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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),

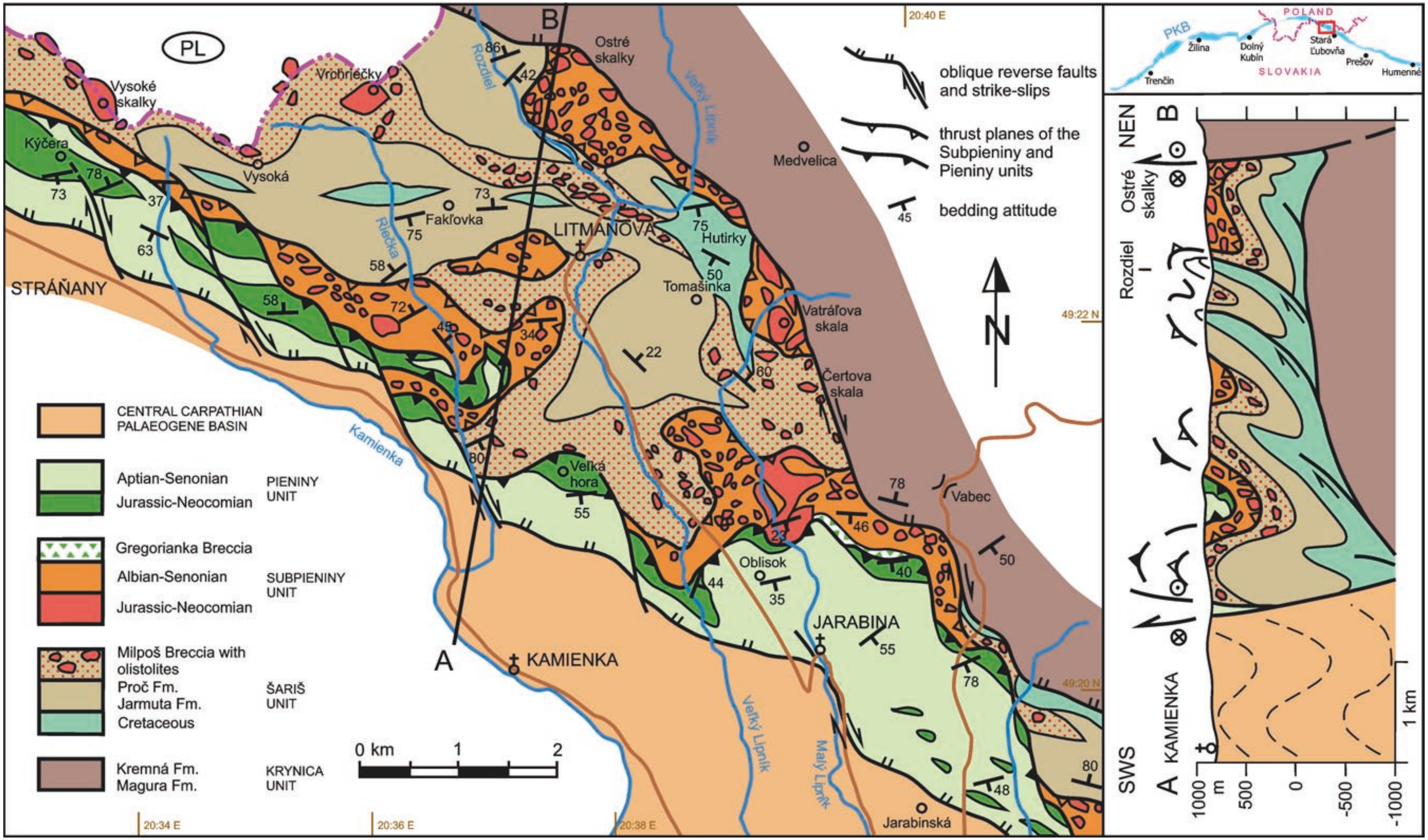

Fig. 1. Simplified geological map and cross-section of the Slovakian part of the Pieniny sector of the Klippen Belt between Stráňany, Litmanová and Jarabina villages (for its eastward continuation up to the Údol village see Plašienka and Mikuš, 2010; their Fig. 2).

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

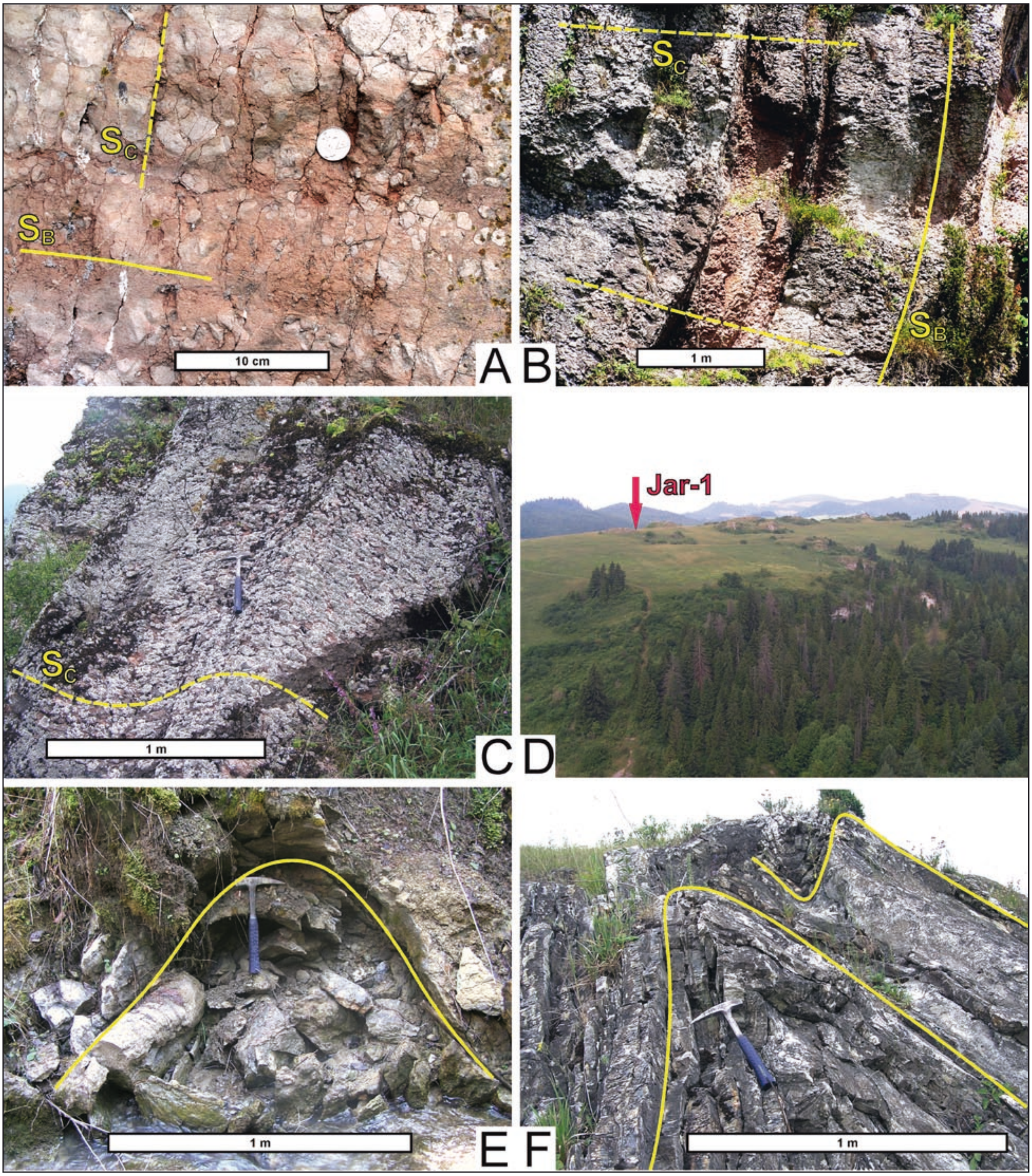

Fig. 2. Field photographs: **A** – bedding (subhorizontal) vs. cleavage (subvertical) relationship in the Czorsztyn nodular limestone (Malý Lipník Valley north of Jarabina); **B** – axial plane cleavage S_C in red nodular limestone, bedding vertical, cleavage horizontal (stumped blocky klippe, Rozdiel 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 Vatrálova 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

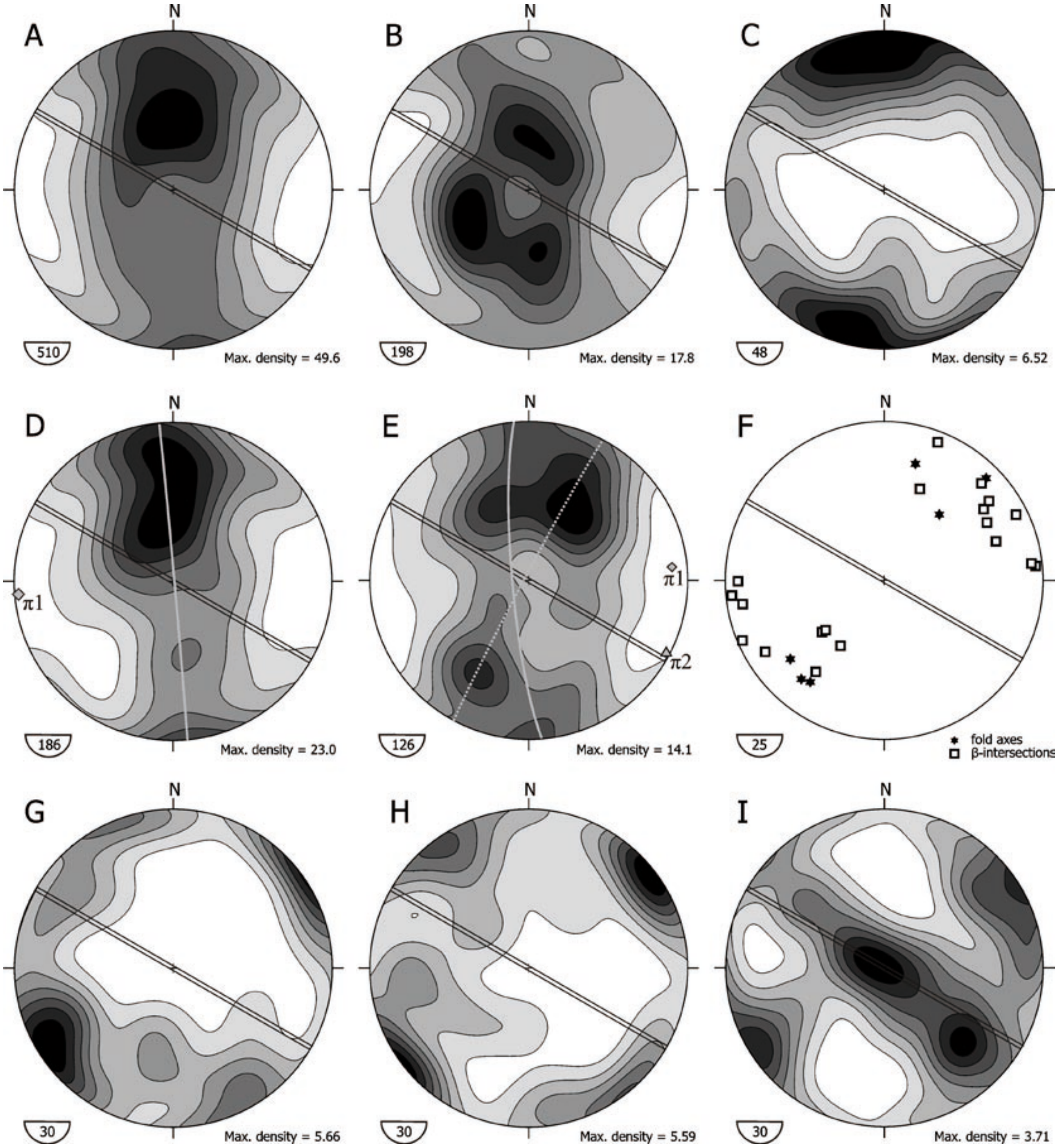

Fig. 3. Structural diagrams showing attitudes of strata and cleavages in the studied area (equal area projection, lower hemisphere): **A** – unsorted poles to bedding from the whole region; **B** – poles to bedding from the blocky klippen; **C** – tilt-corrected poles to S_C cleavage from blocky klippen (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 (π1 poles of both plot at 85 or 265°), while the second girdle with two maxima and corresponding π2 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 π1 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

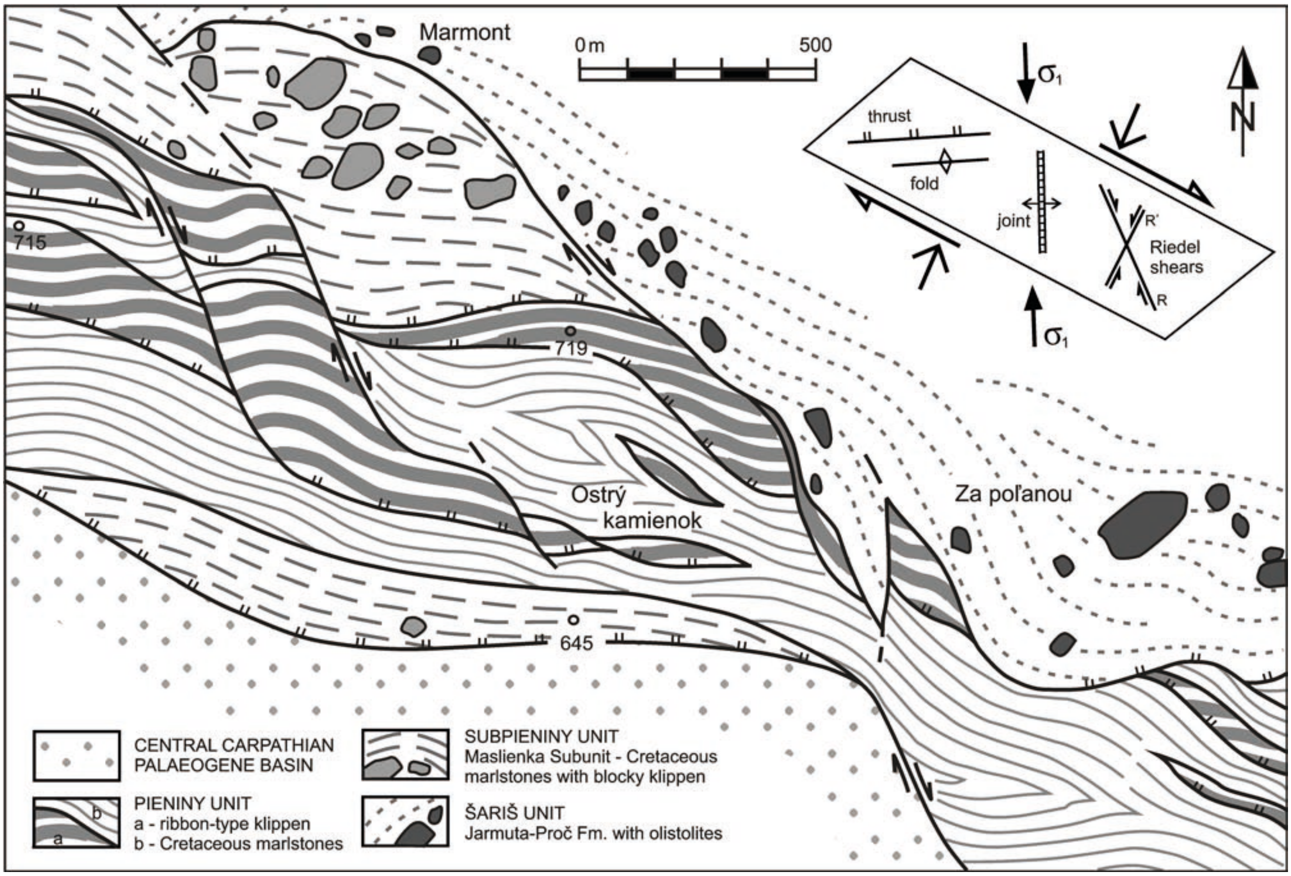

Fig. 4. A sketch map of southern marginal part of the PKB between Chmeľnica and Hajtovka villages showing relationships of bedding strikes to the fault boundaries of rectangular lenses or ribbons of the Pieniny Limestone Formation. The striped hachure outlines the measured or inferred bedding trends. 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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References

Anczkiewicz, A. A., & Świerczewska, A., 2008: Thermal history and exhumation of the Polish Western Outer Carpathians: evidence from combined apatite fission track and illite-smectite data. *In: Garver, J. I., & Montario, M. J. (eds): Proceedings 11th Internat. Conf. Thermochron. Anchorage, Alaska, 1 – 4.*

Andrusov, D., 1938: Étude géologique de la zone des Klippes internes des Carpathes Occidentales, IIIe partie: Tectonique. *Rozpr. St. geol. Úst. Čs. Republ., 9, 135.*

Andrusov, D., 1968: Grundriss der Tektonik der Nördlichen Karpaten. *Bratislava, Vyd. Slov. Akad. Vied, 188 p.*

Andrusov, D., 1974: The Pieniny Klippen Belt (The Carpathians of Czechoslovakia). *In: Maheľ, M. (ed.): Tectonics of the Carpathian-Balkan regions. Bratislava, Geol. Inst. D. Štúr, 145 – 158.*

Beidinger, A., Decker, K., Zamolyi, A., & Lee, E. Y., 2011: Deciphering polyphase deformation in the Žilina segment of the Pieniny Klippen Belt (Steny ridge, NW Slovakia). Abstracts of the 9th CETeG meeting. *Trav. Géophysiques, 40, 5.*

Birkenmajer, K., 1970: Pre-Eocene fold structures in the Pieniny Klippen Belt (Carpathians) of Poland. *Stud. geol. pol., 31, 81 p. (In Polish, English summary.)*

Birkenmajer, K., 1977: Jurassic and Cretaceous lithostratigraphic units of the Pieniny Klippen Belt, Carpathians, Poland. *Stud. geol. pol., 45, 1 – 159.*

Birkenmajer, K., 1983: Strike-slip faults in the northern boundary zone of the Pieniny Klippen Belt, Carpathians. *Studia Geol. Pol., 88, 7 – 32.*

Birkenmajer, K., 1986: Stages of structural evolution of the Pieniny Klippen Belt, Carpathians. *Stud. geol. pol., 88, 7 – 32.*

Bučová, J., Plašienka, D., & Mikuš, V., 2010: Geology and tectonics of the Vršatec klippen area (Pieniny Klippen Belt, Western Slovakia). *University of Thessaloniki. Proceedings of the XIX CBGA Congress, Thessaloniki, Greece. Special Volume, 100, 197 – 207.*

Ferrill, D. A., Morris, A. P., Evans, M. A., Burkhard, M., Groshong, R. H., jr., & Onasch, C. M., 2004: Calcite twin morphology: A low temperature deformation geothermometer. *J. Struct. Geol., 26, 1 521 – 1 529.*

Froitzheim, N., Plašienka, D., & Schuster, R., 2008: Alpine tectonics of the Alps and Western Carpathians. *In: McCann, T. (ed.): The Geology of Central Europe. Volume 2: Mesozoic and Cenozoic. Geological Society Publishing House, London, 1 141 – 1 232.*

Hurai, V., Kihle, J., Kotulová, J., Marko, F., & Świerczewska, A., 2002: Origin of methane in quartz crystals from the Tertiary accretionary wedge and fore-arc basin of the Western Carpathians. *Applied Geochemistry, 17, 1 259 – 1 271.*

Hurai, V., Marko, F., Tokarski, A. K., Świerczewska, A., Kotulová, J., & Biroň, A., 2006: Fluid inclusion evidence for deep burial of the Tertiary accretionary wedge of the Carpathians. *Terra Nova, 18, 440 – 446.*

Jacko, S., & Janočko, J., 2000: Kinematic evolution of the Central--Carpathian Paleogene Basin in the Spišská Magura region (Slovakia). *Bratislava, Slov. Geol. Mag., 6, 4, 409 – 418.*

Janočko, J. (ed.), 2000: Geological map of the Spišská Magura region 1 : 50 000. *Bratislava, State Geol. Inst. D. Štúr.*

Jurewicz, E., 1994: Structural analysis of the Pieniny Klippen Belt at Jaworki, Carpathians, Poland. *Stud. geol. pol., 106, 7 – 87. (In Polish, English summary.)*

Jurewicz, E., 1997: The contact between the Pieniny Klippen Belt and Magura Unit (the Małe Pieniny Mts.). *Geol. Quart., 41, 3, 315 – 326.*

Kováč, M., 2000: Geodynamic, palaeogeographic and structural evolution of the Carpathian-Pannonian region during the Miocene: A new view on the Neogene basins of Slovakia. *Bratislava, Veda, 202 p. (In Slovak.)*

Kováč, M., & Márton, E., 1998: To rotate or not to rotate: Palinspastic reconstruction of the Carpatho-Pannonian area during the Miocene. *Bratislava, Slov. Geol. Mag., 4, 2, 75 – 85.*

Kováč, P., & Hók, J., 1996: Tertiary development of the western part of Klippen Belt. *Bratislava, Slov. Geol. Mag., 2, 136 – 149.*

Krokowski, J., & Tarkowski, R., 1984: Tectonic deformation of ammonites in Upper Jurassic nodular limestone of the Pieniny Klippen Belt, and its structural meaning. *Stud. geol. pol., 83, 85 – 93. (In Polish, English summary.)*

Książkiewicz, M., 1977: The tectonics of the Pieniny Klippes Belt. *In: Książkiewicz, M., Oberc, J., & Pożaryski, W. (eds): Geology of Poland, Vol. IV Tectonics. Publ. House Wydaw. Geol., Warsaw, 519 – 552.*

Leško, B., 1960: Paläogen der Klippenzone in der Ostslowakei. *Geol. Sbor., 11, 1, 95 – 103. (In Slovak, German summary.)*

Ludwiniak, M., 2010: Multi-stage development of the joint network in the flysch rocks of western Podhale (Inner Western Carpathians, Poland). *Acta geol. pol., 60, 283 – 316.*

Mahel, M., 1980: The Peri-klippen zone: nearer characterization and significance. *Bratislava, Miner. Slov., 12, 3, 193 – 207. (In Slovak, English summary.)*

Marko, F., Plašienka, D., & Fodor, L., 1995: Meso-Cenozoic tectonic stress fields within the Alpine-Carpathian transition zone: A review. *Geol. Carpath., 46, 19 – 27.*

Márton, E., & Fodor, L., 1995: Combination of palaeomagnetic and stress data – a case study from North Hungary. *Tectonophysics, 242, 99 – 114.*

Márton, E., Mastella, L., & Tokarski, A. K., 1999: Large counterclockwise rotation of the Inner West Carpathian Paleogene flysch – evidence from paleomagnetic investigations of the Podhale Flysch (Poland). *Physics and Chemistry of the Earth (A), 24, 8, 645 – 649.*

Márton, E., Rauch-Włodarska, M., Krejčí, O., Tokarski, A. K., & Bubík, M., 2009a: An integrated palaeomagnetic and AMS study of the Tertiary flysch from the Outer Western Carpathians. *Geophys. J. International, 177, 925 – 940.*

Márton, E., Jelenska, M., Tokarski, A. K., Soták, J., Kováč, M., & Spišiak, J., 2009b: Current-independent palaeomagnetic declinations in flysch basins: A case study from the Inner Carpathians. *Geodinamica Acta, 22, 1 – 3, 73 – 82.*

Mastella, L., 1975: Flysch tectonics in the eastern part of the Podhale Basin (Carpathians, Poland). *Rocz. Pol. Tow. geol., 45, 361 – 401. (In Polish, English summary.)*

Mello, J., (ed.), 2011: Explanations to the geological map of the Middle Váh Valley 1 : 50 000. *Bratislava, State Geol. Inst. D. Štúr, 378 p. (In Slovak, English summary.)*

Marschalko, R., 1975: Evolution and geotectonic significance of the Klippen Belt Cretaceous flysch in the Carpathian megastructure. *Bratislava, Veda, Vyd. Slov. Akad. Vied, 140 p. (In Slovak, English summary.)*

Matějka, A., (ed.), 1963: Explanations to the general geological map of ČSSR 1 : 200 000, sheet M-34-XXI Spišská Stará Ves. *Bratislava, archiv Geofond, 60 – 132. (In Slovak.)*

Mikuš, V., 2010: Tectonics of the Pieniny sector of the Klippen Belt between the Jarabina and Litmanová villages in eastern Slovakia. *PhD thesis, Dept. Geol. Palaeont., Comenius Univ. Bratislava, 130 p. (In Slovak, English abstract.)*

Mišík, M., 1966: Tentative microscopical classification of veinlets in limestones (based on the Tithonian and Neocomian Limestones of the Manín group of the West Carpathians). *Geol. Sbor., 17, 337 – 344.*

Mišík, M., 1994: Authigenic feldspars in carbonate rocks of the Western Carpathians. *Geol. Carpath., 45, 102 – 111.*

Mišík, M., 1995: Authigenic quartz crystals in the Mesozoic and Paleogene carbonate rocks of the Western Carpathians. *Geol. Carpath., 46, 227 – 239.*

Mišík, M., & Reháková, D., 2009: The limestones of Slovakia. Part 1 – Bioherm, crinoidal, freshwater, ooid and oncoid limestones. *Bratislava, Veda, Vyd. Slov. Akad. Vied, 186 p. (In Slovak.)*

Nemčok, J., 1971: Results of Illyrian folding phase in East-Slovakian Flysch. *Geol. Práce, Spr., 57, 369 – 378. (In Slovak, English summary.)*

Nemčok, J., 1980: Non-traditional view of East-Slovakian Klippen Belt. *Geol. Zbor. Geol. carpath., 31, 563 – 568.*

Nemčok, J., 1990: Geological map of Pieniny and Čergov Mts., Ľubovnianska vrchovina and Ondavská vrchovina uplands 1 : 50 000. *Bratislava, D. Štúr Inst. Geol.*

Nemčok, J., Kullmanová, A., & Ďurkovič, T., 1989: Facies- and stratigraphical analyses of Gregorianka breccias in Klippen Belt of East Slovakia. *Geol. Práce, Spr., 89, 11 – 37. (In Slovak, English summary.)*

Nemčok, J., Zakovič, M., Gašpariková, V., Ďurkovič, T., Snopková, P., Vrana, K., & Hanzel, V., 1990: Explanations to the geological map of Pieniny, Ľubovnianska vrchovina highland and Čergov Mts. 1 : 50 000. *Bratislava, D. Štúr Inst. Geol., 132 p. (In Slovak, English summary.)*

Nemčok, M., & Nemčok, J., 1994: Late Cretaceous deformation of the Pieniny Klippen Belt, West Carpathians. *Tectonophysics, 290, 137 – 167.*

Nemčok, M., Hók, J., Kováč, P., Marko, F., Coward, M. P., Madarás, J., Houghton, J. J., & Bezák, V., 1998: Tertiary extension development and extension/compression interplay in the West Carpathian mountain belt. *Tectonophysics, 239, 81 – 109.*

Oszczypko, N., & Oszczypko-Clowes, M., 2010: The Paleogene and early Neogene stratigraphy of the Beskid Sądecki Range and Lubovnianska Vrchovina (Magura Nappe, Western Outer Carpathians). *Acta geol. pol., 60, 317 – 348.*

Oszczypko, N., Malata, E., Švábenická, L., Golonka, J., & Marko, F., 2004: Jurassic–Cretaceous controversies in the Western Carpathian Flysch: the “black flysch” case study. *Cretaceous Research, 25, 89 – 113.*

Oszczypko, N., Oszczypko-Clowes, M., Golonka, J., & Marko, F., 2005: Oligocene–Lower Miocene sequences of the Pieniny Klippen Belt and adjacent Magura Nappe between Jarabina and the Poprad River (East Slovakia and South Poland): their tectonic position and palaeogeographic implications. *Geol. Quart., 49, 379 – 402.*

Oszczypko, N., Jurewicz, E., & Plašienka, D., 2010: Tectonics of the Klippen Belt and Magura nappe in the eastern part of the Pieniny Mts. (Western Carpathians, Poland and Slovakia) – new approaches and results. Scientific Annals, School of Geology, Aristotle University of Thessaloniki. *Proceedings of the XIX CBGA Congress, Thessaloniki, Greece. Special Volume, 100, 221 – 229.*

Pešková, I., Vojtko, R., Starek, D., & Sliva, Ľ., 2009: Late Eocene to Quaternary deformation and stress field evolution of the Orava region (Western Carpathians). *Acta geol. pol., 59, 73 – 91.*

Plašienka, D., 1995a: Mesozoic evolution of Tatric units in the Malé Karpaty and Považský Inovec Mts.: Implications for the position of the Klape and related units in western Slovakia. *Geol. Carpath., 46, 101 – 112.*

Plašienka, D., 1995b: Cleavages and folds in changing tectonic regimes: the Veľký Bok Mesozoic cover unit of the Veporicum (Nízke Tatry Mts., Central Western Carpathians). *Bratislava, Slov. Geol. Mag., 2, 97 – 113.*

Plašienka, D., 2003: Dynamics of Mesozoic pre-orogenic rifting in the Western Carpathians. *Mitt. Österr. Geol. Gesell., 94 2001, 79 – 98.*

Plašienka, D., & Mikuš, M., 2010: Geological structure of the Pieniny and Šariš sectors of the Klippen Belt between the Litmanová and Drienica villages in Eastern Slovakia. *Bratislava, Miner. Slov., 42, 2, 155 – 178. (In Slovak, English summary.)*

Plašienka, D., Soták, J., & Prokešová, R., 1998: Structural profiles across the Šambron-Kamenica Periklippen Zone of the Central Carpathian Paleogene Basin in NE Slovakia. *Bratislava, Miner. Slov., 29, 173 – 184.*

Ratschbacher, L., Frisch, W., Linzer, H. G., Sperner, B., Meschede, M., Decker, K., Nemčok, M., Nemčok, J., & Grygar, R., 1993: The Pieniny Klippen Belt in the Western Carpathians of northeastern Slovakia: structural evidence for transpression. *Tectonophysics, 226, 471 – 483.*

Rakús, M., & Hók, J., 2005: The Manín and Klape units: Lithostratigraphy, tectonic classification, paleogeographic position and relationship to Váhicum. *Bratislava, Miner. Slov., 37, 9 – 26. (In Slovak, English summary.)*

Salaj, J., 1994: Geology of Middle Váh valley. Klippen and periklippen belt, Súľov Paleogene and Mesozoic of northern part of Strážovské vrchy hills – part 2. *Zem. Plyn Nafta, 39, 4, 197 – 395. (In Slovak, English summary.)*

Salaj, J., 2006: Microbiostratigraphy of the Gosau development in the Klape Unit, Western Carpathian Paleoalpine accretionary belt. *Bratislava, Miner. Slov., 38, 1 – 6.*

Scheibner, E., 1967: Carpathian Klippen Belt. *In: Buday, T., Cicha, I., Hanzlíková, E., Chmelík, F., Koráb, T., Kuthan, M., Nemčok, J., Pícha, F., Roth, Z., Seneš, J., Scheibner, E., Stráník, Z., Vaškovský, I., & Žebera, K., (eds.): Regional geology of Czechoslovakia. Vol. II Western Carpathians, part 2. Akademie, Praha, 7 – 108.*

Sikora, W., 1971: Esquisse de la tectogénèse de la zone des Klippes des Pieniny en Pologne d´après de nouvelles données géologiques. *Rocz. Pol. Tow. Geol., 41, 1, 221 – 239. (In Russian, French résumé).*

Sikora, W., 1974: The Pieniny Klippen Belt (Polish Carpathians). *In: Maheľ, M., (ed.): Tectonics of the Carpathian-Balkan regions. Bratislava, Geol. Inst. D. Štúr, 177 – 180.*

Srnánek, J., & Salaj, J., 1965: Remarks to the geology of the Pieniny part of Klippen Belt in the wider vicinity of Stará Ľubovňa. *Geol. Práce, Spr., 35, 61 – 72. (In Slovak, English summary.)*

Stille, H., 1924: Grundfragen der vergleichenden Tektonik. *Verl. Gebr. Borntraeger, Berlin, 443 p.*

Stráník, Z., 1965: Zur Geologie des Magura-Flysches im Gebirge Čerchovské pohoří und Ondavská vrchovina. *Sbor. Geol. Vied, rad ZK, 3, 125 – 178. (In Czech, German summary.)*

Šimonová, V., & Plašienka, D., 2011: Fault kinematics and palaeostress analysis in the Butkov quarry (Manín Unit, Western Carpathians). *Acta geol. Slov., 3, 21 – 31. (In Slovak, English summary.)*

Świerczewska, A., 2005: The interplay of the thermal and structural histories of the Magura Nappe (Outer Carpathians) in Poland and Slovakia. *Mineralogia Polonica, 36, 2, 91 – 144.*

Uhlig, V., 1903: Bau und Bild der Karpathen. *In: Diener, C., Hoernes, R., Suess, F. E., & Uhlig, V., (eds): Bau und Bild Österreichs mit einem Vorworte von Eduard Suess. F. Tempsky, Wien und G. Freytag, Leipzig, 649 – 911.*

Uhlig, V., 1907: Über die Tektonik der Karpathen. *Sitzungsberichte der Kaiserischen Akademie der Wissenschaften, matematisch-naturwissenschaftliche Klasse, 116, 1, 871 – 982.*

Vojtko, R., Tokárová, E., Sliva, Ľ., & Pešková, I., 2010: Cenozoic palaeostress field reconstruction and revised tectonic history in the northern part of the Central Western Carpathians (the Spišská Magura and Tatra Mountains). *Geol. Carpath., 61, 211 – 225.*

Wierzbowski, A., Aubrecht, R., Krobicki, M., Matyja, B. A., & Schlögl, J., 2004: Stratigraphy and palaeogeographic position of the Jurassic Czertezik Succession, Pieniny Klippen Belt (Western Carpathians) of Poland and Eastern Slovakia. *Annales Soc. Geol. Polon., 74, 237 – 256.*

Wójcik-Tabol, P., 2003: Reflectance of dispersed organic matter particles in shales of the Magierowa Member in the Pieniny Klippen Belt compared with clay crystallinity and isotopical data. *Mineralogical Society of Poland – Special Papers, 22, 236 – 239.*

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