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Structure and evolution of the Pieniny Klippen Belt and its position in the Western Carpathian framework

PLASIENKA, D.

Department of Geology and Palaeontology, Faculty of Natural Sciences, Comenius University, Mlynska dolina G, 842 15 Bratislava, Slovakia: plasienka@fns.uniba.sk

Introduction

The Pieniny Klippen Belt (PKB) is probably the most conspicuous structural zone of the entire Carpathian arc. Picturesque landscape, complex structure and abundance of especially Jurassic fossils have been drawing the geologists' and palaeontologists' attention for more than 150 years (e.g., STUR 1860, NEUMAYR 1870, UHLIG 1890, 1903, ANDRUSOV 1931, 1938 etc., BIRKENMAJER 1960, 1977 etc., MISIK 1997; and many others). The PKB is a narrow (merely several km), but lengthy (up to 600 km) zone dominated by Miocene wrench tectonics (RATSCHBACHER et al. 1993, KOVAC & HOK 1996) that separates the External Western Carpathians (EWC - Flysch Belt, Tertiary accretionary wedge) from the Central Western Carpathians (CWC - Cretaceous basement/cover nappe stack). The PKB involves predominantly Jurassic, Cretaceous and Palaeogene sediments with variable lithology and intricate internal structure. During the long-termed intense research, these have been subdivided into numerous lithostratigraphic and tectonic units of originally distant palaeogeographic provenances, hence witnessing excessive shortening and dispersal within this restricted zone. The PKB has often been characterized as a tectonic megabreccia, mélange, or even it was speculated to represent a huge chaotic sedimentary body - olistostrome (NEMCOK 1980). However, the peculiar „block-in-matrix" structure of the PKB appears to be result of late stages of the deformation history of the PKB units, governed by along-strike wrench movements. These obliterated, in places completely, former thrusting-related structures with a regular arrangement of nappe units. Consequently, the mutual relationships of various PKB units and the neighbouring tectonic zones still remains a matter of controversy and no general agreement has been achieved even in some fundamental questions until now.

The purpose of this paper is to present some new results and ideas developed during the recent research focussed on structural evolution of zones along the EWC/CWC boundary, i.e. the PKB and adjacent units. Our results partially, or even completely in some cases, contradict the previous views. In particular, new opinions concern the relations of the klippen to surrounding rocks, as well as the number and hierarchy of tectonic units incorporated into the PKB structure. In the following, we shall present them briefly.

Structure of the PKB

From bottom to top (and generally from N towards S), the following units, partly or fully incorporated and/or closely juxtaposed to the PKB, are distinguished (Fig. 1):

The **Magura Superunit** (Magura Belt of the EWC; Senonian - Oligocene, predominantly flysch lithologies) is in a contact with PKB in north-western and eastern Slovakia. In the Middle Vah Valley, the PKB directly juxtaposes the Bystrica Unit, which otherwise occupies the central position in the Magura Belt. This contact is purely tectonic and relatively young (Middle Miocene) and has a character of oblique slip dextral/reverse fault zone. It indicates an extensive backthrusting, since the PKB units are overturned towards the S as well (Fig. 1C). In the Orava region and further east in eastern Slovakia, the PKB contacts the Krynica Unit, which is dominated by the Eocene Magura-type sandstones (Fig. 1A, B). The lowermost PKB Saris Unit overrides the most internal elements of the Krynica Unit terminated by Oligocene to Lower Miocene deposits (OSZCZYPKO et al. 2005).

The **Biele Karpaty Superunit** is the innermost element of the SW part of the Flysch Belt which differs considerably from the Magura units by its composition (mostly carbonate material in clastic formations) and stratigraphic extent (Cretaceous - Lower Eocene; POTFAJ 1993). It consists of several thrust sheets, the two higher being in contact with the PKB (Fig. 1E, F). The Biele Karpaty Unit has no direct analogues east of the Middle Vah Valley. On the other hand, its continuation to the Laab Nappe of the Eastern Alpine Rhenodanubian Flysch Zone has been proposed by several authors (e.g., SCHNABEL 1982).

The **Oravic Superunit** (known also as the „Pieninic" units or „Pienides" in older literature - e.g., ANDRUSOV 1974) embraces the typical PKB units of their own, which are characterized by the peculiar „klippen tectonic style". The lowermost element of the eastern PKB s.s., the **Saris Unit** (Fig. 1A), was formerly considered to be a part of the „klippen mantle". It consists of varied Upper Jurassic to Upper Cretaceous pelagic sediments followed by

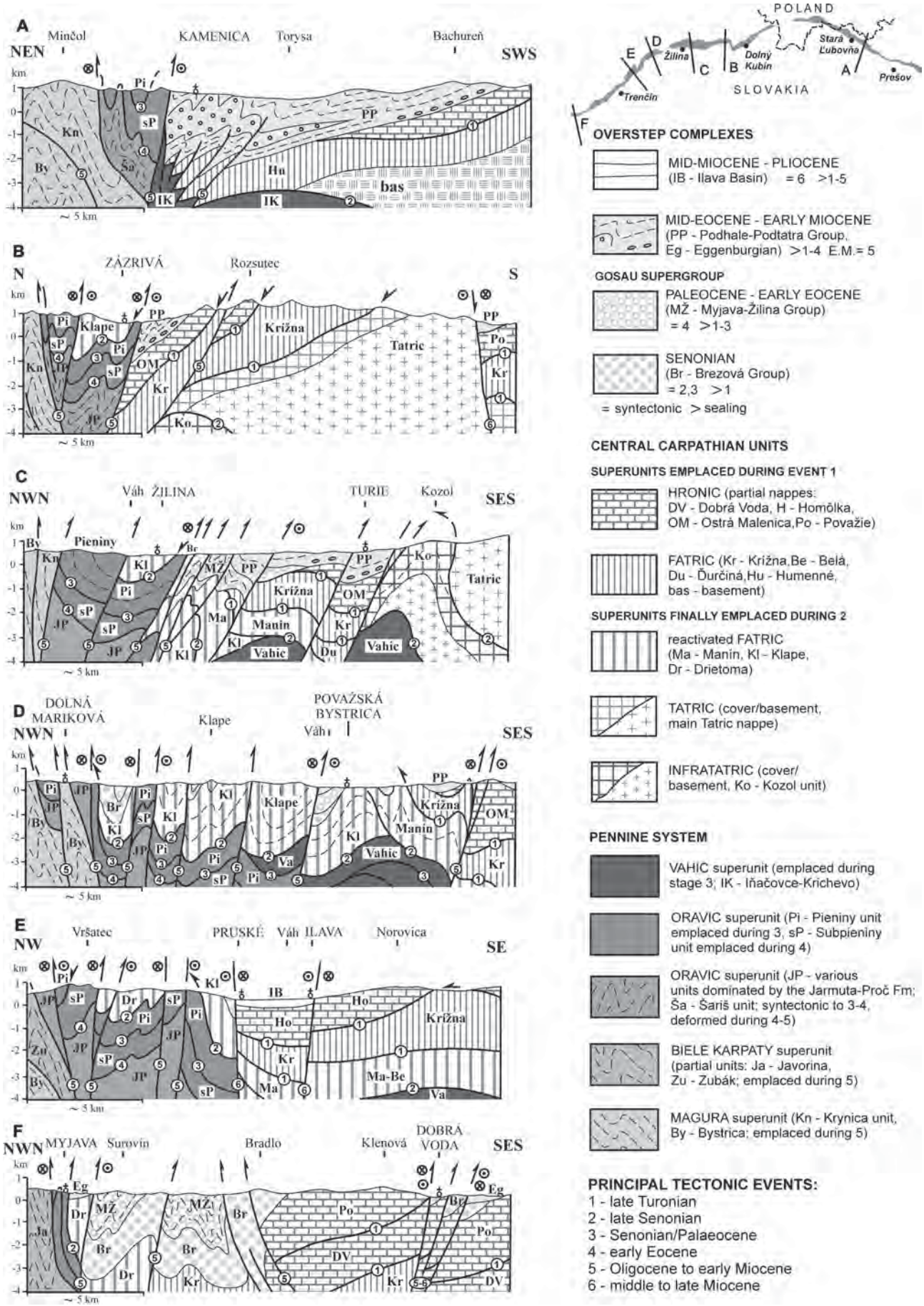

Fig. 1. Cross-sections across the PKB showing relationships of its principal units.

Maastrichtian - Lower Eocene, deep marine, pelagic (variegated shales) and clastic (turbidites, mass-flows) deposits. The latter are known as the Jarmuta and/or Proc Fm. and involve also chaotic olistostrome bodies (Milpos Breccia) with olistolites dominantly derived from the overlying Subpieniny Nappe (Fig. 2). These were considered as klippen, i.e. tectonic lenses until now. The overriding Czorsztyn-type units form imbricated thrust sheets, their fronts passing gradually into mass-flows inserted within and above the Jarmuta-Proc flysch, thus indicating close sedimentary and tectonic relationships of the Saris Unit and the overlying units.

For the higher nappe sheet of the PKB, we come back to the old Uhlig's term **Subpieniny Unit** (Uhlig 1907). The Subpieniny Nappe includes the most widespread Czorsztyn Succession, as well as the Pruske, Niedzica, Czertezik and similar „transitional" successions derived from the Czorsztyn Ridge and its slopes. Lithology and stratigraphy of these successions were described in numerous papers (e.g., Birkenmajer 1977, 1986). The Subpieniny Nappe has a stable structural position, but it is strongly imbricated or even disintegrated internally. The youngest sediments of the Czorsztyn-type successions are the Upper Senonian Jarmuta-type calcareous sandstones overlain by olistostrome breccias (Gregorianka Breccia - cf. Nemcok et al. 1989; Fig. 2). These breccias only contain material derived from the still higher Pieniny Nappe (Upper Jurassic radiolarites, Lower Cretaceous biancône-type limestones). The Subpieniny Unit is characterized by a „mature" klippen style, with blocky klippen composed of massive Middle - Upper Jurassic limestones embedded in a soft matrix of Upper Cretaceous marls.

The higher most Oravic tectonic unit of the PKB - the **Pieniny Nappe** is clearly independent from the Subpieniny Nappe, but includes several differing lithostratigraphic successions as well (Pieniny s.s., Kysuca-Branisko, Podbiel-Orava, Nizna). The Pieniny Unit is strongly folded and imbricated, but generally continuous. It overlies the Subpieniny Unit, but in places directly the Saris Unit. Usually it forms the southernmost zone of the eastern PKB. In the western PKB part, it is dominated by the basinal Kysuca Succession (Hettangian - Campanian). The eastern part is ranged to a still more deep-basinal Pieniny Succession which is usually detached at the base of Middle/ Upper Jurassic radiolarites.

All the Oravic units are characterized by an independent palaeogeographic position around the Middle Penninic swell known as the Czorsztyn Ridge, which was a continental ribbon separated by oceanic domains from the Central Carpathian (Austroalpine) plate to the south and from the North European Platform to the north (South Penninic-Vahic and North Penninic-Rhenodanubian-Magura Oceans, respectively - e.g., Plasienka 2003). Unlike the Austroalpine units, the Oravic Superunit involves more-or-less continuous Jurassic - Cretaceous stratigraphic successions reaching as late as the Early Eocene in the most external zones.

The „non-Oravic" units of the CWC-Austroalpine provenance incorporated into the PKB *sensu lato* are generally ranged to the **Fatric Superunit** (Krizna and related nappes - cf. Fig. 1). These are widespread in the western PKB part, especially in its broadest Puchov sector. They mostly occur in the south-eastern zone of the PKB, designated as the „Periklippen Belt" by Mahel (1980), where they always structurally overlie the Oravic units of the PKB *sensu stricto*. Three large units compose the „non-Oravic" Periklippen zone. The **Drietoma Unit**, embracing the Upper Triassic (Carpathian Keuper Fm.) - Cenomanian, chiefly basinal succession, predominates in the SW part of the PKB (Hok et al. 2009). It shows close structural links to the overlying CWC nappe systems - the Fatric Krizna Nappe and Hronic Nedzov Nappe, as well as to the mid-Cretaceous (Albian - Cenomanian) synorogenic flysch with „exotic" conglomerates. These provide a link to the huge **Klape Unit**, which prevails in the Middle Vah Valley. This is composed of some thousand metres thick mid-Cretaceous wildflysch complex (the Klape Flysch) with big olistolites of Triassic and Jurassic carbonates (e.g., the spectacular Klape Klippe - Marschalko 1986). In the Povazska Bystrica area, the belt of the Klape Unit is up to 15 km wide, composed of four to five juxtaposed subunits divided by antiformal strips of the Kysuca Unit and/or synforms of overstepping Gosau sediments (Fig. 1D). These Klape subunits are considered to represent strike-slip duplexes, accumulation of which caused exceptional broadening of the PKB in the Puchov sector. The SE-most component of the Periklippen Belt is the **Manin Unit**. It's Lower Jurassic - Cenomanian sequence (including the characteristic Urgon-type platform limestones) closely relates to the ridge-type successions of the Fatric Superunit (e.g., the Bela Unit in the Strazovske vrchy Mts. - Mahel 1978). However, many authors prefer the Tatric affiliation of the Manin Unit (e.g., Rakus & Hok 2005). The Manin Unit is dominated by mid-Cretaceous hemipelagic and flysch formations, older stiff limestones build several large „klippen", which are in fact brachyanticlines. Contrary to earlier views, the Senonian sediments in the Klape and Manin Zone are supposed to represent a post-nappe, Gosau-type cover (Fig. 1D). The mid-Cretaceous flysch of the Manin Unit is from the SE overridden by the frontal elements of the typical Krizna Nappe. Nevertheless, a strip of another puzzling element - the Kostolec Unit (Andrusov 1938) occurs there as well. Presently, the blocky Kostolec klippen of shallow-water Jurassic limestones embedded in the mid-Cretaceous flysch are regarded as olistolites of an unknown (Hronic?) provenance (Rakus & Hok 2005).

The „non-Oravic" units participate to a lesser extent in the eastern PKB structure compared to the western one. The large, composite **Haligovce Klippe** in the Slovak Pieniny Mts is usually correlated with the Manin Unit. This is mainly based on distinct facies similarities (e.g., the Urgon-type limestones), the high structural position above the Oravic units, as well as on overstepping Palaeogene rocks analogous to the Myjava-Zilina Group. The Haligovce Unit also contains Middle Triassic carbonates - an unusual feature for the PKB. Further east, a few km SW of the PKB proper, a structural elevation of the Humenné Mts. occurs, which is composed of typical Fatric elements (Krizna Nappe). The **Humenne Unit** is strongly imbricated with SW-verging system of backthrusts, i.e. it occupies a position in the SW limb of the PKB transpressional structural fan (Fig. 1A).

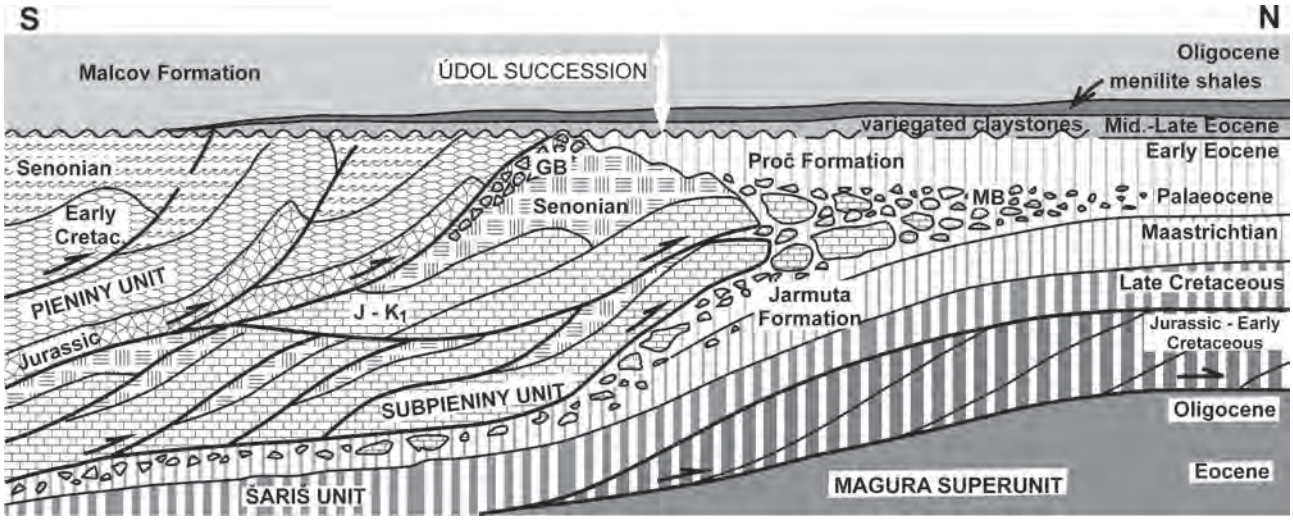

Fig. 2. Scheme of the pre-Miocene relationships of the Oravic units in the future PKB (eastern Slovakia). GB - Gregorianka Breccia, MB - Milpos Breccia.

In western Slovakia, the southern boundary of the PKB against the CWC is followed by deformed Palaeocene - Lower Eocene sediments known as the „Periklippen Palaeogene“ (**Myjava-Zilina** Group - Fig. 1). In the westernmost part of the PKB and CWC (Male Karpaty Mts.), these build the upper part of the Gosau Supergroup (including the Senonian **Brezova** Group) in a situation analogous to the position of Gosau sediments in the Northern Calcareous Alps (NCA, e.g., WAGREICH & MARSCHALKO 1995). Gosau sediments in the NCA and Malé Karpaty Mts. are interconnected through the „Giesshübl Syncline“ drilled in the substratum of the Neogene Vienna Basin (e.g., WESSELY 1992).

Further NE in the Middle Vah Valley, the Myjava-Zilina Group is closely related to Eocene - Oligocene sediments of the Central Carpathian Palaeogene Basin (CCPB; **Podhale-Podtatra** Group), which spreads far to the south lying above the cover nappes of the CWC. In areas close to the PKB, the transgressive base of the CCPB is formed by exceptionally thick Lower Eocene dolomite breccias (Sulov Conglomerates, cf. MARSCHALKO & SAMUEL 1993). In general, the Gosau-type Brezova and Myjava-Zilina Groups are characterized by pelagic marls and calcareous flysch formations with a frequent shallow-water biogenic detritus and Maastrichtian - Palaeocene reef-derived olistolites (e.g., the Kambühel Limestone). In the eastern PKB part, the Magura vs. PKB tectonic contact is sealed by the Middle Eocene - Oligocene sediments of the Udol Succession (Fig. 2), which is composed of Middle - Upper Eocene variegated shales, Globigerina marls, menilite shales and Oligocene calcareous flysch of the Malcov Formation (see OSZCZYPKO et al. 2005 for details). These formations exhibit close facies relationships to the southward adjacent, coeval sediments of the CCPB. However, the contact of the PKB with the CCPB is formed by steep oblique dextral backthrusts here (Fig. 1A).

Tectonic evolution

Superposition of the PKB nappe units was strongly modified by post-Oligocene deformation, but it is still well recognizable in several places. As revealed by the structural position, age range of sedimentary successions included and by the inferred age and composition of coarse-grained synorogenic clastic deposits, stacking of the PKB units progressed from the mid-Cretaceous emplacement of the Fatric nappes followed by sequentional structuralization of the Oravic units. The Pieniny Unit overrode the Subpieniny around the Cretaceous/Palaeogene boundary, then thrusting propagated northwards throughout the Palaeocene - Lower Eocene (Subpieniny + Pieniny over Saris) and terminated by the local Lower Miocene thrusting of the Saris Unit and the overlying nappe and overstepping complexes above the Magura Superunit (Fig. 2). This compressional tectonic scenario was interrupted by the Middle/Late Eocene extension followed by Oligocene subsidence. Renewed compression/transpression and wrench faulting then occurred during the Lower Miocene. In spite of this complicated tectonic history, the data about the post-depositional thermal history indicate that the PKB sediments were never buried to considerable depths, and all the deformation occurred in the brittle field. For this reason it is assumed that shallow thrusting did not generate a significant burial and the PKB units must have always occupied a high structural position. This would indicate a prevailingly footwall-propagated, „piggy-back“ mode of thin-skinned thrusting.

The Lower Miocene transpressional event generated the final form of the PKB that is restricted to a large-scale bivergent, positive „flower“ structure indicated by the surface structural data, as well as by the seismic reflection profiles and deep drillings. The flower is usually centred by a generally vertical zone of the PKB, in which strike-slipping prevailed (Fig. 1). The along-strike wrench movements led to the formation of the typical „klippen“ tectonic style caused by pervasive brittle faulting that

destructed earlier fold-and-thrust structures. All PKB rocks are structurally characterized by numerous slickensides dominated by dextral oblique- and strike-slips subparallel to the PKB boundaries. The Lower Miocene dextral transpression is presumably related to the counter-clockwise rotation of the CWC block with respect to the EWC accretionary wedge and underlying North European Platform (NEP), which was accompanied by narrowing and bending of the PKB.

Summing up, the overall tectonic scenario includes piggy-back mode of forward thrusting, formation of a fold-and-thrust belt capped by synorogenic sedimentary basins and some out-of-sequence thrusting as the principal tectonic regime during the Late Cretaceous and earliest Palaeogene, followed by Eocene extension and Oligocene - Lower Miocene dextral transpression responsible for the steepening and narrowing of the PKB that acquired its final tectonic style.

Position of the PKB in the Carpathian mega-structure

It is known for many decades that the surface trend of the PKB more-or-less follows the trend of crustal-anomaly zones indicated by various geophysical measurements (such as gravity minimum, change in polarity of the Wiese vectors, Moho steps, earthquake foci, etc.). These were identified with the so-called „Peripieniny lineament“ in the past, which was considered as a long-living, deep-seated fault zone of a very old origin (e.g., Sikora 1976). The modern geophysical investigations (deep seismic reflection and refraction profiling, gravity modelling, magnetotelluric measurements, etc.) have confirmed the presence of a crustal-scale boundary roughly corresponding to the surface trend of the PKB, which represents the boundary between the North European Platform (NEP) and the so-called ALCAPA block (Tertiary drifting assembly of Adria-related terranes) in deeper crustal levels. The results of seismic waves velocities, refraction and reflection investigations, as well as gravity (density) modelling showed important differences between the ALCAPA and European crust properties, which confirms that the PKB as a near-surface tectonic element is closely related to a deep crustal or even lithospheric boundary between two major parts of the Carpathian orogenic system (e.g., Bielik et al. 2004).

In general, the above-described tectonic development documents a transfer of the PKB units from an accretionary wedge toe to its rear, governed by the footwall-propagated thrusting style. In spite of some out-of-sequence thrusting and subsequent extension and subsidence, the PKB Oravic units remained always in a high structural position, escaped a considerable burial and therefore show a very low degree of recrystallization and ductile strain. In this high structural position within the rear part of developing EWC accretionary wedge, the original fold-and-thrust belt was then narrowed, stretched and disintegrated. This occurred after diminishing of the crustal convergence and growth of the accretionary wedge due to a soft collision between the NEP and the ALCAPA block at depth, which was also accompanied by large-scale counterclockwise rotation of ALCAPA with respect to NEP. As a result, the PKB remained fixed to this deep-seated crustal boundary and its intricate internal edifice combines both the early shallow nappe structures and the late deep-seated, orogen-parallel wrench movements.

Conclusions

In summary, we present a list of the most important new results that partially, or even entirely in some cases, contradict the earlier views:

- The Subpieniny (Czorsztyn) Unit is neither autochthonous, nor the lowermost element of the PKB structure - it is underlain by the newly defined Saris Unit in eastern and by the Biele Karpaty Unit in western Slovakia;
- The Saris Unit includes pelagic Cretaceous sediments followed by coarsening-upward Maastrichtian - Lower Eocene synorogenic deep-marine clastics (Jarmuta/Proc Fm.); consequently the „Klippen Belt Palaeogene“ does not represent the „klippen mantle“, but constitutes an independent structural unit;
- The overthrust processes in the PKB Oravic units are registered by synorogenic tectono-sedimentary breccias in several units and stratigraphic levels, hence they enable stratigraphic dating of tectonic events;
- The breccias often carry blocks of particularly the Czorsztyn-type Jurassic limestones - a significant fraction of „klippen“ is in fact represented by olistolites;
- In several sectors of the PKB relics of early fold-thrust structures may be identified; the PKB originally corresponded to a broad, but thin fold-thrust sheet covering a considerable southern portion of the EWC accretionary wedge that developed during the Palaeogene;
- The tectonic deformation processes were for a long time, but interruptedly accompanied by deposition of overstepping formations that seal older structures, but which were deformed later together with their substratum;
- An important extensional event affected the PKB and adjacent zones during the Eocene, which was likely related to an extensional collapse of overthickened rear parts of the developing EWC accretionary wedge and was followed by Oligocene subsidence;
- The „klippen tectonic style“ (block-in-matrix) resulted from the Lower Miocene transpressional deformation and disintegration of the original fold-thrust structure;
- The present-day position of the PKB is confined to a subvertical lithospheric-scale boundary between the ALCAPA block and the margin of the NEP downflexed below the EWC accretionary complex.

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