 50 000 (Bajaník and Vozárová, eds., 1983). The early evolution of Paleozoic sedimentary basin is characterized with cyclic flyschoid sedimentation accompanied with synchronous acid, resp. bimodal volcanism during Upper Cambrian to Lower Devonian. Products of this early evolutionary stage were included into the **Gelnica Group (Vlachovo, Bystrý potok and Drnava Fms.).** Younger Devonian-Lower Carboniferous? **Rakovec Group (Štós, Smrečinka and Sykavka Fms.)** consists of rocks originating during changed paleogeographic conditions of prevailing basalt volcanic activity. The volcanosedimentary evolution of the basin has been interrupted in Bretonian phase. Following Carboniferous transgression with shallow-marine sedimentation in the environment of delta fans was reflected in the **Črmeľ** and **Dobšiná Groups** (**Ochtiná, Rudňany, Zlatník** and **Hámor Fms.**), present in the area of the North Gemeric zone. Deepening of the sedimentary basin has activated the volcanic activity with the effusions of paleobasats and volcaniclastics. The termination of the Carboniferous sedimentation with the parallic sequences of **Hámor Fm.** was caused by Asturian phase of epeirogenic character. In Permian (**Krompachy Group; Knola, Petrova hora** and **Novoveská Huta Fms.**), the coarse--detritic material with two horizons of acid volcanism has deposited in differentiated basins in continental conditions. The end of the Permian sedimentation of lagoonal character was followed by the shallow marine sedimentation **(Stratená Group)** in the environment of stable shelf with locally developed zones of pelagic sedimentation.

Upper Paleozoic sedimentation on the south of **Gemericum (Rožňava Fm. of the Gočaltovo Group)** had firstly the character of wild rivers ramifying into alluvial lowland. The margin of the basin **(Štítnik Fm.)** was situated on faults with the occasional volcanic activity. The coastal sedimentation in the conditions of stable shelf continued till the Middle Anisian. In Pelsonian there occurred first tectonic activity, deepening of the sedimentary basin, basic volcanism and gradual sedimentation of rocks included into **Meliata Group**.

Recently the above described research stream has applied the terrane concept (Vozárová and Vozár, 1993, 1996; Vozár et al., 2010). According this, the Gemericum consists of the **Spiš Composite Terrane**, representing a relict of subducted oceanic to intermediate crust, and the **Gelnica Terrane**, being a relic of the forearc basin associated with ensialic volcanic arc on an active continental margin. Lithology and stratigraphy of the Carboniferous-Permian basins reflects the Late Variscan collisional events and southern polarity of Variscan orogeny in the Western Carpathians.

Synchronously with the above presented concept a model of continual Lower Paleozoic riftogenesis on continental crust with the stages of marine transgression, shelf development, rift activation

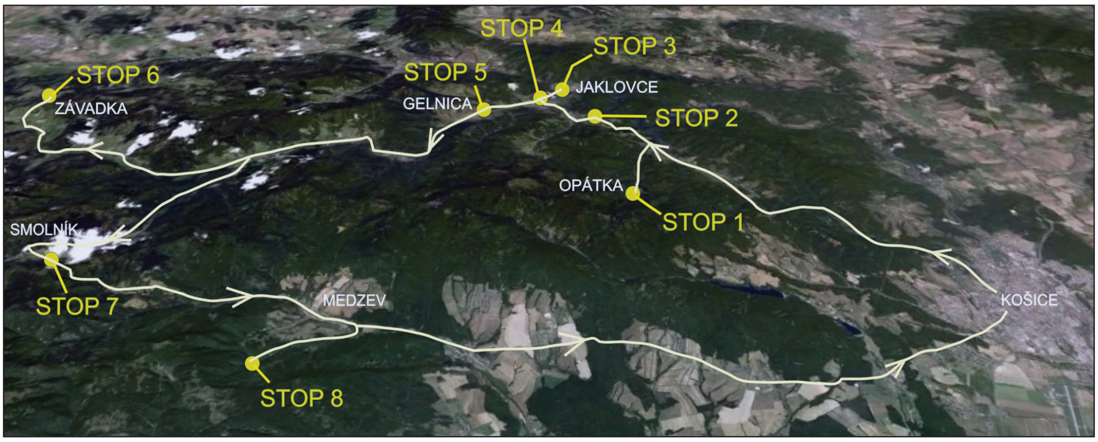

Fig. 1. The route focussed on Lower Paleozoic sequences of Gemericum (localities 1, 5, 7 – Opátka, Gelnica, Smolník), as well as the multiple overprint in the contact zone of Gemericum with Veporicum (3 – Margecany). The loc. 2 above the Veľký Folkmar village allows a general explanation of general tectonic setting with sceneric view on majority of tectonic units. The differing tectonometamorphic overprint of two types of conglomerates in the North-Gemeric zone is on display at Závadka village (loc. 6). The instructive localities of exhumed Meliaticum are accessible at Jaklovce village (4) in the North-Gemeric zone, as well as in the Šugovská dolina valley (8) in the Southern Gemericum. The base-map is taken from the Google Earth.

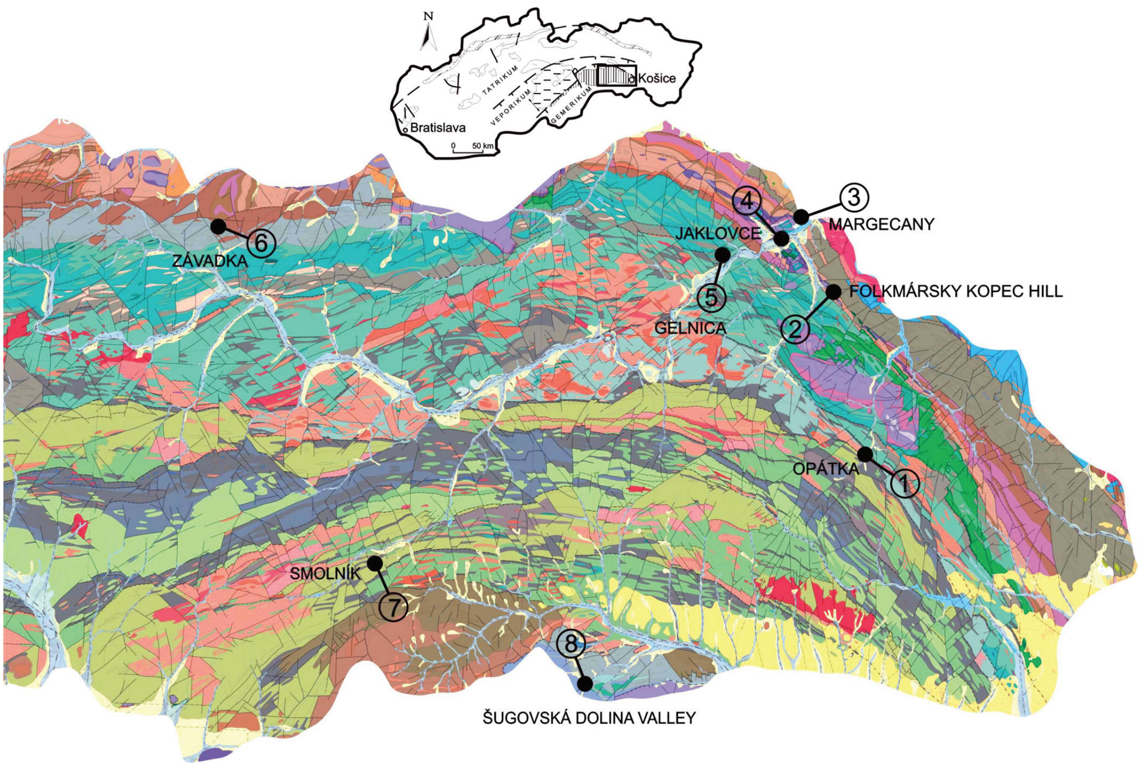

Fig. 2. Position of important geological localities of the eastern Gemericum in the General geological map of the Spiš-Gemer Ore Mts. (Grecula et al., 2009).

and rapid rifting has been developed (Grecula, 1982). Batygenetic phase has finished with volcanic phase. The ground for riftogenic model (l.c.) has been based on time-synchronization of the Lower Paleozoic sedimentary-volcanic activity with generally uniform facial development in the single Lower Paleozoic **Volovec Group**. Geodynamic evolution of sedimentary basin has been reflected in the uniformly distinguished formations for the whole sedimentary space. Lower **Betliar Fm.** is detritic, consisting from the black laminated pelitic-silty phyllites, with lydites and carbonates in the upper part of the formation **(Holec Beds)**. Middle, **Smolnik Fm.** consists of variegated green phyllites and flysch psammitic-pelitic sediments. Volcanic rocks of basalt-keratophyre formation are present at the base of the Smolnik Fm. (Lower Variegated Volcanic Complex). Upper, volcanic **Hnilec Fm.,** is formed with Upper Variegated Volcanic Complex at the base and spatially differentiated volcanic horizon in upper parts. On the north of Gemericum the basic volcanic products prevail, while in the middle and south of the territory the acid and intermediate volcanics of rhyolite, dacite and andesite nature are preferably present. The concept was made more detail in the General geological map of the Spiš-Gemer Ore Mts. at a scale 1 : 50 000 (Grecula et al., 2009) and accompanied Explanations to geological map (Grecula and Kobulský, 2011). The Volovec Group was upgraded to **Volovec Supergroup** consisting of Rakovec Group and Gelnica Group, though the lithological division on Betliar, Smolník and Hnilec Formations in both groups remained preserved after earlier concept (Grecula, 1982 a following works). This division we will apply in the following text.

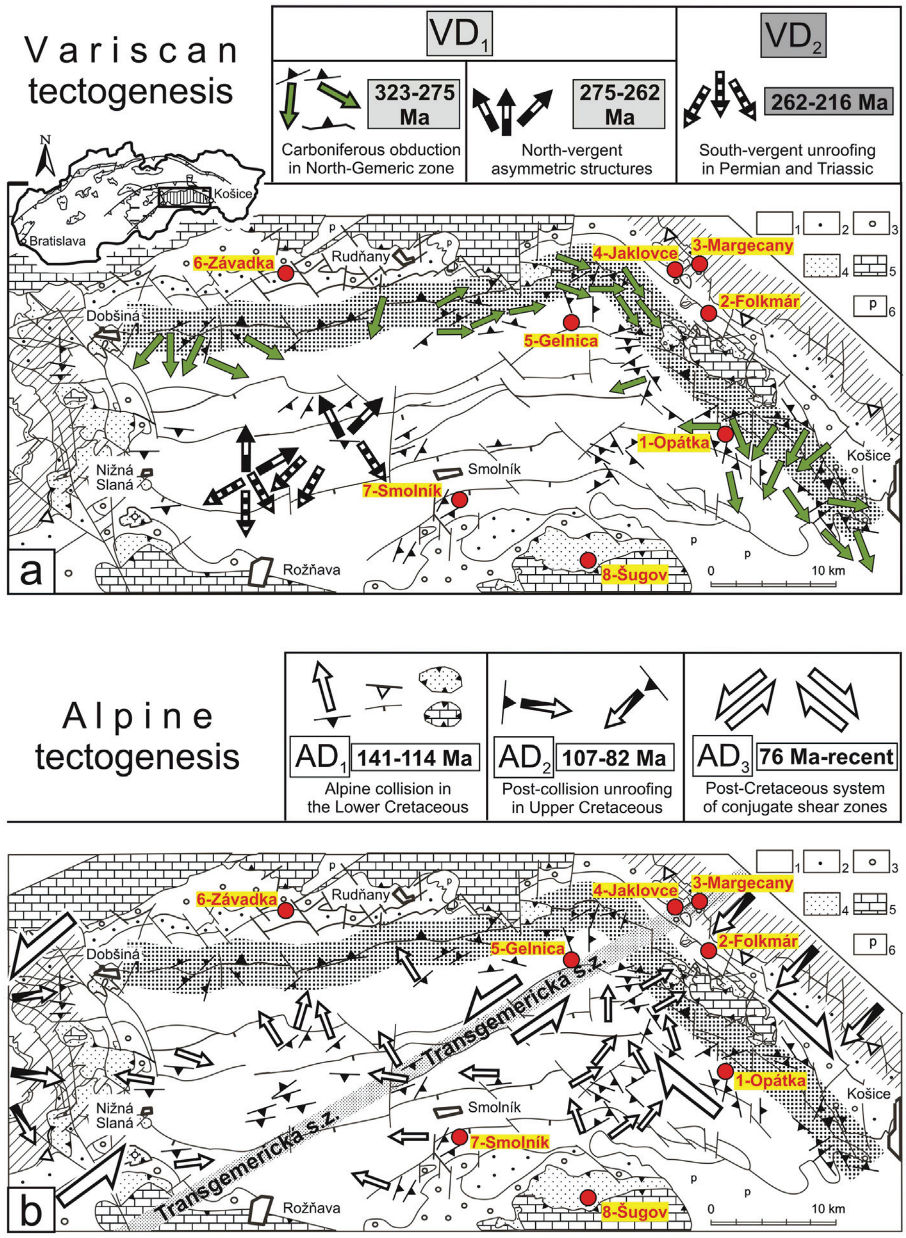

Fig. 3. Kinematics of Variscan and Alpine tectogeneses (Németh in Radvanec et al., 2007) and the position of instructive localities, related to Variscan and Alpine tectonic setting. 1 – Lower Paleozoic sequences of Gemericum; 2 – Carboniferous rocks of Gemericum and in the contact zone of Gemericum with Veporicum; 3 – Permian rocks of Gemericum; 4 – Upper Paleozoic and Mesozoic rocks of Meliaticum; 5 – Mesozoic rocks of Silicicum; 6 – Paleogene.

The south-vergent collisional closure of the Lower Paleozoic basin caused the origin of the Variscan *Rakovec suture zone* (Németh, 2002) with exhumed dismembered ophiolitic suite of the central part of former basin. The Westphalian age of the collision is supposed by geological criteria, as well as the Westphalian cooling age 314.1 Ma of detrital mica in post-collisional Upper Carboniferous (Stephanian) detrital sequence near the town of Dobšiná (Dallmeyer et al., 2006).

Two principal deformation phases were distinguished in the Variscan evolution of the Gemeric domain (Németh in Radvanec et al., 2007), being indicated by the monazite-uraninite isochrones (Konečný, ibid.): VD_1 – the south-vergent Carboniferous exhumation and obduction in the North Gemeric zone (323–275 Ma; origin of the Rakovec geosuture). At the end of this phase after the pressure release an extension episode initiated a less distinct north-vergent sliding/unroofing, revealed by microstructures (Németh in Radvanec et al., 2007; 275–262 Ma). It also indicated the beginning of the origin of the Permo-Mesozoic sedimentary basin in the North-Gemeric zone. The following era of dominant south-vergent unroofing (VD_2 phase, 262–216 Ma) resulted in the origin of extended Mesozoic sedimentary basin (Meliata-Hallstatt basin) in the South-Gemeric zone (Németh in l.c.).

As revealed by overprinting relations and geochronological data, the closure of the basin in the South-Gemeric zone (AD_1 phase; Lower Cretaceous; 141–114 Ma) caused the north-vergent imbrication of the Gemeric sequences, overthrusting of Gemericum as a basement nappe on Veporicum, but also a transport of superficial nappes including the Meliatic nappe (Bôrka nappe) and Silicic nappe. The sinistral transpression kinematics at the beginning of the AD_1 collision prevailed, and the suture zone (Rožňava discontinuity zone) originated. The overthrusting of the basement nappe of Gemericum on Veporicum and the thermal consequences of the thickened crust caused the south-vergent unroofing of the overthrusted Gemeric sequences from Veporicum in Upper Cretaceous phase AD_2 (107–82 Ma; cf. Maluski et al., 1993; Dallmeyer et al., 1996, 2006, a.o.). Because the recent arc-bending of the contact zone between both megaunits, caused by conjugate shearing in AD_3 (76 Ma-recent), the meso- and microstructural evidences of AD_2 unroofing demonstrate apparently contradicting vergence – in the western contact zone the unroofing is towards east and south-east, but in eastern contact zone towards the south-west (Németh, 2002). From the conjugate AD_3 shear zones in presented area of the eastern part of Gemericum the sinistral ENE–WSW trending Transgemeric shear zone and the dextral Košice–Margecany shear zone trending NW–SE (cf. Grecula et al., 1990) play the most important role in the recent tectonic setting of this territory.

Important localities demonstrating the geological and tectonic evolution of the eastern part of Gemeric domain

1 – Opátka village – Outcrops of tectonized Lower Paleozoic metapyroclastics of intermediate and acid volcanism of the Hnilec Formation of Gelnica Group in closeness of the Rakovec suture zone. Location at the southern end of the village, 48°47'02.03'' S, 21°03'15.04'' E.

The rocks are located in the footwall position close to the Variscan overthrust plane of exhumed Rakovec Group. The Variscan exhumation is reflected in the NNE to NE dip of primary foliation with ESE trending lineations (VD_1). Numerous asymmetric structures produced in ductile régime demonstrate the dextral south-vergent exhumation. The Alpine AD_1 imbrication is relatively poor due to the rigid overprinted lithology and is observable by rare faults dipping to SW (Fig. 5).

2 – Folkmarský kopec hill – The saddle between the Ružín water reservoir and the village of Veľký Folkmar, the sceneric view from both sides of the state road, 48°50'58.13'' N, 21°01'54.72'' E (Fig. 6).

The view towards the NNW visualizes the position of four principal megatectonic units of the Western Carpathians: Gemericum (the surrounding of observation point), Meliaticum in the North-Gemeric zone in allochthonous position, as well as Veporicum and Tatricum in the backside (the Branisko Mts.). The view to E manifests the Veporicum with its Permo-Triassic and Jurassic cover, as well as Carboniferous and Permian sequences in the outliers of Hronicum located on Veporicum in the apical parts of the hills. The contact between both megaunits – Gemericum and Veporicum – demonstrates multiple overprint by the AD_1 (NE-vergent overthrusting) and AD_2 (SW-vergent unroofing) phases, and moreover it is sheared by the dextral Košice–Margecany (Fig. 7) shear zone of AD_3 phase. In classical interpretations the dividing line between both megaunits was represented by the Lubeník–Margecany line (e.g. Maheľ, 1986), having attributed only overthrusting kinematics (of AD_1 phase).

3 – Margecany – The immediate contact of overthrusted cover sequences of Gemericum on Veporic crystalline basement. The Veporic cover was removed by tectonic reduction during three deformation phases $AD_{1–3}$. The cut of the state road between Jaklovce and Krompachy near the Margecany church, 48°53'13.39'' N, 21°00'22.27'' E (Fig. 8).

The Veporicum of the Čierna hora Mts. manifests the highly sheared Alpine fold-thrust setting of NW–SE trend. The antiformal core consists of crystalline basement rocks, rimmed by the Upper Carboniferous, Permian, Triassic and Upper Jurassic cover formations. They are overlain by the Choč nappe (Carboniferous-Triassic of

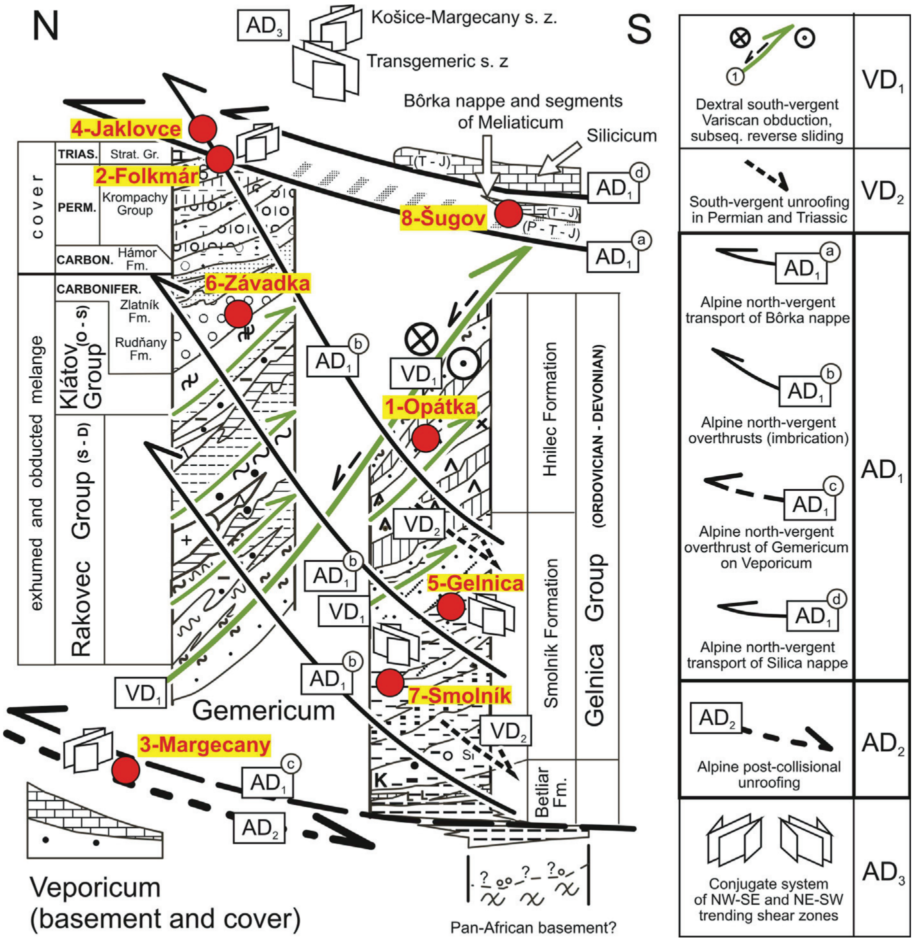

Fig. 4. Lithotectonic relations in the Gemeric domain (modified after Németh, 2005, and Németh in Radvanec et al., 2007) and position of instructive localities covering a wide range of lithotectonic relations.

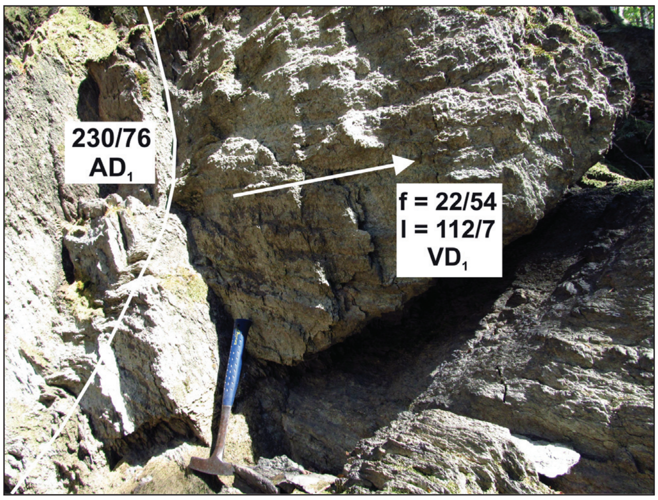

Fig. 5. Ductile VD_1 stretching lineations indicating tectonic transport to SE and brittle-ductile AD_1 faults penetrating earlier setting. Tectonized metapyroclastics of the upper parts of Gelnica Group at the southern end of Opátka village. Photo Z. Németh.

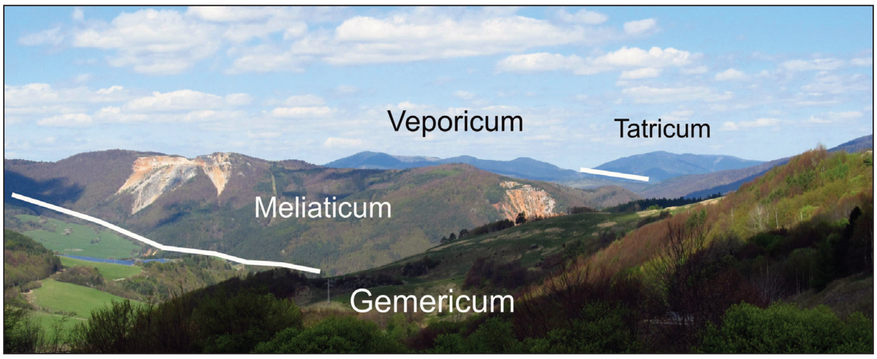

Fig. 6. Panoramatic view to NNW from the Folkmársky kopec hill demonstrates the zonality of the main megatectonic units of the Alpine setting of the Western Carpathians – the nappe outlier of Meliaticum in the North-Gemeric zone, as well as Veporicum and Tatricum in the Branisko Mts. Photo Z. Németh.

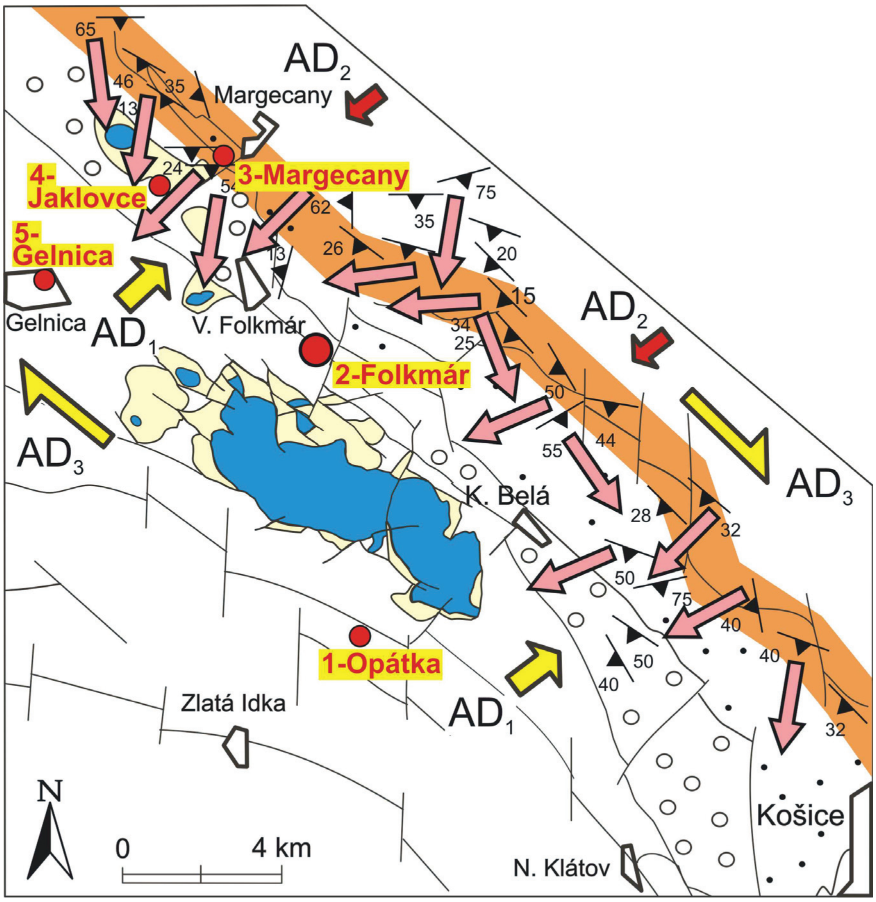

Fig. 7. The study of asymmetric mesostructures and microtectonic indicators, including the LPO of quartzites and calcitic marbles, has revealed the unroofing kinematics of the AD_2 phase, as prevailing ductile deformation regime in the monomineral lithologies of the Veporic cover (Németh, 2001). The lithology in the map corresponds with that in Fig. 3. Locality 2 – Folkmarský kopec hill is visualized by the red circle.

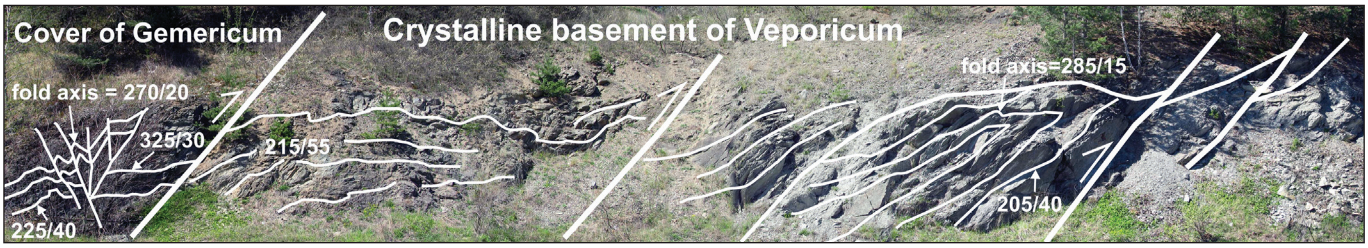

Fig. 8. The overthrust of Gemericum on Veporicum during AD_1 as manifested in the road cut trending SW–NE, i.e. being transversal to the contact zone. The overthrusting is indicated by pervasive mylonitization (S/C structures, porphyroclasts, mica-fishes, shear bands). Despite, also post--collision AD_2 unroofing is observable by asymmetric structures, but the dominating is the dextral shearing during AD_3 reactivating the earlier disjunctive structures. Veporic crystalline basement consists of the Bujanová Complex gneissose diaphtorites and migmatitic amphibolites, having locally preserved Variscan ductile deformation. The Gemericum in the cross-cut (left – SW part of the picture) is built of Upper Carboniferous conglomerates of Hámor Fm., intercalated by greywackes, sandstones and black schists. Height of the view is 6 m.

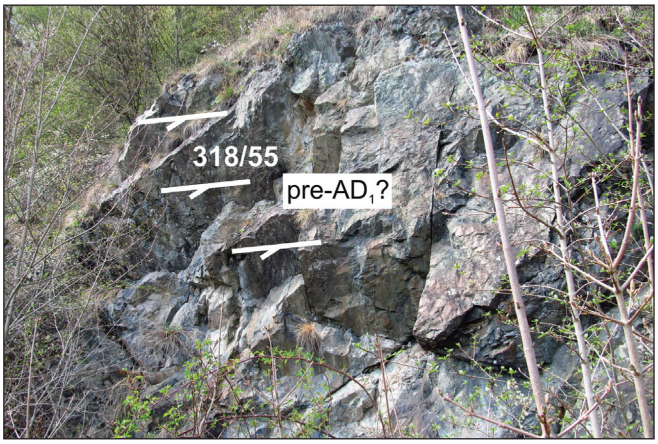

Fig. 9. In the SE part of the elongated outcrop near the directorate building of the lime-producing factory at the Jaklovce village, the exhumed Meliatic suite is affected by the AD_3 shearing trending ENE–WSW and dipping to SSE (148/60°). Contrary to this, the outcrop located 200 m to SW, as well as the suite in the upper parts of the sequence manifest the older cleavage dipping to NW (318/55°) and corresponding with the bedding and secondary foliation in the quarry in the upper part of the Kurtová skala hill (gen. 330/55°), having proved the position of the allochthonous outlier of Meliaticum (cf. Németh et al., 2012). Orientation of photographs is top to W. Photos by Z. Németh.

Hronicum). The position of this outlier indicates the most probable primary sedimentary area of the Hronicum in the suture between Gemericum and Veporicum, or less probable south of Gemericum.

The Veporic crystalline basement consists of three lithostratigraphical units (Jacko, 1985). The lowermost Lodina Complex is composed mainly of diaphtoritic gneisses (incl. phyllonites) intercalated by thin aphibolite bodies. The Miklušovce Complex is in tectonic overlier, consisting of migmatites and local aplitic-granite bodies. The highest positioned is the Bujanová Complex, rimming prevailingly the SW limb of the antiform (towards the Gemericum), and composed mainly of tabular granodiorite bodies intruded into the gneissose-migmatitic bodies and amphibolites.

Despite the strong Alpine shearing, also the Lower Paleozoic Ar/Ar plateau age was revealed from phyllonite muscovites (Dallmeyer et al., 2006; sample G-9 ibid.; 329.6 ± 0.2 Ma), indicating the preserved remnants of the Variscan south-vergent thrusting inside the crystalline basement – the overthrusting of the Miklušovce and Bujanová complexes on the Lodina Complex. The metamorphic paragenesis of the sample was quartz-muscovite-chlorite-epidote--ilmenite (diaphtorite of gneiss).

4 – <u>Jaklovce</u> – The artificial railway cut in the vicinity of the directorate building of the lime-producing factory, 48°52' 45.87'' N, 20°59'47.45'' E (Fig. 9).

The melange of Meliaticum in the North-Gemeric zone, consisting of ultramafic rocks, gabbros and basalts in the environment of radiolarites and marbles. The allochthonous position of the sequence in the area of the Kurtová skala hill was recently proved by paleopiezometry (Németh et al., 2012), as well as by the principal angular discordance of its NW-dipping exhumation setting, contrasting with the general NW–SE trending $AD_{1–3}$ tectonic plan (l.c.). The internal setting of the succession of silicitic schists with basalt and diastrophic breccia in the Meliatic Jurassic accretion prism cropping out in the presented locality was published by Putiš et al. (2011), providing the new zircon U-Pb SIMS SHRIMP data.

The Middle Triassic beds of reddish and greenish cherty schists, marbles and radiolarites contain thin basaltic tuff interbeds and 3 m thick basaltic bed in the upper part of the sequence. A zircon concordant age of 359 ± 7 Ma is interpreted (l.c.) as the Lower Carboniferous source age of zircon grains, present in this Middle Triassic basalt, because its age is well constrained with the findings of Middle Triassic radiolarites in the hosting Middle Triassic cherty beds. Zircon morphology indicated the S-type (Gemeric) granites as the source rocks. Metabasalts, metadolerites and metacherts, with still preserved magmatic ophitic or amygdaloidal textures, contain actinolite rimmed by ferrowinchite/winchite/riebeckite in metamorphic veins. It indicates a higher-pressure metamorphic overprint that is well-known and dated from the Meliatic Bôrka nappe as the Upper Jurassic (l.c.). Similarly, the thin veinlets with the blue sodic amphibole compositionally close to magnesioriebeckite in this rock sequence were found by Ivan et al. (2009). Probably a short-lasting individual metamorphic phase at elevated pressure (~600 MPa) was responsible for the formation of the magnesioriebeckite/riebeckite veinlets, followed by the pressure relaxation and short metamorphic overprint in the greenschist facies conditions (300 MPa; l.c.). This metamorphic evolution can be interpreted as a manifestation of the Meliata ocean subduction in the Upper Jurassic, when the oceanic rocks were involved into the uppermost part of the subducting slab and subsequently exhumed and tectonized. Moreover, the concept of subduction, exhumation and transport of the rock sequence, recently located as a Meliatic outlier at the village of Jaklovce, is well confirmed by the finding of the highest until revealed differential stresses in calcitic marbles in this suite, reaching 429.55 MPa (Németh et al., 2012).

5 – <u>Gelnica</u> – Plastic deformation of the Lower Paleozoic chlorite-sericite phyllites of the greenschists facies of the Smolník Fm., Gelnica Group, reflects the sinistral shearing directly in the Transgemeric shear zone trending ENE–WSW. Extended outcrop with numerous kinematic indicators, including a-tectonites, allows to study mesostructures in two nearly perpendicular sections – parallel with the AD_3 shearing and perpendicular to this shearing. Road cut 360 m to SW of the main railway station in the town of Gelnica, 49°51'24.43'' N, 20°56'41.34'' E (Fig. 10).

6 – <u>Závadka</u> – Strongly contrasting tectonometamorphic overprint of two conglomeratic facies: the Carboniferous Rudňany Conglomerates (Westphalian) of the Rudňany Fm. of Dobšiná Group exhumed in VD_1 and the cover Permian conglomerates (Knola Fm., Krompachy Group), deformed during Alpine AD_1 imbrication. Outcrops at the Závadka village, north of the village of Nálepkovo. Old quarry in the Rudňany Conglomerates is located at the state road to SE of Závadka, 48°51'42.58''. Extended outcrops of the Permian conglomerates are located to SSW of Závadka, 48°51'42.51'' N, 20°36'53.54'' E (Figs. 11 and 12).

The peculiarity of the polymict Carboniferous Rudňany Conglomerates is their higher pressure metamorphism (Radvanec, 1998) and strong recrystallization, which is striking also in visited locality. In numerous cases the differences among particuliar clasts and the matrix are obscured to such level that a rock obtains an appearance resembling e.g. basalt. The conglomerate consists of clasts of crystalline basement (e.g. gneisses, mica-schists, amphibolites; the most probable is the Veporic basement), as well

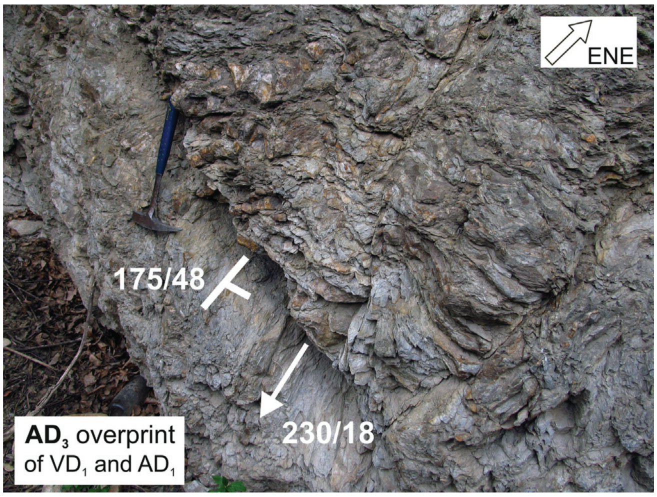

Fig. 10. Alpine AD_3 overprint of former Variscan VD_1 deformation, related to the ESE-vergent overthrusting of the exhumed Rakovec mélange in the hanging wall, and, moreover, being imbricated by the AD_1 north-vergent thrusting. Locality Gelnica. Photo Z. Németh.

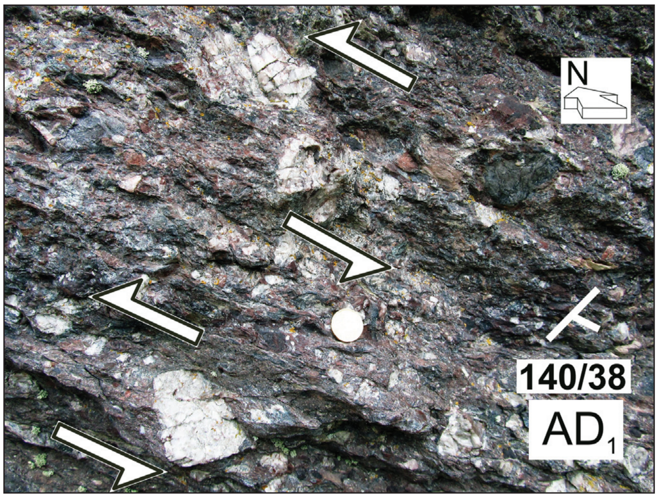

Fig. 12. Brittle-ductile Alpine overprint in Permian cover conglomerates indicates top-to-the NW tectonic imbrication during AD_1 phase Závadka.

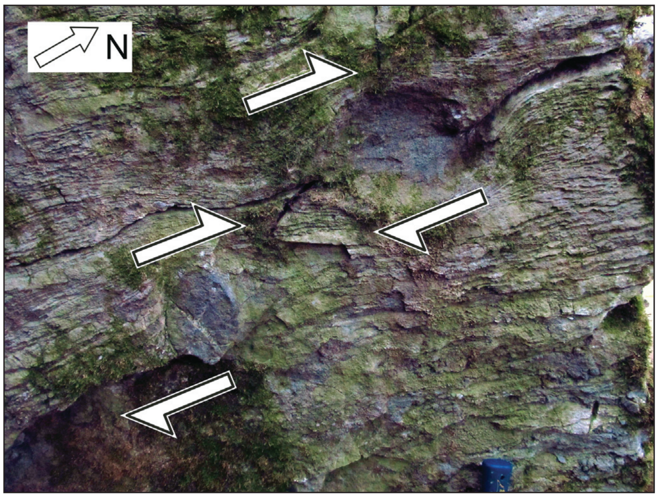

Fig. 13. Rotated porphyroclasts of glaucophanites in the calcitic marbles. Besides blue amphibole of glaucophane composition the metabasites contain albite, epidote, phengite, titanite and rarely also garnet, paragonite and Na-pyroxene. At the contact with marble they usually contain actinolite. Blue amphibole is zoned with purple-blue core rich in Fe^{3+} and pale-blue rim rich in Al. Na-pyroxene occurs in some coarse-grained unfoliated metabasites and it is mostly of aegirine composition. Maximum jadeite content found in pyroxene in this locality was 53 mol.% (Faryad and Henjes-Kunst, 1995). Locality Šugovská dolina valley. Photo Z. Németh. ▶

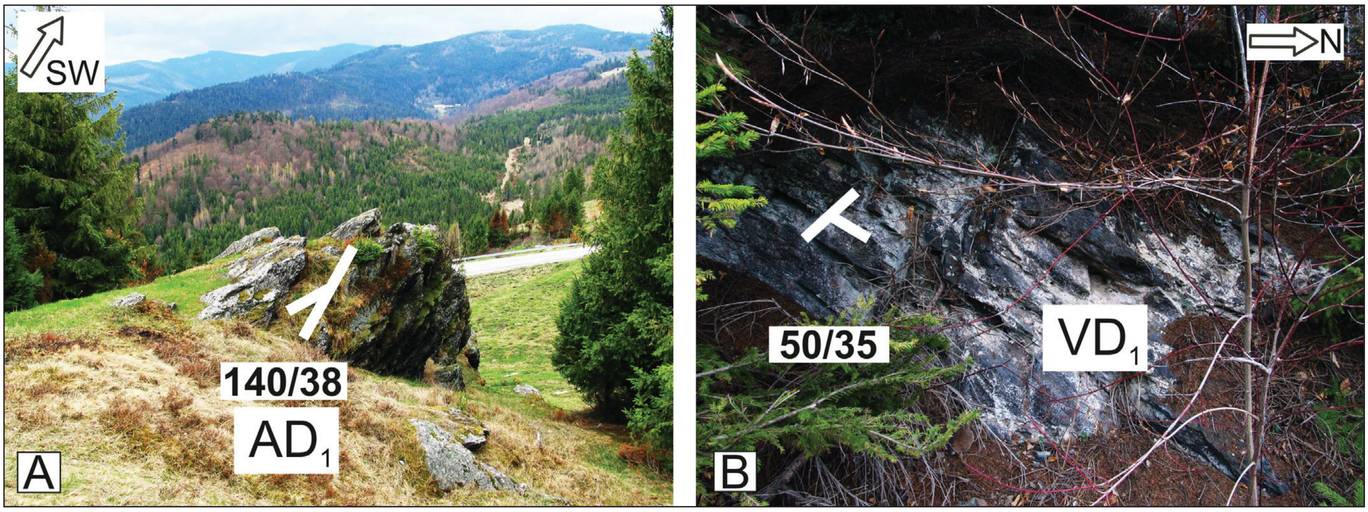

Fig. 11A, B. Contrasting dip of secondary foliation in the Permian conglomerates of the Knola Fm. (**A;** 140/38; imbrication during AD_1), and Carboniferous strongly recrystallized conglomerates of Rudňany Fm. (**B;** 50/35, deformation during Wesphalian exhumation). Locality Závadka.

as lithology close to Rakovec oceanic zone of Gemericum (basalts, green schists), but also of Lower Paleozoic Gelnica Group (e.g. quartz pebbles). The metaconglomerate occurs in two modes of mineral assemblages (l.c.): The first one of M1 metamorphism (Grt_{Alm} + Hbl + Png_1 + Pl_1 + Chl_1 + Rtl_1 + Spn_1 + Ilm_1 + Tur_1 + C + Ap + Qtz) is present in clasts. This mineral assemblage was stable in the younger M2 metamorphism. The second and younger mineral assemblage M2 (Act + Png_2 + Pl_2(Ab) + Chl_{2-3} + Hem + Ti-Hem + Psb + Psr + Ilm_2 + Rtl_2 + Spn_2 + inclusions of Cal in Hem + Tur_2 + Qtz) crystallized in the high-pressure metamorphism of P-T conditions around 12 Kbar, 600–550 °C. The retrograde metamorphism M2 stopped at 8 Kbar and 520–530 °C (l.c.).

There is necessary to mention that in the eastern part of Gemericum also facies of the Rudňany Conglomerates occur, which underwent only diagenesis and a weak metamorphic overprint of greenschists facies. The changes of metamorphic gradient along the strip of Rudňany Conglomerates agree with the concept of non--linearity of geological (convergent) boundaries (Németh, 2003), and indicate their M2 metamorphism as subduction one and a trench as the place where their detritus was cumulated.

7 – Smolník – The Lower Paleozoic chlorite-sericite schists of Smolník Fm. of Gelnica Group in the southern Gemericum, overprint by Alpine shearing and origin of steeply dipping secondary foliation. Outcrops at chapel near the state road app. 500 m south of the town of Smolník; 48°43'26.32'' N, 20°43'59.02'' E.

The outcrop behind the chapel manifests moderate dip to south (180-190/0-30) and numerous kinematic indicators. The double overprint relates to deformation phases VD_1 and AD_1. Following the road to SE the steeply dipping chlorite-sericite quartzy schists are observable of ENE–WSW trend (150/65-90). This position relates with a disjunctive shear zone of AD_3 phase.

8 – Šugovská dolina valley – Exhumed Mesozoic Meliatic suite of glaucophanites and marbles. Rotated glaucophanite porphyroclasts (diameter up to 12 cm) in marbles demonstrate the top-to-the north shearing.Termination of the Šugovská dolina valley app. 600 m to SSE of the Šugov ranch; 48°40'12.43'' N, 20°52'42.43'' E (Fig. 13).

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New knowledge about the geological setting of Zemplinicum in the Zemplínske vrchy Mts.

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Abstract

Article presents new geological and tectonic setting of Zemplinicum, the tectonic unit cropping out in the Zemplínske vrchy Mts. in the southern part of the easternmost Slovakia. The main emphasis is given on lithostratigraphy of the Upper Carboniferous-Permian-Mesozoic cover sequences and Neogene prevailingly extrusive volcanic bodies. The geological setting of the Zemplínske vrchy Mts. is interpreted without the partial nappes, as well as without the lower and upper tectonic slices in the Ladmovce area. The repetition of the Carboniferous and Permian fms. in the deep boreholes in the E side of the territory is interpreted by the faults of the NNW–SSE trend of the overthrust character with steep dip to WSW. Different situation is in the N and NW part of the territory, where in the anthracite deposit Veľká Tŕňa the steep backward thrusts of NNW–SSE trend dipping to ENE were verified. The Zemplinicum in the Zemplínske vrchy Mts. has a block tectonic setting with segmentation by the above mentioned NNW–SSE trending faults, as well as the younger fault system of NE–SW (to ENE–WSW) trends with variegated displacement amplitude.

Key words: lithology, tectonics, Zemplinicum, Zemplínske vrchy Mts., Western Carpathians

The horst of Zemplinicum, cropping out in the Zemplínske vrchy Mts., is located in the southern part of the easternmost Slovakia (Fig. 1). The horst is surrounded by the Neogene molasse sediments, and locally, at the margins and depressions also by the volcanic sequences (Baňacký et al., 1988, 1989).

Zemplinicum consists of crystalline basement and the Upper Paleozoic and Mesozoic cover (Figs. 2–4). The crystalline basement is cropping out only in the area of the Byšta village – the Byšta Complex of the Upper Proterozoic(?) to Lower Carboniferous age. It consists of metamorphosed rocks (gneisses, amphibolites, migmatites), usually tectonized and forming blastomylonites. The non-metamorphosed Upper Paleozoic cover sequences are peculiar in comparison with those in other units of the Western Carpathians (Grecula et al., 1982; Együd et al., 1985; Kobulský et al., 1989, 1992,

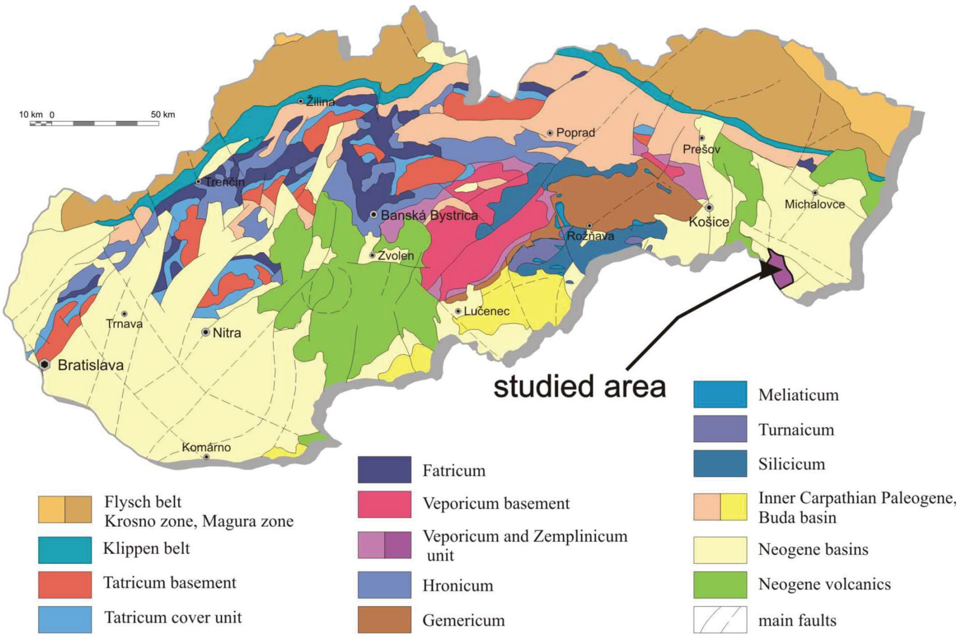

Fig. 1. Position of Zemplinicum in the general tectonic scheme of the Western Carpathians.

2011). The lowermost of the Upper Paleozoic sequences (Fig. 4) are represented by the Čierna hora Fm. (Westphalian C–D). They consist of cyclic alternation of the fine-grained conglomerates, sandstones and schists with interbeds of rhyolite volcaniclastics. The higher deposited Čerhov Fm. is characterized by the cyclic alternation of coarse-grained conglomerates, sandstones and schists, locally with the coal seams (Westphalian C–D) and the Tŕňa Fm. of coal cycles and cyclothemes, where the fine-grained conglomerates, sandstones and schists alternate with the metaantracite seams (Stephanian A–B). The supreme part of the Uppermost Carboniferous was formed by the volcanosedimentary Šimonov vrch Fm. of prevailing sandstones and schists with conglomerates and often rhyolite and rhyodacite volcaniclastic interbeds (Stephanian C–D).

The Lower Permian (Fig. 4) is represented by the Kašov Fm. with characteristic presence of variegated sandstones and shales with conglomerate and rhyodacite volcanic and volcaniclastic interbeds. The Upper Permian is formed with Bara Fm. – polymict

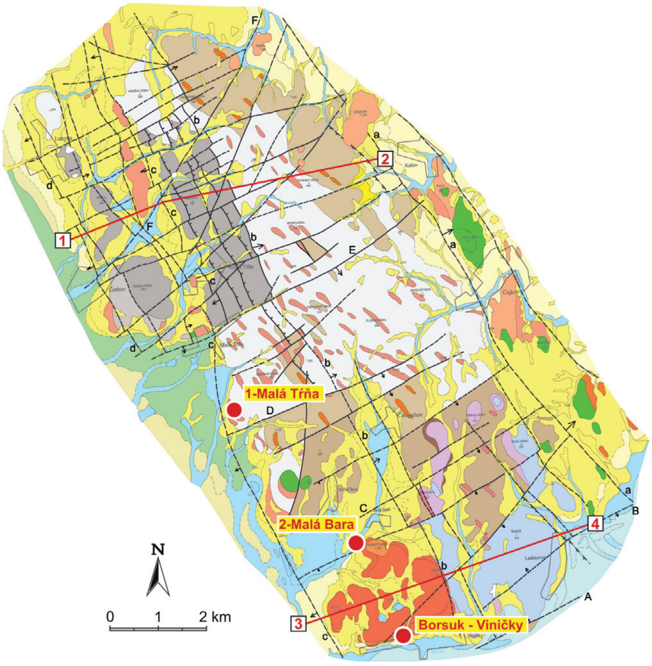

Fig. 2. Tectonic scheme of the Zemplínske vrchy Mts. (Kobulský and Gazdačko in Kobulský et al., 2011) with position of localities 1 and 2, as well as the position of volcanic body Borsuk. Tectonic scheme indicates the principal overthrusts and faults. Two dominating trends of faults were revealed: Faults of NW–SE direction: a – Somotor fault; b – Viničky fault; c – Tŕňa fault; d – Čerhov fault. Faults of NE–SW direction: A – Poľana fault; B – Kapušany fault; C – Zemplín fault; D – Cejkov fault; E – Kašov fault; F – transversal Hrčeľ fault. The detail information about the lithology is available comparing two cross-sections in Fig. 3.

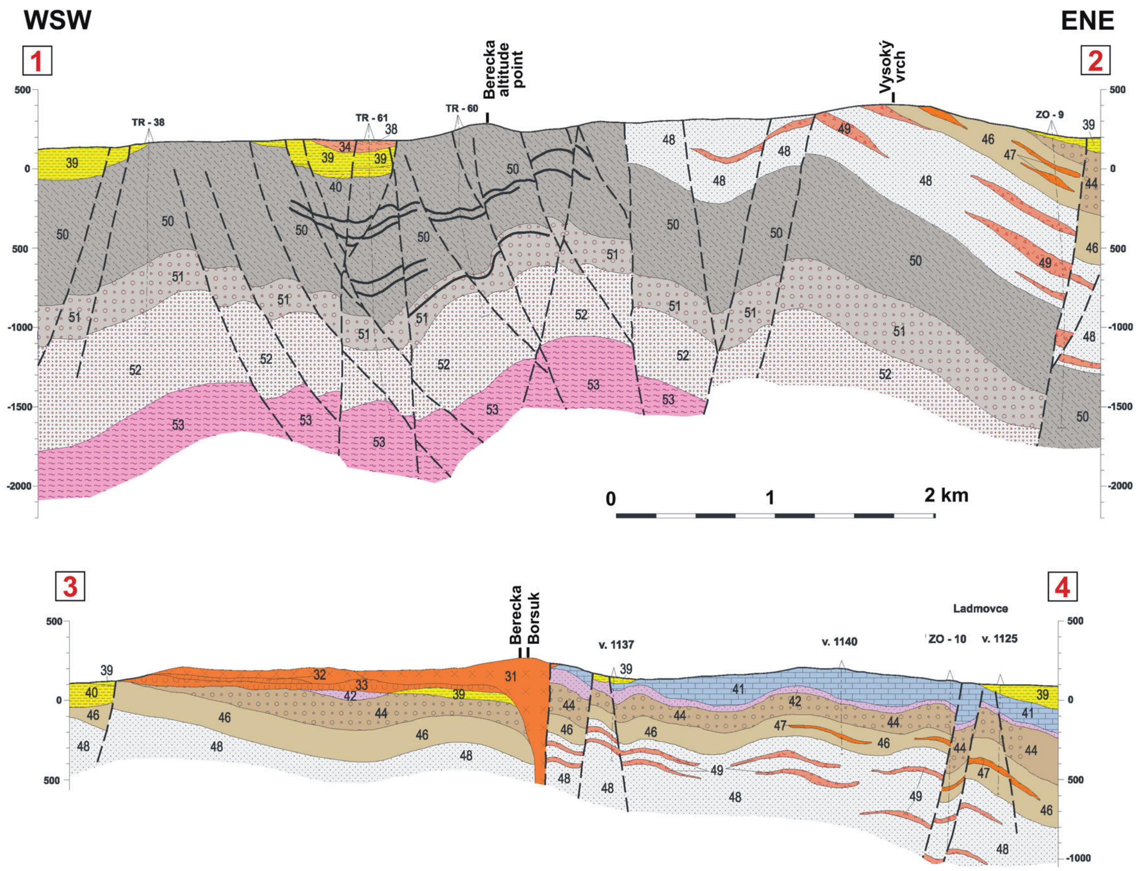

Fig. 3. The cross-sections trending WSW–ENE through the Zemplinicum in the Zemlínske vrchy Mts. (Kobulský and Gazdačko in Kobulský et al., 2011). The numbers of distinguished sequences in the cross-section corresponds with the description at the lithostratigraphic columns in Figs. 4 and 5.

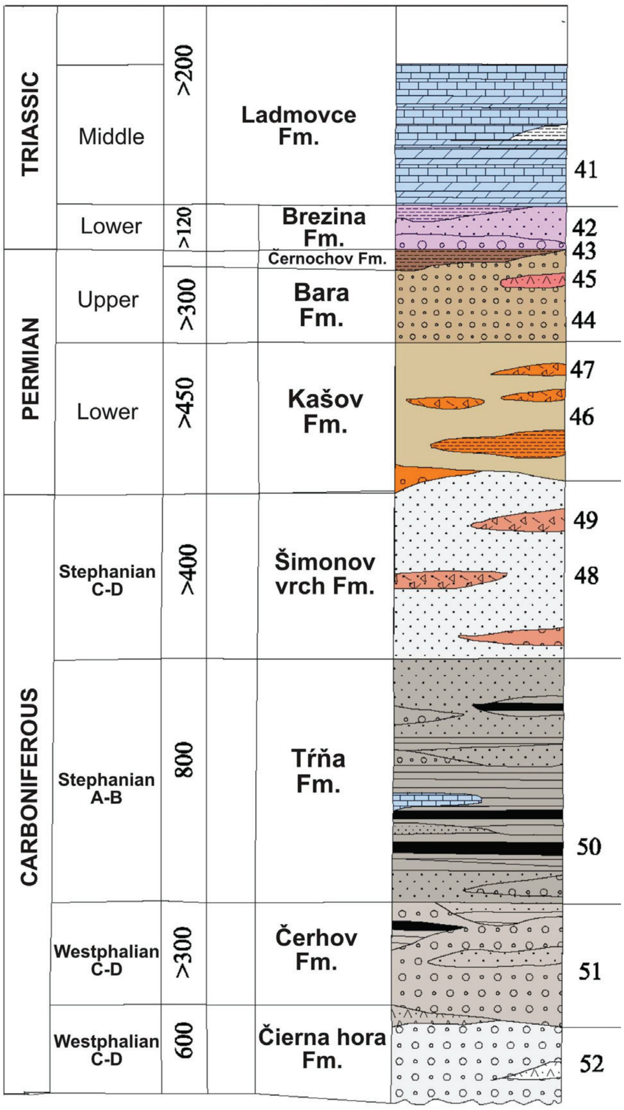

Fig. 4. Lithostratigraphic column of the Zemplinicum cover sequences in the area of the Zemplínske vrchy Mts. (Kobulský and Gazdačko in Kobulský et al., 2011). Lithology: **Ladmovce Fm.** (Anisian – Ladinian): 41 – dark-grey limestones, dark and light dolomites, locally with interbeds of clayey and marly shales, rauchwackes and breccia, **Brezina Fm.** (Lower Triassic): 42 – sandstones, quartzstones, conglomerates, variegated clayey shales, in the upper position the interbeds of dolomite, calcareous shales and gypsum, **Černochov Fm.** (Upper Permian): 43 – Thin-bedded brown-red silty claystones, rare interbeds of conglomerate, sandstone and siltstone, **Bara Fm.:** 44 – polymict conglomerates, variegated sandstones and shales with U-bearing horizon; 45 – interbeds of volcaniclastics (Upper Permian); **Kašov Fm.** (Lower Permian): 46 – variegated sandstones and shales with conglomerate interbeds; 47 – interbeds of rhyolites and their volcaniclastics; **Šimonov vrch Fm.** (Stephanian C–D): 48 – sandstones and shales with interbeds of conglomerates; 49 – interbeds of rhyolites with rhyolite-dacite volcaniclastics; **Tŕňa Fm.** (Stephanian A–B): 50 – cyclic alternation of fine-grained conglomerates, sandstones and dark-shales, often with the coal seams; **Čerhov Fm.** (Westphalian C–D): 51 – cyclic alternation of coarse-grained conglomerates, sandstones and schists, rare coal seams; **Čierna hora Fm.** (Westphalian C–D): 52 – cyclic alternation of fine-grained conglomerates, sandstones and shales with interbeds of rhyolite volcaniclastics.

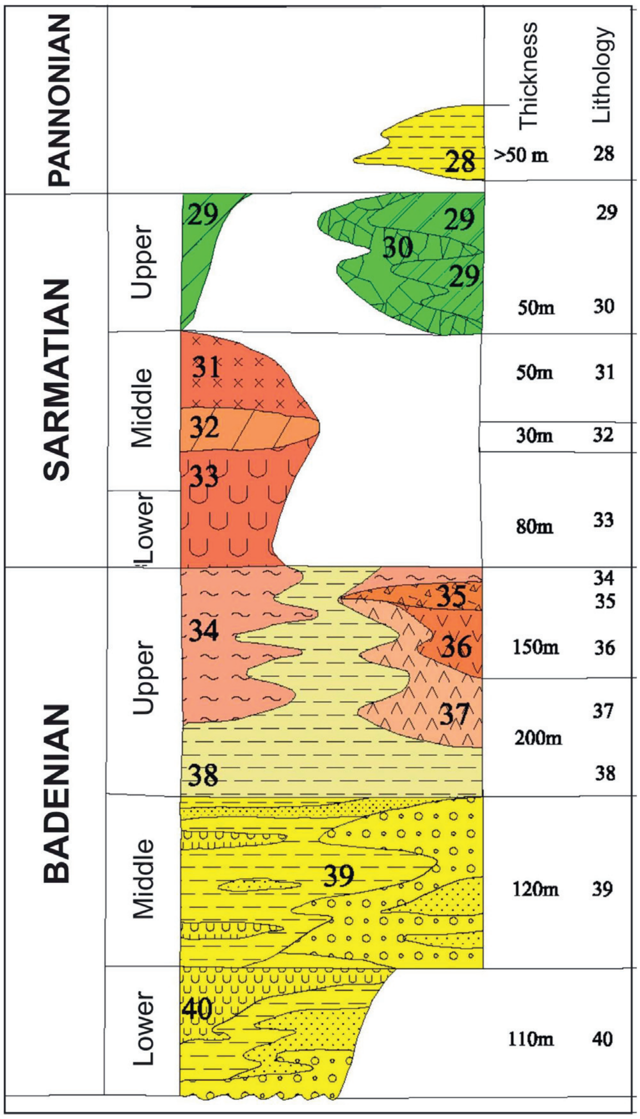

Fig. 5. Lithostratigraphic column of Neogene in the area of the Zemplínske vrchy Mts. (Kobulský and Gazdačko in Kobulský et al., 2011). Pannonian: 28 – **Sečovce Fm.** – grey, brown-grey and patchy clays, calcareous clays; Sarmatian: 29 – lava flows of basaltic pyroxene andesites; 30 – hyaloclastite breccia of pyroxene andesites; 31 – rhyolite extrusions with transition into the lava flows; 32 – perlite; 33 – rhyolite volcaniclastics; Badenian: 34 – rhyodacite pumice tuffs; 35 – redeposited rhyodacite volcaniclastics; 36 – extrusions of coarse-porphyric rhyodacite; 37 – extrusions and lava flows of fine--porphyric rhyodacite; 38 – **Lastomírov Fm.** – calcareous claystones with interbeds of sandstones and siltstones, interbeds of tuffites; 39 – **Vranov Fm.** – calcareous siltstones, sandstones, interbeds of conglomerates, claystones or clays and tuffs; 40 – **Nižný Hrabovec Fm.** – siltstones with interbeds of sandstones and conglomerates, claystones and tuffs.

conglomerates, variegated sandstones and shales with uranium--bearing horizon and rare interbeds of volcaniclastics. The transition from the Upper Permian into the Lower Triassic is represented by the Černochov Fm. with the brown-red silty claystones, locally with intercalations of conglomerates, sandstones and siltstones. The base of Mesozoic is formed by the Brezina Fm. (Lower Triassic) – sandstones, quartzstones, conglomerates, variegated clayey shales, upper interbeds of dolomite, calcareous shales and gypsum. The youngest Middle Triassic Ladmovce Fm. is composed of limestones and dolomites, locally with interbeds of shales. In the SE margin of the Zemplínske vrchy Mts. at the village of Nová Vieska near Bodrog river, the Upper Cretaceous to ?Paleogene age were determined in the Neogene underlier by the borehole, though their enlistment into the Zemplinicum is recently uncertain.

Zemplinicum is covered with the Neogene sediments (Fig. 5) of the Nižný Hrabovec (Lower Badenian), Vranov (Middle Badenian), Lastomírov (Upper Badenian) and Sečovce (Pannonian) formations (calcareous and non-calcareous claystones, siltstones, sandstones, conglomerates, locally with interbeds of tuffs, tuffites, sands, silts, clays and the coal clays).

Besides Carboniferous-Triassic sediments, the geological setting of the territory is formed also by Neogene volcanics, being buried and/or cropping out in the form of extrusions, lava flows and necks: extrusions of coarse-porphyric rhyodacite and rhyodacite pumice tuffs (Upper Badenian); extrusions and lava flows of fine-porphyric rhyodacite and rhyodacite pumice tuffs (Upper Badenian); rhyolite volcaniclastics, rhyolite extrusions with transitions to lava flow, locally perlitized (Lower – Middle Sarmatian); lava flows of basaltic andesites and hyaloclastic breccia (Upper Sarmatian).

The Quaternary cover consists of eolitic and proluvial sediments of the Riss and Wűrm, as well as the fluvial and deluvial sediments of Holocene.

The geological setting of the Zemplínske vrchy Mts. we interpret without the partial nappes as were previously distinguished by Grecula et al. (1982; the Cejkov, Ladmovce and Borša nappes) or by Felber (1991) as the lower and upper slices in the Ladmovce area.

Fig. 6a. Volcaniclastic horizon of the Šimonov vrch Fm. dipping to ENE (72/50), being penetrated by the cleavage system of cm to dm order (175/75). The height of the outrop is 4 m. The road cut south of the village of Malá Tŕňa (Locality 1). Photo Ľ. Gazdačko.

Fig. 6b. Rhythmic alternation of volcaniclastic and siliciclastic beds in the Carboniferous Šimonov vrch Fm. in the road cut south of the village of Malá Tŕňa (Locality 1). Photo Ľ. Gazdačko.

Fig. 6c. Brown-red silty claystones of the Upper Permian Černochov Fms. in the quarry south of the village of Malá Bara (Locality 2). Photo Ľ. Gazdačko.

Fig. 6d. Intercalations of polymict conglomerates in claystones of the Černochov Fm. in the quarry south of the village of Malá Bara (Locality 2). Photo Ľ. Gazdačko.

The repetition of the Carboniferous and Permian fms. in the deep boreholes in the E side of the territory we interpret by the faults of the NNW–SSE trend of the overthrust character with steep dip to WSW (Figs. 2 and 3).

Different situation is in the N and NW part of the territory, where in the anthracite deposit Veľká Tŕňa the steep backward thrusts of NNW–SSE trend dipping to ENE were verified (Kobulský et al., 1992). The Zemplinicum in the Zemplínske vrchy Mts. has a block-type tectonic setting with segmentation by the NNW–SSE trending faults, as well as the younger fault system of NE–SW (to ENE–WSW) trends with variegated displacement amplitude (Kobulský et al., 2011).

To observe the lithology, two localities are suggested as the most instructive:

1 – Malá Tŕňa – outcrop of Carboniferous rhyolite-rhyodacite volcaniclastics of the Šimonov vrch Fm. (Stephanian C-D)

Outcrop of volcaniclastic rocks long ca 60 m is located ca 750 m south of the village of Malá Tŕňa in the western side of the Zemplínske vrchy Mts. (Figs. 6a, b). The beds thick 10 to 30 cm are formed with the light-grey, grey-brown and light-brownish, rarely light-greenish, volcaniclastics (tuffs, ignimbrites, tuffites) and siliciclastics (fine-grained quartzites with thin beds of sericite-, locally sandy shales).

Volcaniclastics – tuffs and tuffites – are formed with very fine-grained and solidified ash with fragments of volcanic class. Fabric is ashy to vitrophyric. The tuffs and tuffites locally contain increased content of sericite. Locally the volcaniclastics have the coarse-grained structure. Matrix was recrystallized at the beginning of vitrification. The rock can be classified as tuffite – ignimbrite. The beds are rarely formed with the crystalloclastic tuff with partially recrystallized matrix. They have angular disintegration.

Siliciclastics are represented by the sericite schists and quartzy sandstones. Schists consist of sericite (ca 80 %, which originated by the recrystallization of illite) and quartz (ca 20 %). Quartzy sandstones are formed of quartz (85 %) and rare plagioclase fragments (5 %). Pebbles are located in the clayey intergranular matrix. The quartz pebbles are rounded to semi-rounded and consist of several types. The quartzy sandstones contain the small pebbles of volcanites, formed with recrystallized volcanic class with small porphyroclasts of plagioclase.

Bedding: 72/50° to 82/30. Penetrative cleavage of cm to dm order and dip 175/75. The joint system 10/85 forms a fan structure. In the outcrop, located more to the south, the penetrative normal fault 216/70 (dip of beds by 25 cm) is accompanied with a complementary system 282/85.

2 – Malá Bara – outcrop of the brown-red claystones with the interbeds of conglomerates and sandstones of the Černochov Fms. (Upper Permian)

Old quarry and a new road cut (with a length ca 60 m) is located ca 400 m to SE of the village of Malá Bara at the SW side of the Zemplínske vrchy Mts.

In the lower part of the quarry the brown-red silty claystones of the Černochov Fm. are prevailing (Fig. 6c), containing dm interbeds of conglomerates (pebbles of quartz and black silicites of 3 cm diameter) and transiting upwards into the medium- to fine-grained sandstones. The upper part of the small cycle with normal gradation is terminated with cm intercalations of the red and green sandy claystones. The supreme parts of the formation in the southern part of the quarry are represented by claystones and siltstones of the redbrown and red colours with rare small concretions of the pink carbonates and thin veinlets of the leafy chlorite.

Conglomerates are fine-grained and formed with semi-rounded to rounded pebbles of quartz, plagioclase and quartzite (65 %; diameter up to 0.5 cm, sporadically up to 3 cm) in the clayey matrix (Fig. 6c). Also rare agate clasts were found. Matrix is clayey with disseminated hematite.

Clayey shales are fine-grained recrystallized hematitic pelites of the brown-red colour without distinct lamination. The matrix contains the small quartz fragments (up to 0.3 mm) and flakes of fine-grained muscovite–sericite. Rarely the clayey shales contain clusters formed by larger grains of quartz and sericitized plagioclase cemented by the clay with small ratio of hematite pigment.

The dip of bedding is 178/45, 164/42 and in southermore occurrences 188/55. Joints: AC_1 = 232/75 to 264/65 – slickensides without lineations, the complementary system AC_2 = 68/85. In the southern part of the outcrop on plane 180/90 a fan structure was found. In the joint 14/60 the striations inclined 6° to west were found.

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Geological evolution of the rhyolite extrusive body of Borsuk – central part – based on documentation of the workings in the wine cellar at the village of Viničky (Zemplínske vrchy Mts., Eastern Slovakia)

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Abstract

Article presents newly excavated underground spaces in the Neogene rhyolite extrusive body of Borsuk in the Zemplínske vrchy Mts., mined for the wine cellars. Numerous volcanological phenomena are shown in photodocumentation with their precise location inside the extrusive body, applying the 3D visualization of underground spaces.

Key words: rhyolite extrusive body, pyroclastic surges, phreatomagmatic pyroclastic flows, autoclastic breccia, lapilli, Neogene, Viničky area, Zemplínske vrchy Mts.

The rhyolite extrusive body Borsuk (altitude point 267 m a.s.l.) is located in the south-eastern part of the Zemplín horst (Fig. 1), north of the Viničky village (Fig. 2). The workings (wine cellars) were dug out for the Tokaj Company Viničky in the basal parts of this extrusive body, built of the horizon of volcaniclastic rocks deposited on their pre-Tertiary basement.

Exploited galleries, regarding their relation to deposit conditions of the volcaniclastic rocks, can be characterized as cross-cuts, directional galleries, inclined galleries, exploitation shaft and "domes" (Fig. 3).

Domes represent atypical workings of the cylindrical shape with a diameter up to 3.5 m, height up to 3 m and approximately hemispherical ceiling. The total length of mined workings located in four horizons is 805.49 m, and, concerning the documentation, also 116.0 m^2 of excavation faces in a total number 17 must be added to this number. The length of the exploitation shaft is 28.5 m (Tab. 1A, B, C, D).

Workings have penetrated the volcaniclastic and extrusive--intrusive rhyolite bodies. A substantial part of the workings was mined in volcaniclastic rocks. Three principal eruption activities, derived from various, distant centres, with relatively numerous particuliar eruption phases were identified, being represented prevailingly by the formation of fallen and flow pyroclastic deposits. They are divided by the hiatus, forming the erosive paleorelief and partial flooding of the former surface. They represent a time boundary between the distinguished 2nd and 3rd stages of volcanic activity.

Among the volcaniclastic rocks the pyroclastic rock types are distinctly dominating. They are represented by the sequences of pyroclastic pumice fluxes in a typical development (Fig. 4). Their total thickness is preliminarily estimated to 15 m. In the stratigraphic underlier of these volcanic surges mainly the thick beds of mainly ashy tuffs occur with thin interbeds of pumice lapilli tuffs (Fig. 5).

In the ash tuffs of the second eruption activity (Fig. 6), the accretionary-enveloped (Figs. 7a, c) as well as armored (Figs. 7b, d) lapilli were identified.

This finding documents the phreatomagmatic type of eruption and deposition in the proximal to distal positions in relation to the eruption centre.

The time hiatus among individual volcanic phases in terrestrial environment (with local occurrence of fluvial environment), are documented by the erosion surface of older volcaniclastic sediments and the occurrence of flora casts in fine-grained tuffitic micaceous sandstones (Fig. 8).

The phreatomagmatic volcaniclastics were deposited on the sand (Fig. 9), consisting of pyroclastic flows and surges – ashy--pumice, debris-flows as well as gravitation flows – avalanches. The dip of the slope of initial conus was 25° to 30°. Characteristic is the presence of polymict fragments, rarely even boulders of underlying Permian sediments (Fig. 10). We suppose that the complex of volcanic and pyroclastic rocks probable belonged to a smaller separate volcano, being later distinctly eroded and covered after the final penetration of the extrusive dome, as well as having probable transition into the lava flow in the direction from the E (NE) to the W (SW).

In the mining spaces, the syngenetic decomposition of the marginal parts of the extrusive dome and its autoclastic breccia has occurred with their subsequent gravitation collapse (Figs. 11 and 12). During these processes, the underlying parts of older pyroclastic sediments were often incorporated in the form of fragments boulders and blocs. Their margins manifest the thermic effects of the surrounding flaming gravitation flow. The origin of perlites in individual fragments and blocks indicates the subaquatic environment during the evolution of the extrusive body.

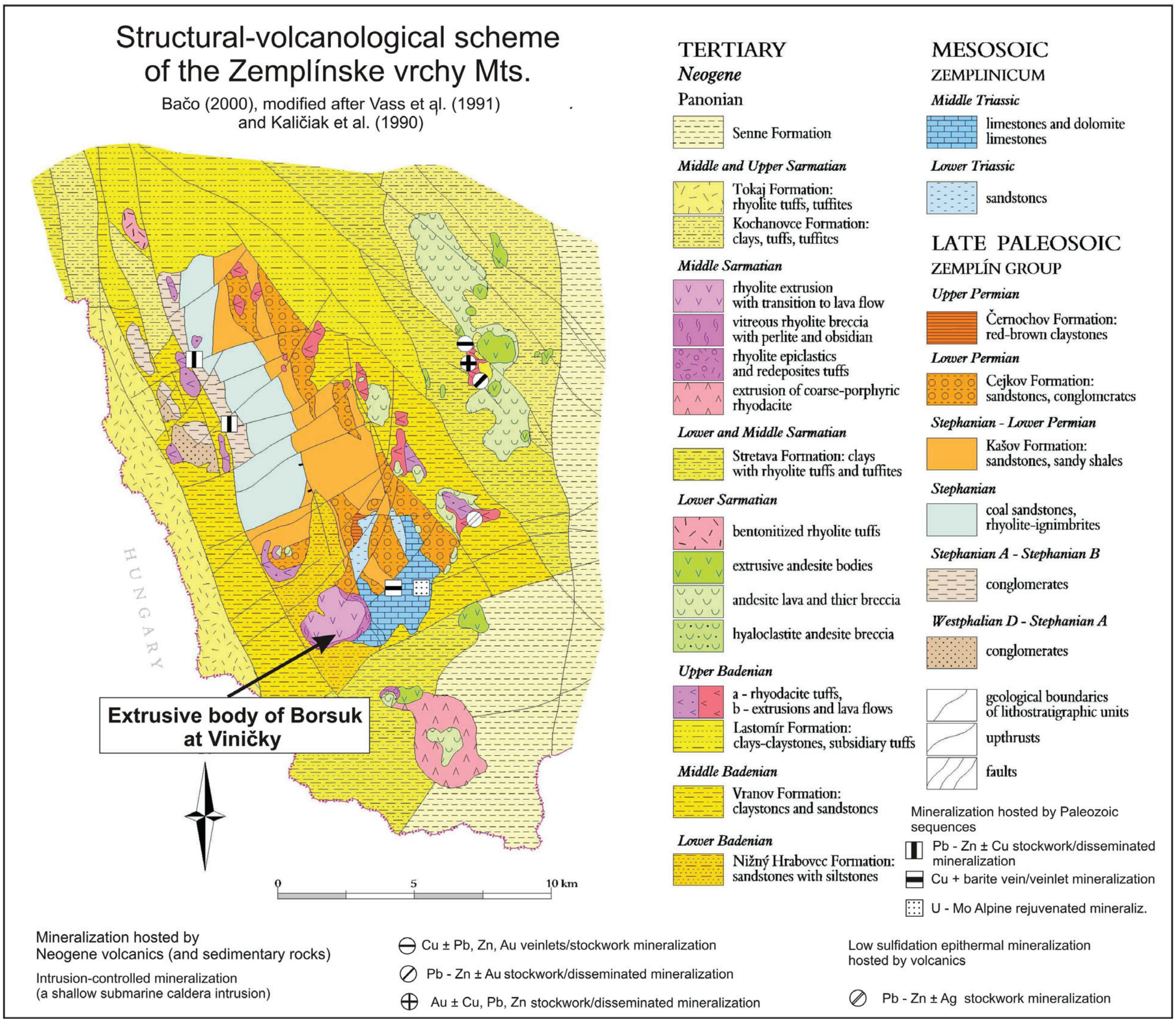


Fig. 1. Position of the extrusive body of Borsuk at the village of Viničky visualized on structural-volcanological scheme of the Zemplínske vrchy Mts. (Bačo, 2000, modified after Vass et al., 1991, and Kaličiak et al., 1990).

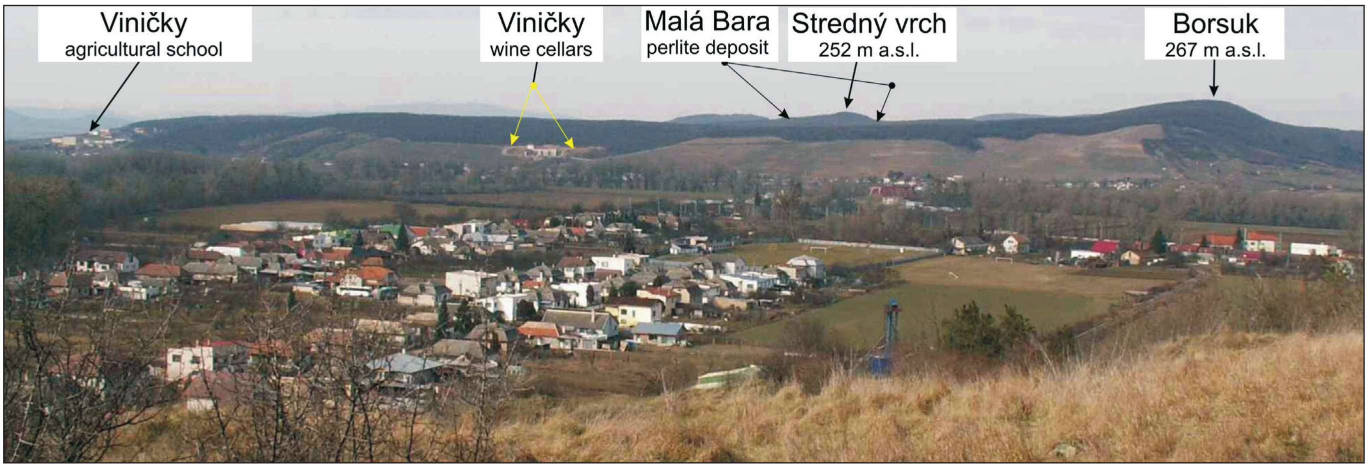


Fig. 2. Sceneric view on extrusive body Borsuk from the south northward. The village of Streda nad Bodrogom is located in the foreground, the village Viničky in the background. Photo P. Bačo.

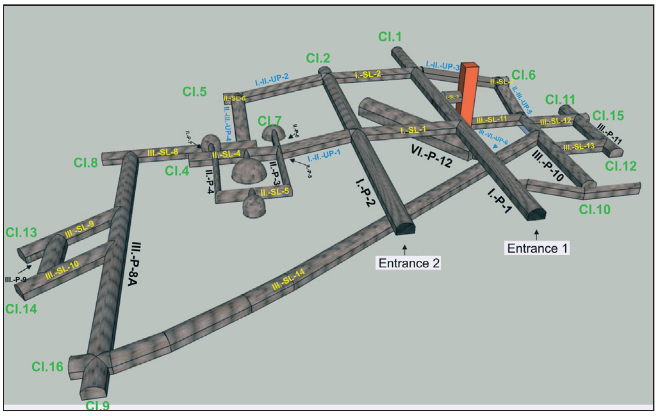


Fig. 3. Viničky – wine cellars. Designation and the space distribution of workings in 3D visualization.

Fig. 4. Sequence of pyroclastic surges. The pyroclastic surge contains a bed of fallen ash with a base surge. Location – Viničky, cellar, III.-SL-14B, left side, 24 m. Photo P. Bačo.

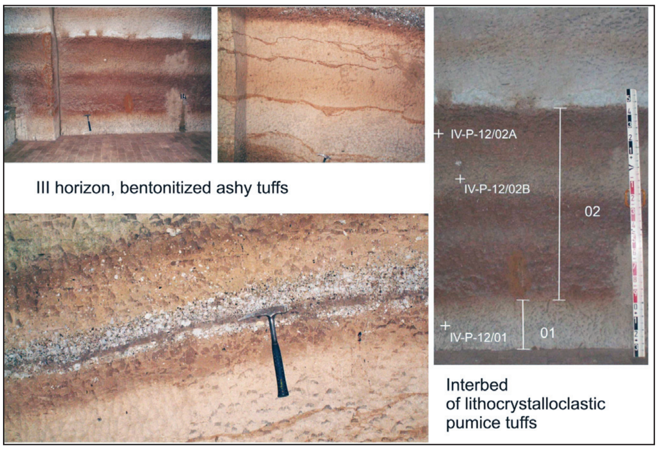
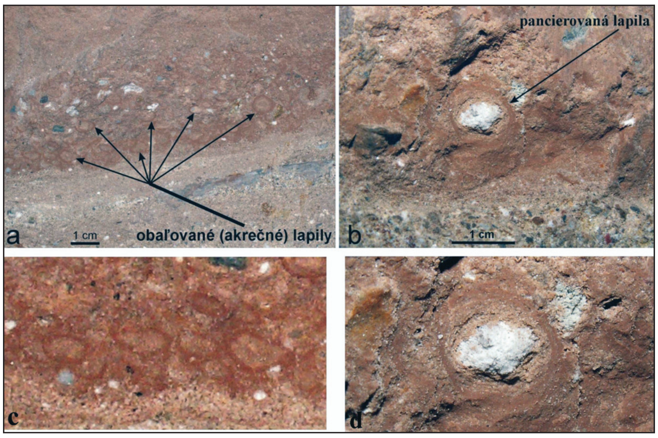


Fig. 5. Bentonitized ashy and pumice-ashy tuffs with distinguished eruption phases. Individual phases are highlighted by the solidification paleosurface. Photo P. Bačo.

Fig. 6. Succession of ashy and pumice–ashy pyroclastic deposits with the presence of accretionary lapilli. Location – Viničky, cellar, III.-SL-8 – Cl8. Photo P. Bačo.



Figs. 7a, b, c, d. Various types of lapilli in the ashy horizon. Location – Viničky, cellar, III.-SL-8 – Cl8. Photo P. Bačo.

Fig. 8. Erosion surface of the underlying ashy rhyolite tuffs. In the tight overlier the tuffitic micaceous sands with the flora casts occur. Location – Viničky, cellar, III.-P-8A3, right side, 10.5 m. Photo P. Bačo.

Fig. 9. Phreatomagmatic pyroclastic flows, surges and dry gravitation flows – avalanches. Dip of the cone slope was 25°. Location – Viničky, cellar, III.-P-8 – Cl9. Photo P. Bačo.

Fig. 10. Polymict fragments and boulders in the slope sediments of the primary cone developed on eroded underlier of the older, mainly ashy, rhyolite tuffs. Location – Viničky, cellar, III.-SL-9B. Photo P. Bačo.

Fig. 11. The gravitation flow of the original autoclastic breccia dragged away the block of the former pyroclastic sediments with the distinct thermic effect of the blazing surrounding environment. Location – Viničky, cellar, I.-P-2 – Cl-2. Photo P. Bačo.

Fig. 12. Detail of the autoclastic breccia with angular shape of fragments to boulders from the various levels of individual bodies, manifesting the gravitation displacement. Location – Viničky, cellar, I.-P-1B, right side, B, 6.4 m. Photo P. Bačo.

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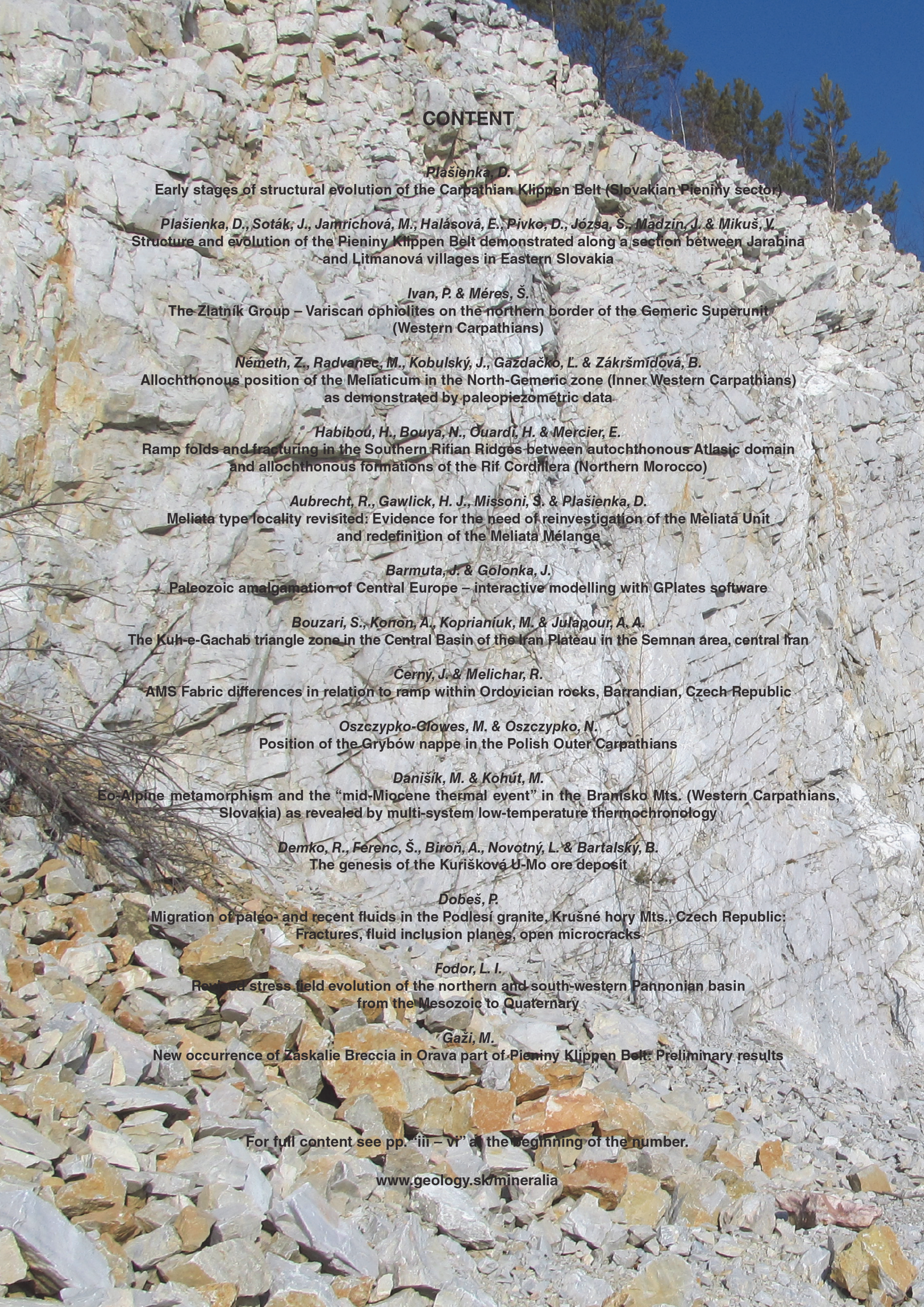

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