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ORIGINAL PAPER

Variable structural styles and tectonic evolution of an ancient backstop boundary: the Pieniny Klippen Belt of the Western Carpathians

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Abstract
The Pieniny Klippen Belt (PKB) and adjoining zones form a narrow, but lengthy belt that separates the Cretaceous nappe stack of the Central (Austroalpine) and the Cenozoic accretionary wedge of the External Western Carpathians (Flysch Belt). The PKB shares units and structures of both, in addition to the distinctive Oravic units, derived from a continental fragment in the Middle Penninic position. In map view, the northward-convex PKB consists of two branches—the western one striking roughly SW–NE and the eastern one oriented in the NW–SE direction. The western branch experienced a continuous NW–SE convergence and forward accretion of units derived from the foreland plate during the Late Cretaceous up to Oligocene. The developing accretionary wedge was supported by the backstop of the Central Carpathians. In contrast, the eastern branch originated by separation of PKB units and their dextral translation along the NE margin of the Central Carpathian block in the Late Eocene. During the Miocene reorganization of plate movements in the Carpathian area, the situation reversed. The eastern, formerly dextral transform margin was converted to the frontal backstop of the eastern part of the accretionary wedge. In contrast, the western, previously orthogonally convergent branch was affected by along-strike sinistral movements. Despite these considerable kinematic changes, the PKB remained fixed to both backstop edges and records deformation structures and associated sediments differentiated into several evolutionary stages.

Keywords Western Carpathians · Klippen Belt · Tectonic evolution · Cretaceous · Paleogene

Introduction

The Alpine-type mountain belts typically exhibit a long-lasting outward orogenic progradation of deformation processes that might have included subduction of not only one, but two or even more oceanic zones (e.g., Frisch 1979). In the Eastern Alps and Western Carpathians, the Jurassic–Paleogene orogenic processes resulted from subduction and ensuing collision of two independent oceanic realms. The first eo-Alpine cycle was related to the Late Jurassic closure of the Triassic–Jurassic, Neotethys-related Meliata Ocean, while the second cycle was connected with the Late Cretaceous to Paleogene subduction of the Atlantic-related Pennine oceanic branches (Alpine Tethys or Alpine Atlantic; Kozur 1991; Plašienka 1997; Thöni and Jagoutz 1993; Froitzheim et al. 1996; Dallmeyer et al. 1996; von Blanckenburg and Davies 1996; Neubauer et al. 2000; Missoni and Gawlick 2011; Gawlick and Missoni 2019). As a result, the inner Eastern Alpine–Western Carpathian zones (Austroalpine units in general—e.g., Schmid et al. 2008) originated

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subsequently to the first Tethyan cycle by post-collision stacking of basement and cover thrust sheets that resulted in crustal thickening of the developing orogenic wedge. During the Pennine cycle, the orogenic shortening prograded towards the stable North European Platform by subduction of the Pennine oceanic realm. The orogenic wedge grew by frontal accretion of sedimentary units scraped off the subducting ocean and intervening intra-oceanic continental fragments. In the Western Alps, the ocean-derived remnants are represented by the Lower and Upper Penninic units that originated from the northern Valais and southern Ligurian–Piemont oceanic branches, respectively. The Middle Penninic continental units represent accreted fragments of the Briançonnais and Margna–Sesia (Cervinia) continental ribbons (e.g., Schmid et al. 2004; Froitzheim et al. 2008 and references therein). The Penninic units of the Eastern Alps include ocean-derived complexes in the Penninic windows (Engadin, Tauern, Rechnitz) and the frontal Rhenodanubian Flysch Belt.

In the Western Carpathians, the Penninic units are represented by the Oravic cover nappes of the Pieniny Klippen Belt that were presumably derived from a continental fragment in the Middle Penninic position, and by the External Carpathian Flysch Belt, which is an accretionary wedge composed of sediments detached from the subducted North Pennine (Magura) and Moldavian oceanic lithosphere (Tomek 1993; Picha et al. 2006; Ślączka et al. 2006; Froitzheim et al. 2008; Oszczypko et al. 2015; Kováč et al. 2016, 2017 and references therein). The presence of the Upper Penninic oceanic units in the Western Carpathians is arguable, since their possible surface exposures are restricted to the Považský Inovec Mts only (see Fig. 1; e.g., Plašienka 2012a, 2018a). Most likely, they are still hidden below the Tatric (Lower Austroalpine) thick-skinned thrust sheet (e.g., Tomek 1993; Bielik et al. 2004).

Majority of modern active continental margins is characterized by the ocean-ward tapering accretionary wedge composed of sediments scraped off the subducting oceanic lithosphere. From the hinterland, the accretionary wedge is supported by the rigid buttress formed by the consolidated continental lithosphere of the upper tectonic plate. In the reflection seismic sections of the contemporary active margins, the wedge vs. buttress transition is interpreted as a sharp boundary known as the backstop. Most of analogue

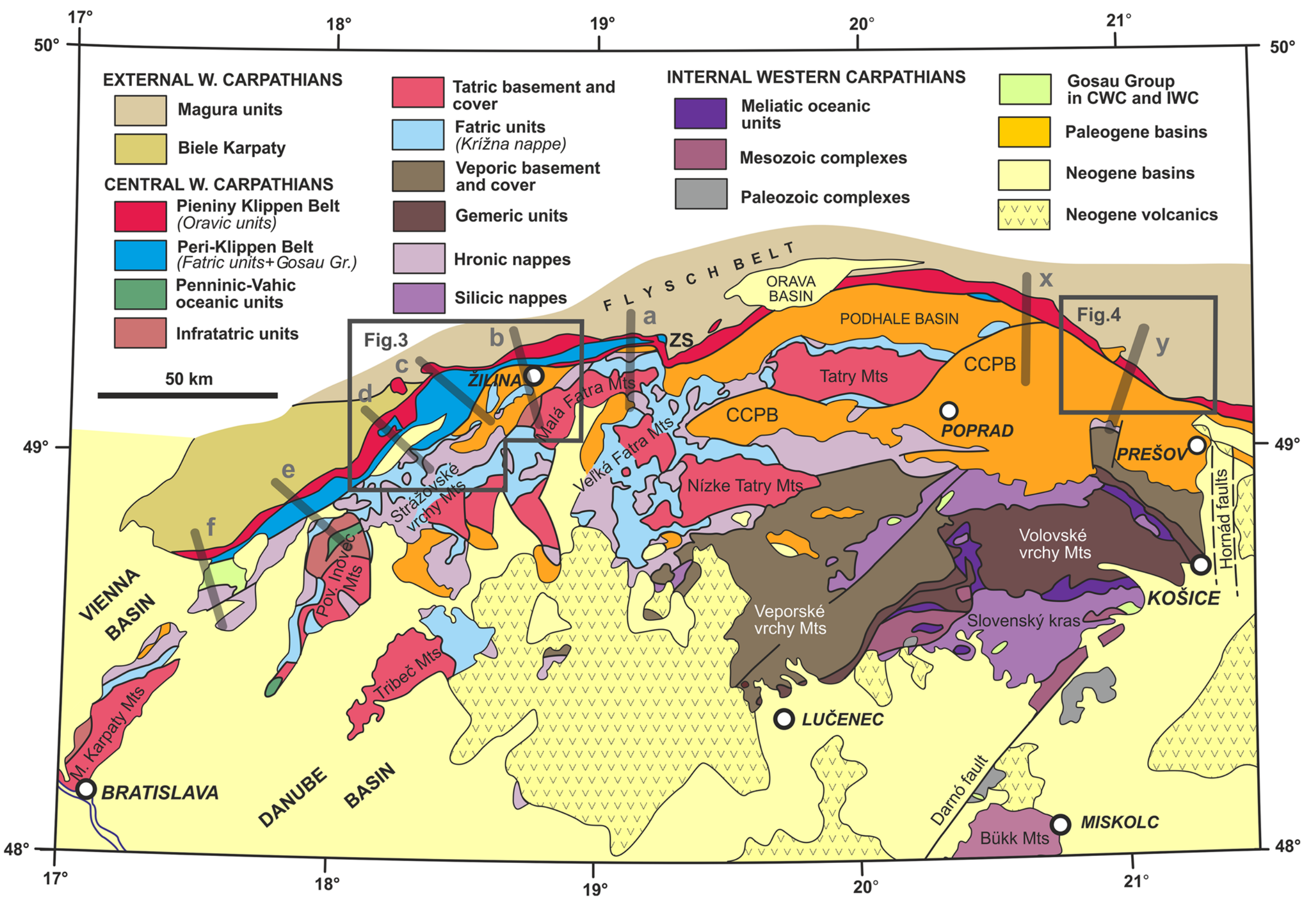


Fig. 1 Position of the Pieniny Klippen Belt in the tectonic framework of the Western Carpathians. Cross-section traces *a*–*f* and *x*, *y* are interpreted in Fig. 2. Rectangles indicate detailed maps in Figs. 3 and 4. *CCPB* Central Carpathian Paleogene Basin, *ZS* Zázrivá sigmoid

or numerical models presume that almost all deformation related to convergence is realized within the accretionary wedge beyond the backstop (e.g., Burbidge and Braun 2002; Kopp and Kukowski 2003; Soto et al. 2006; Storti et al. 2001, 2007; Graveleau et al. 2012 and references therein), or beyond pin points in balanced cross sections (Nemčok et al. 1998, 2000, 2006; Behrmann et al. 2000; Gągała et al. 2012; Castelluccio et al. 2015), while only minor, if any shortening might have affected the buttress area. On the other hand, the field-based study of ancient wedge/buttress boundaries is often obliterated by strong modifications by superimposed collisional deformation processes, like, for instance, in the Alps. By chance, the Western Carpathians is a type of orogen in which the convergence ceased by a "soft collision" (e.g., Sperner et al. 2002); therefore, many original structural features and relationships have been preserved and can be interpreted in terms of tectonic development of the orogenic wedge in its pre-collision state.

In this paper, we present sedimentary and structural data and evolutionary tectonic model of a prominent regional Carpathian unit—the Pieniny Klippen Belt. In particular, we describe how its units were detached from an independent palaeogeographic, intra-oceanic ridge-type domain during the Late Cretaceous-to-Paleogene progradation of the Western Carpathian orogenic wedge. Presently, the PKB follows a narrow backstop zone between the External Carpathian Flysch Belt, representing the Cenozoic frontal accretionary complex, and the Cretaceous stack of thick- and thin-skinned thrust sheets of the Central Carpathian zones in the hinterland position.

Geological framework

The Pieniny Klippen Belt (PKB) is situated between the Central Western Carpathians (CWC) and the External Carpathians (EWC), where it extends for some 600 km as a merely few km wide zone (Fig. 1). This conspicuous structural zone has got its name (e.g., Stur 1860; Neumayr 1871; Uhlig 1890, 1904, 1907) from a picturesque landscape formed by the klippen, formed by the relatively stiff, erosion-resistant Middle Jurassic-to-Lower Cretaceous limestones, which are surrounded by Upper Cretaceous and Paleogene shales, marls and flysch deposits. The PKB sedimentary successions were detached from an unknown pre-Jurassic basement and stacked in a system of thrust sheets, subsequently strongly modified by out-of-sequence and back-thrusting, wrenching, and extension. As a result, the PKB has a typical block-in-matrix structure in many places, whereas the original nappe structure is only partially preserved.

Two PKB branches are distinguished from the point of view of composition and structure. The western, roughly WSW–ENE (60°) striking and slightly NNW-ward-arching branch is perpendicularly truncated by an N–S-trending fault zone with dextral offset known as the Zázrivá sigmoid (ZS in Fig. 1; cf. Kováč and Hók 1993). The eastern branch forms a northward convex arc in its north-westernmost part in Poland, and then strikes ESE (120°) as an almost straight zone in eastern Slovakia with continuation to south-western Ukraine.

The Jurassic-to-Paleogene sedimentary successions of the PKB show variable lithologies and complex structural relationships. We distinguish two principally different types of units involved in the PKB structure. The most typical are the Oravic units that occur all-along the PKB. They were derived from an independent palaeogeographic domain, presumably a continental fragment in the Middle Penninic position (so-called Czorsztyn Ridge and its slopes—e.g., Birkenmajer 1977, 1986). However, especially the western PKB branch incorporates also frontal elements of the CWC (Austroalpine) nappe system, along with their post-thrusting, overstepping Gosau cover (Fig. 1; Plašienka 2012a, 2018a; Plašienka and Soták 2015), which shared a large part of their structural history with the Oravic units.

In the following text, we characterize the structure and tectonic evolution of the innermost elements of the EWC Flysch Belt (Biele Karpaty and Magura superunits) adjacent to the PKB, the PKB proper composed of the Oravic units (PKB s.s.), the transitional elements towards the CWC (so-called Peri-Klippen zone), and adjacent frontal CWC units (Tatric and Fatric; Fig. 1). In the supplement to this paper (Online Resource 1), we briefly describe the composition, lithostratigraphy, and development of synorogenic clastic sediments of units involved, which are summarized in the tectonostratigraphic scheme (Fig. S1 in the Online Resource 1).

Regional tectonics, evolutionary stages

The overall structure of the PKB and adjacent zones is illustrated by a series of regional cross sections of its western and eastern branches (Fig. 2a–f, x–z, respectively). It can be seen that in spite of the Oravic units are present all along the PKB, their inner structure and relationships to both the EWC and CWC zones differ from place to place, sometimes to a considerable extent. The western part is characterized by a long-termed protracting shortening which obliterated the original nappe structure and finally has led to verticalized structures realized by backthrusting and backward tilting of sedimentary units (Fig. 2a–d). Well core data (borehole Lu-1; Leško et al. 1978) and density modelling (Šamajová et al. 2018) in the westernmost PKB part (Fig. 2e–f) point to a significant overthrusting of the inner part of the EWC Flysch Belt by the PKB Oravic and Peri-Klippen Fatric units. In contrast, the eastern PKB

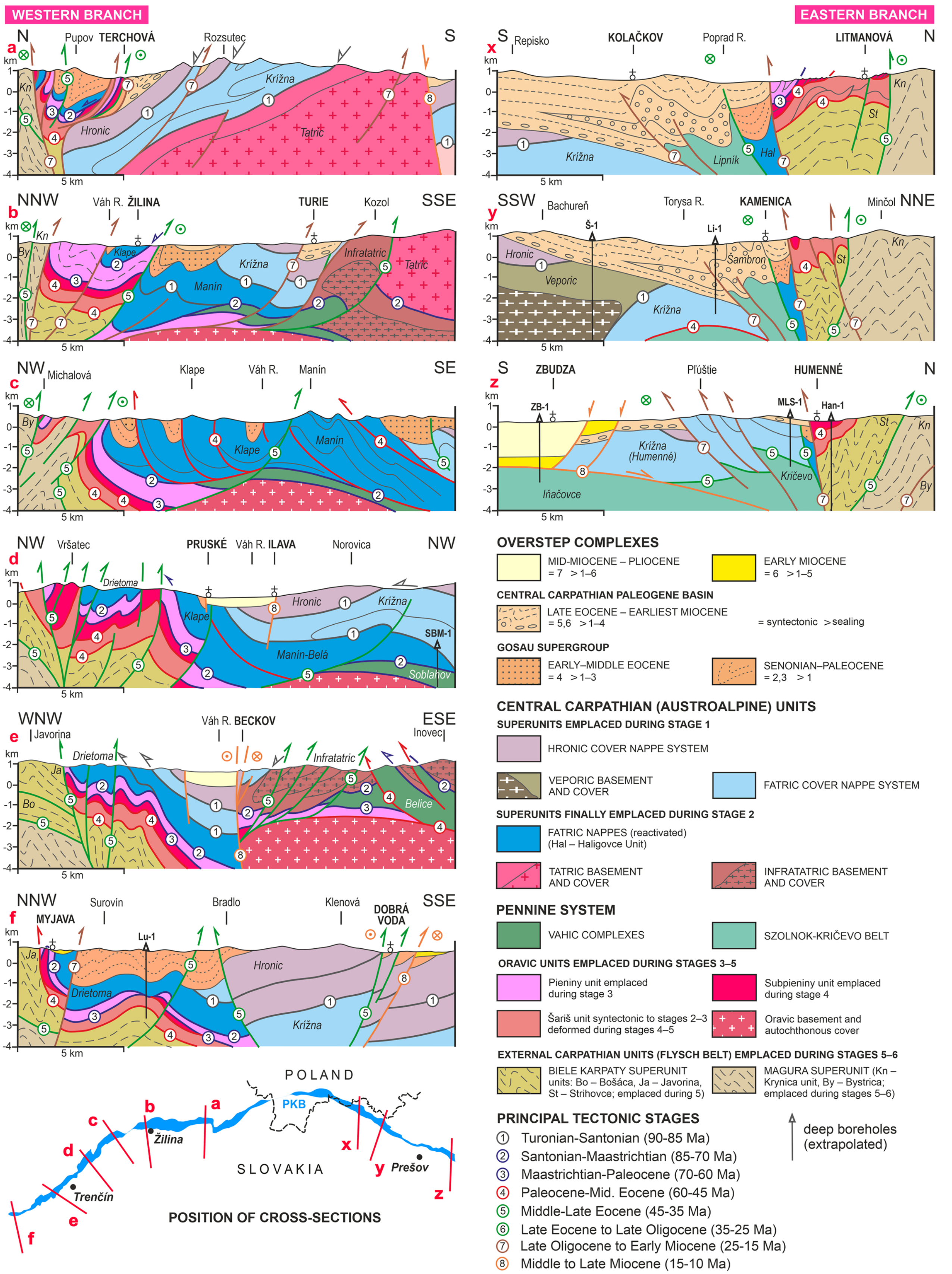


Fig. 2 Cross sections demonstrating the structural variability of selected sectors along the PKB. For further descriptions, see the text

branch exhibits partially preserved early thrust structures of Oravic units bounded by distinct subvertical oblique-slip faults (Fig. 2x–z). Herein, we exemplify tectonic developments of these two structurally different settings by the area of the Middle Váh River Valley in western Slovakia (Fig. 3) and by the Čergov Mts in north-eastern Slovakia (Fig. 4), respectively.

Both areas are characterized by a complex geological structure of a number of tectonic units occurring in a belt embracing the outer parts of the CWC nappe stack, PKB with the Peri-Klippen zone, and inner parts of the EWC accretionary wedge. We have distinguished eight principal tectonic evolutionary stages, which document a long-term (ca 80 Myr) continuous convergence expressed by forward thrusting and stacking of sedimentary units that were detached from their underthrust basement and sequentially accreted to the tip of the propagating orogenic wedge.

The western PKB branch (Middle Váh River Valley)

The western, SW–NE-to-WSW–ENE-trending branch of the PKB is exemplified by the area around the middle course of the Váh River Valley (Figs. 1, 3). Based on the mesoscopic structural analyses, the tectonic evolution of parts of this region has been examined in works of Nemčok and Nemčok (1994), Kováč and Hók (1996), Bučová et al. (2010), Bučová (2013), Šimonová and Plašienka (2017), Plašienka et al. (2018) and Plašienka (2019). Minor and broad-scale structures of the adjacent part of the EWC Flysch Belt were described for instance in papers by Roth (1980), Aleksandrowski (1989), Decker and Peresson (1996), Nemčok et al. (1998), Marko et al. (2000), Picha et al. (2006), Hrouda et al. (2009), Plašienka et al. (2010), or Beidinger and Decker (2016). The inferred tectonic scenario includes the following phases:

1. The first stage only concerns the CWC cover nappe systems of the Fatric and Hronic superunits. As revealed by the sedimentary rock record (see Online Resource 1), they were emplaced over the Tatric basement and cover units during the latest Turonian at earliest, but possibly also little later during the Coniacian to Santonian in the outer zones (Pelech et al. 2017), i.e., some 90–85 Ma ago (Plašienka 2018a, 2019, and references therein). In that time, the frontal Fatric nappe elements (Manín and Klape-Drietoma) were emplaced beyond the outer Tatric margin over the Vahic oceanic crust, which started to subduct below the Tatric margin at about the same time. In the CWC area, the top-to-NW thrusting direction of the Fatric nappes was documented by Plašienka (2003) and Prokešová et al. (2012).
2. During subduction of the Váh (Ligurian−Piemont) Ocean, the frontal CWC nappe units of the present Peri-Klippen zone formed the primary accretionary wedge. After elimination of the Vahic oceanic lithosphere, these units were thrust over the southern foot of the Oravic continental fragment—the depositional place of the later Pieniny Unit. Based on the sedimentary record (Online Resource 1), this phase embraced a considerable time period from the Santonian to early Maastrichtian (ca 85–70 Ma ago). However, a remnant oceanic basin remained open in the eastern part of the convergence zone probably until the Eocene (the Iňačovce−Kričevo zone; Fig. 2y, z; e.g., Kováč et al. 2016, and references therein).
3. After subduction of the Vahic lithosphere was completed in the western PKB branch, the outer (Tatric) CWC margin of the came into collision with the Oravic continental domain. Shortening continued by detachment of the basinal Pieniny-type successions and their thrusting over the elevated part of the Oravic continental ribbon (Czorsztyn Ridge), which is recorded by the latest Cretaceous trench-type flysch deposits and olistostrome bodies in the underlying Czorsztyn-type successions of the future Subpieniny Unit (Online Resource 1). In a continuation with the previous stage, the third stage lasted probably until the Middle Paleocene (60 Ma). Available structural data reveal the W-to-NW-ward vergence of these structures (Plašienka et al. 2018 and references therein).
4. During underthrusting of the Oravic crustal domain below the prograding CWC orogenic wedge, the Subpieniny and Šariš units were sequentially detached and accreted to the front of the growing accretionary wedge. Finally, also the Biele Karpaty units of the present EWC Flysch Belt were involved in the thrusting processes and incorporated by the wedge during the Middle Eocene, as documented by the sedimentary record (Online Resource 1). Contemporaneously, during the Paleocene to Middle Eocene (60–ca 45 Ma ago), the wedge propagated by alternation of shortening and extensional events controlled by changes in the critical taper of the wedge (Plašienka and Soták 2015). These events were defined on the basis of the sedimentary record in the piggyback Gosau basins developed atop the deformed wedge composed of the Manín, Klape, and Drietoma units, as well as in the coeval trench-type wildflysch basins of the Oravic units that developed in front of the advancing accretionary wedge (Online Resource 1).

Throughout the fourth stage, the frontal CWC units in the Peri-Klippen zone and Oravic units of the PKB formed a united accretionary complex characterized by forward thrusting with development of a typical wedge shape. Deformation structures of this stage substantially affected the general tectonic structure of the PKB and adjacent zones (Figs. 2, 3, 4). The most prominent are the brachyanticlines in the Manín Unit (Fig. 3; cf. Plašienka et al. 2018) and a series of imbricates in the Klape Unit that incorporate also the Gosau deposits (Fig. 3; cf. Plašienka 2019). The rear wedge part thickened by upright folding and out-of-sequence thrusting causing steepening and back tilting of partial thrust sheets and imbricates. Horizontal-axis rotation into a steep to subvertical position of sedimentary units has led to rotation of earlier structures that developed in the subhorizontally lying beds originally (see inset b in Fig. 3). The pre-tilting compressional structures include conjugate sets of strike-slip shear fractures in particular, which were documented at several localities in the Manín and Klape units, as well as in the early Paleogene Gosau strata (Bučová 2013; empty arrows in Fig. 3). These originated probably during the second stage; after back-rotation into a horizontal position, they reveal NW–SE-oriented horizontal contraction. In general, the principal compression axis related to the fourth stage oscillated around the NW–SE direction. This direction corresponds to the convergence path between the Austroalpine upper plate and the European lower plate at the north-eastern edge of Adria (e.g., Handy et al. 2015), which was oriented SSW–NNE before the Miocene counter-clockwise rotation.

5. Further development of the convergence zone was characterized by an accelerating expansion of the wedge by sequential frontal accretion of the Biele Karpaty and Magura units (Middle–Late Eocene, 45–35 Ma; Figs. 2, 3). Considering the presumably oceanic crustal basement of these units, it indicates a commencement of subduction of the North Pennine (Rhenodanubian–Magura) oceanic zone during the Middle Eocene in its western part. After the Lutetian collapse (Plašienka and Soták 2015), the rear part of the wedge thickened by back-tilting and verticalization up to overturning of bedding and earlier structures, especially along the axial zones of the wedge centred by the PKB (inset in Fig. 3). Except the conjugate shear fractures, the rotated older deformation features in the Flysch Belt units include also small-scale thrust ramps and ramp-flat systems (see Marko et al. 2000; Beidinger and Decker 2016). As the wedge was further strongly compressed, its rear and hinterland were affected by back-thrusting. Regionally, the most important backthrusts occur at the boundary between the EWC Flysch Belt and PKB and between the Klape and Manín units (Figs. 2, 3), but numerous smaller scale backthrusts and NW-dipping reverse faults are distributed over large areas of the Strážovské vrchy Mts (Maheľ 1985; Pečeňa and Vojtko 2011; Pelech and Olšavský 2018, see Fig. 3). Thus, in general, the wedge grew by frontal accretion and its thickened axial and rear parts were affected by backtilting and ultimately also backthrusting during stages (3)–(5): see inset b in Fig. 3.

   Foreland-directed forethrusts in the Magura units and hinterland-directed backthrusts in the PKB and CWC areas are arranged in a broad-scale fanwise structure centred in the Bystrica Unit (thick white dot-and-dash line in Fig. 3). This axial zone of the asymmetric EWC wedge is identified with the deepest part of the accretionary wedge indicated also by the gravity minimum of the Western Carpathian orogen (e.g., Tomek 1993; Picha et al. 2006; Alasonati Tašárová et al. 2008). Accordingly, starting from the fifth stage, the PKB Oravic units were fully attached to the upper CWC plate of the convergence zone, i.e., they had already occurred in a backstop position with respect to the onward growing EWC accretionary wedge.

   In the northern part of the region depicted in Fig. 3, the PKB/CWC contact turns to the W–E direction. At the same time, the PKB along with the Peri-Klippen zone are considerably narrowed with a necking zone around town of Bytča. Eastward, the Kysuca segment of the PKB is characterized by the largest occurrence of the Oravic Pieniny (Kysuca) Unit overridden by the Klape Unit and juxtaposed to the Gosau (Myjava−Hričov and Súľov, see Online Resource 1) and Central Carpathian Paleogene Basin (CCPB) deposits towards the south (Fig. 3). Strata are steeply N-dipping and affected by dextral strike-slipping along the W–E-trending contact zone, which is designated as the Bytča–Žilina fault zone limiting the southern PKB boundary towards the east. This is likely an effect of a non-linear, rounded outer edge of the indenting CWC rigid buttress. The southwestern part was shaped by orthogonal NW–SE contraction with SW–NE structural trends, while the northern W–E edge, oblique to the shortening direction, was affected by dextral strike-slipping and transpression. These structures were documented in large, but temporary artificial outcrops west of town Žilina (Bučová 2013).

6. Late Eocene-to-Late Oligocene (35–25 Ma) deformation reflects protracting NW–SE shortening. In general, faults of the sixth stage, slickensides, and fractures are treated as post-tilting structures in the PKB and bordering zones. They originated after the bedding planes and pre-existing deformation structures were externally rotated into a steep, vertical or even overturned position due to piggyback folding and thrusting. During the sixth stage, internal fold-thrust structure of the Magura units was completed in the western part of the EWC Flysch Belt and the outer Moldavian units (Fore-Magura, Silesian, Subsilesian) of the EWC Flysch Belt were sequentially accreted (Picha et al. 2006).

According to the palaeostress interpretations of brittle fault and joint structures all along the PKB and adjoining zones, the resolved maximum horizontal stress axis and shortening direction shifted gradually from the W–E, through NW–SE, then N–S towards the SW–NE direction during the Eocene to Miocene (e.g., Aleksandrowski 1989; Marko et al. 1995; Kováč et al. 1995; Fodor et al. 1999; Pešková et al. 2009, 2012; Bučová et al. 2010; Vojtko et al. 2010; Mikuš 2010; Sůkalová et al. 2011; Bučová 2013; Šimonová and Plašienka 2017). However, this stress field rotation becomes apparent only if the mid-Miocene counter-clockwise (CCW) block rotation of the whole Western Carpathian part of AlCaPa by some 50–60° is taken into account (e.g.,

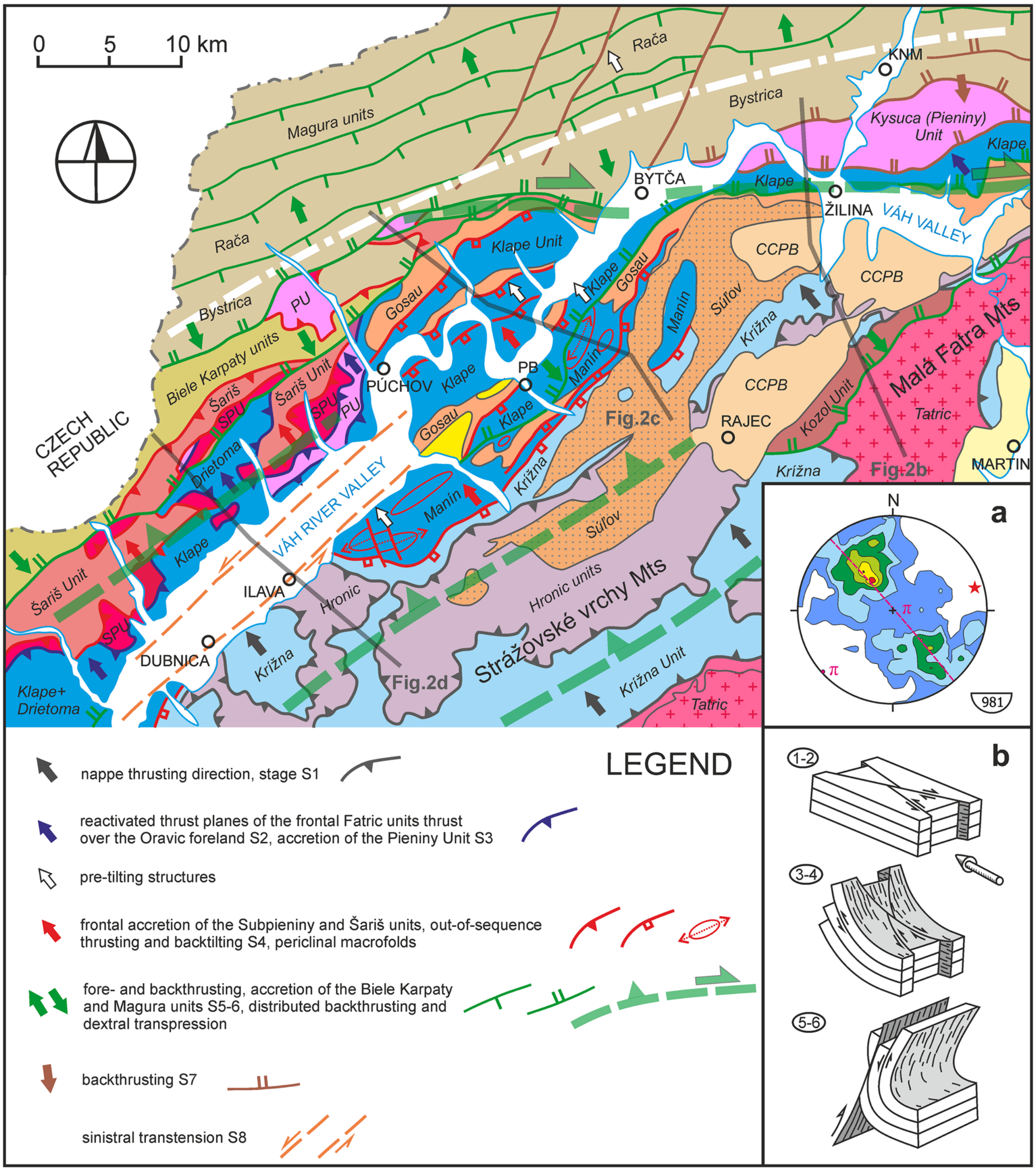


Fig. 3 Tectonic scheme of the PKB and adjacent zones in the Middle Váh river Valley of western Slovakia (cf. Figure 1). For the colour code of tectonic units, see Fig. 2. **a** Cumulative stereographic plot (poles to bedding, equal area, lower hemisphere) of bedding planes of the Peri-Klippen, Oravic, Biele Karpaty and Magura units depicted in the map. The red asterisk represents the mean of measured and constructed fold axes. **b** Characteristic modification of pre-tilting structures of stages 1–2 by subsequent stages 3–6. *PU* Pieniny Unit, *SPU* Subpieniny Unit, *KNM* Kysucké Nové Mesto town

Márton et al. 2013, 2015). Consequently, all pre-Middle Miocene structures have to be back-rotated by the same value. Then the reconstructed maximum horizontal stress axis becomes approximately NNW–SSE to N–S oriented for a long period from the Late Cretaceous to the Early Miocene (Marko et al. 1995; Márton and Fodor 1995; Šimonová and Plašienka 2017). The documented Middle Miocene-to-Pliocene clockwise shift of the palaeostress field that post-dated the block rotation affected the entire Western Carpathians already in the present coordinates.

An important clue to the evaluation of structures at the transition between the generally SW–NE striking western and NW–SE trending eastern segments of the EWC Flysch Belt was provided by Aleksandrowski (1989). His detailed structural analysis of the Magura nappe from the Babia Góra region near the apical part of the northward-convex Carpathian bend (NW of the Orava Basin in Fig. 1) revealed two distinct folding events. The region is dominated by the map-scale folds and thrusts trending SW–NE to W–E, which are overprinted by lesser folds with the WNW–ESE-to-NW–SE axial trends, thus forming the type 1 interference pattern (sensu Ramsay 1967). According to Aleksandrowski (1989), the older fold-thrust trails developed before the final overthrust of the Magura nappe, while the younger folds affected also the outer, Silesian−Krosno units of the Flysch Belt. These changes were triggered by the dextral rotation of the regional stress field connected with the NW–SE convergence dominating in the Eastern Alps and in the western part of the EWC substituted by the escape-dominated SW–NE compression in the central and eastern segments of the EWC (Decker and Peresson 1996; see the discussion section).

7. Late Oligocene-to-early Middle Miocene (25–15 Ma) stage is characterized by the gradual shift of the maximum compression direction from NW–SE to the overall N–S orientation. Important south-vergent backthrusting occurred along the W–E-trending Kysuca sector of the PKB east of Bytča town (Fig. 3), whereby the PKB units were thrust over the Paleogene Gosau and CCPB complexes overlying the CWC nappe units for a distance of at least 5 km (Fig. 2a; cf. Pešková et al. 2012). Southward backthrusting affected also more inner CWC zones, for instance, the prominent N-dipping reverse fault on the ridge of Mt. Rozsutec (Fig. 2a), as well as in other areas of the Malá Fatra Mts (e.g., Sentpetery and Hók 2012; Fig. 2a).

   During the late Early Miocene to early Middle Miocene (ca 18.5–14.5 Ma), the large-scale counter-clockwise block rotation of the entire Western Carpathian domain in the order of 50–60° occurred (Márton et al. 2015). Timing and amount of this rotation were further discussed by Kováč et al. (2017). Throughout the sixth stage, the stress field remained constant in the N–S orientation of the maximum compression axis; thus, the recorded brittle structures register an apparent clockwise shift of the stress field (Márton and Fodor 1995; Marko et al. 1995; Šimonová and Plašienka 2017). As a result, the south-directed backthrusts in the northern part of the region were probably generated at the very end of this period, i.e., in the post-rotation Middle Miocene times.
8. During the post-rotation Middle-to-early Late Miocene times (15–10 Ma), the western EWC branch became to be fixed to the foreland plate (Bohemian Massif; cf. Picha et al. 2006). Ongoing NE-directed movement of the Carpathian part of the AlCaPa microplate resulted in the overall transtensional regime. Major sinistral strike-slip zones extending from the Eastern Alps affected the zones along the PKB by development of the extensive Vienna Basin at the Alpine–Carpathian junction area (e.g., Royden 1985; Csontos et al. 1992; Fodor 1995; Salcher et al. 2012), but also with opening of several other small pull-aparts along the Váh River Valley (Trenčín and Ilava basins, Fig. 2d–f) up to the northernmost PKB bend from its WSW-to-ESE-trending sectors (Orava Basin in Fig. 1; e.g., Ludwiniak et al. 2019 and references therein). The brittle structural record reveals shifting of the maximum horizontal stress axis from the N–S to the SW–NE orientation as documented at numerous places (e.g., Marko et al. 1995; Kováč and Hók 1996; Šimonová and Plašienka 2017). The SW–NE-trending thrust faults separating nappes of the EWC Flysch Belt were also partly reactivated as left-lateral strike slips (Decker and Peresson 1996; Beidinger and Decker 2016). Simultaneously, the only important transversal fault—the N–S-trending Zázrivá–Párnica dextral offset of the PKB originated. It is the northern part of the Central Slovak fault system (Kováč and Hók 1993), so-called Zázrivá sigmoid (ZS in Fig. 1).

The eastern PKB branch (Čergov Mountains)

The eastern PKB branch stretches as a 3–5 km narrow zone in the WNW–ESE direction from the Slovak-Polish Pieniny Mts towards the foots of the Čergov Mts and further east to the Šariš region of eastern Slovakia (Figs. 1, 4), before entering Ukraine. Here, the PKB is distinctly fault-bounded against the Paleogene flysch complexes of the Krynica Unit of the Magura nappe system toward the NE, as well as against the flysch deposits of the Central Carpathian Paleogene Basin (CCPB) toward the SW. The bounding faults are steeply NE-dipping up to vertical and show a complex kinematic history (e.g., Ludwiniak 2018 and references therein). Thanks to this specific geomorphologic situation, the PKB with its various klippen types (Plašienka 2018b) forms a picturesque rugged landscape amidst a mildly shaped relief developed in soft flysch complexes.

Unlike the western PKB branch, the eastern branch is dominantly composed of the Oravic units (Šariš, Subpieniny and Pieniny from bottom to top) with frequently well-preserved original nappe edifice revealed by detailed mapping and structural studies (Jurewicz 1994, 1997, 2005, 2018; Plašienka and Mikuš 2010; Plašienka 2012b). In places, the original nappe structure was strongly modified by superimposed out-of-sequence thrusting, dextral transpression and backthrusting (e.g., Ratschbacher et al. 1993; Nemčok and Nemčok 1994).

Similarly like in the western PKB branch, eight principal phases are distinguished in the tectonic development of the eastern branch. However, their expression in the structure of the PKB and adjoining zones is different (compare cross sections a–f and x–z in Fig. 2). While the inner PKB structure originated during the third and fourth stage, its boundaries and neighbouring units were mainly affected by the stages 5–8. It is inferred that the PKB structures of the stages 2–4 originated along with the western PKB branch, but subsequently, the eastern PKB segments were detached and transported south-eastward during the fifth stage (Fig. 5).

Due to the thick Paleogene cover, the structure of the eastern Peri-Klippen zones south-east of the PKB s.s. is poorly known. Nevertheless, several deep boreholes in the area encountered rock complexes that are not known from the surface. In particular, these are the Iňačovce and Kričevo units drilled in the basement of the Neogene deposits of the Transcarpathian Basin (e.g., Soták et al. 2005). The Iňačovce Unit is a dismembered complex of Mesozoic to Paleogene, low-grade metamorphosed rocks with embedded serpentinite bodies, while the Kričevo Unit consists of variegated, unmetamorphosed Cretaceous to Paleogene deposits (cf. Plašienka and Soták 2015). Similar sediments were drilled also below the Mesozoic rocks of the Humenné Unit (Soták et al. 1997; Fig. 2z), which is a lost outlier of the Fatric nappe system surrounded by deposits of the CCPB in eastern Slovakia. The Humenné Unit is strongly affected by backthrusts apparently related to the flower structure developed along the eastern PKB branch (Jacko and Schmidt 1994; Fig. 3z).

In the Pieniny Mts further towards NW, rocks correlative with the Kričevo Unit are occasionally appearing at the surface as narrow slices along the southern bounding fault of the PKB. These are composed of Upper Cretaceous to Eocene deep-marine deposits (Maruszyna Unit in Poland and Lipník Unit in Slovakia just south of the Haligovka klippe—Plašienka and Soták 2015). Owing to scarcity of data, mutual relationships of the Iňačovce, Kričevo, and Maruszyna–Lipník units are not clear. Possible oceanic provenance and connections to the Szolnok–Sava Belt have been considered by Schmid et al. (2008), Plašienka and Soták (2015) and Kováč et al. (2016)—see the Online Resource 1.

In the Čergov sector (Fig. 4), the southern PKB margin is followed by an anticlinal Šambron–Kamenica Zone (cf. Plašienka et al. 1998 and references therein) that exposes exceptionally thick conglomerate bodies of the Šambron Fm (Marschalko 1975) surrounded by the Oligocene deposits of the CCPB. It is inferred that these conglomerates represent the upper structural level of the Maruszyna–Lipník Unit (Online Resource 1) and originated during the eastward translation of the PKB and attached CWC elements along the southern PKB transform boundary (Plašienka and Soták 2015; see below).

1. The first thrusting phase of the CWC cover nappes cannot be documented directly in this region, since the CWC units are largely hidden by the Paleogene deposits of the CCPB. They are, however, interpreted in the cross-sections, partly based on deep drillings (Figs. 2, 4).
2. There is only one occurrence of the CWC nappe unit within the fault-bounded eastern PKB branch. This is the relatively small Haligovka klippe in the Pieniny Mts (Fig. 1). Its strata succession includes Triassic-to-mid-Cretaceous formations akin to the Manín Unit or other shallow-water Fatric successions (see references in Plašienka and Soták 2015; Plašienka 2019). The Haligovce Unit overrides the Oravic Pieniny Unit and carries also the uppermost Cretaceous–Paleogene Gosau sediments (Online Resource 1; cf. Plašienka et al. 2017). Accordingly, it should have been emplaced during the second stage, analogously like the Manín and Klape units in the western PKB branch were.
3. The third stage is represented by structures related to thrusting of the Pieniny Unit over the Jarmuta flysch basin of the later Subpieniny Unit. The thrusting is well constrained by the sedimentary record to the latest Cretaceous to earliest Paleogene (Plašienka and Mikuš 2010; Plašienka 2012a, b; Plašienka et al. 2012; Plašienka and Soták 2015).
4. Out-of-sequence reverse faults and associated folds of the fourth stage prevail in the internal structure of the PKB. They are W–E to WNW–ESE (ca 90°–110°) striking with northern vergency and cause multiple repetition of thrust imbricates especially in the Šariš Unit, which dominates the PKB structure at the present erosional level (area north of town Lipany in Fig. 4). These thrusts were coeval or shortly postdated the NNW-verging forethrust of the Subpieniny Unit that occurred during the Paleocene to Middle Eocene, as documented by the synorogenic wildflysch deposits in the later Šariš Unit (Online Resource 1). Hence, the thrusts and reverse faults of the fourth stage are oblique

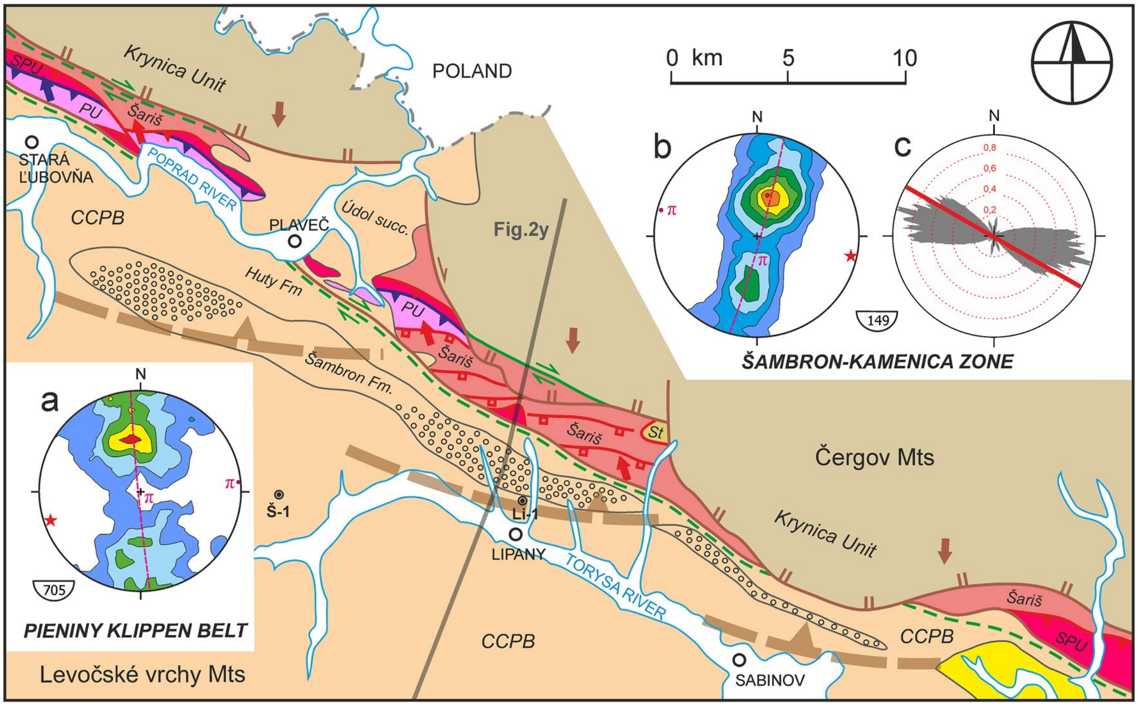


Fig. 4 Arrangement and structure of the PKB and neighbouring units in the Slovakian Pieniny and Čergov Mts (cf. Figure 1). For the colour code, abbreviations of tectonic units and other marks see the legend to Fig. 2. Stereographic diagrams: **a** poles to bedding of the PKB Oravic units; **b** poles to bedding of Paleogene sediments of the Šambron–Kamenica zone; **c** the same data plotted as bedding strikes in the rose diagram, the red line represents the overall strike of the PKB eastern branch. See "Discussion: the tectonic model" in the text

to the general WNW–ESE (120°) trend of the eastern PKB branch (Fig. 4; see also Ratschbacher et al. 1993; Jurewicz 1994; Plašienka 2012b). Poles to bedding of Oravic units in the stereographic projection are distributed along the NNW–SSE-to-N–S-trending girdle, nearly parallel to those in the western branch (inset a in Fig. 3 and inset a in Fig. 4). Supposedly, both were achieved next to each other during the stages 2–4, and subsequently split by the dextral shear corridor. Slight clockwise rotation of the great circle in the eastern PKB branch was likely caused by the dextral drag of bedding measured especially in soft marlstones and shales, but axes of mesoscopic, NW-vergent folds are still scattered around the SW–NE direction (Plašienka 2012b), like in the western branch (Plašienka et al. 2018).

At the end of the fourth stage, during the Middle Eocene, the Šariš Unit overrode the Biele Karpaty Unit in the western PKB branch. It is questionable, however, whether this can be documented also in the eastern branch. Relying on the flat overthrust structures of the Oravic units, altogether not more than 2–3 km thick, these should be underlain by some more external units, presumably Magura-related (e.g., Plašienka 2012b; Plašienka et al. 2017). This interpretation was corroborated by results of the Hanušovce Han-1 deep well (Leško et al. 1984) and indicated by local seismic reflection profiles in the Polish Pieniny Mts (Golonka et al. 2019). Since the eastern PKB composed of Oravic units is sharply fault-bounded in most cases, this underlying unit cannot be directly observed. The north-eastern boundary of the easternmost Slovakian PKB segment is followed by the so-called Strihovce Unit, which is the Paleocene–Eocene flysch complex showing close affinity to the Biele Karpaty units of the western PKB branch (Potfaj in Bezák et al. 2004; Online Resource 1). Similarly like there, the Strihovce flysch deposits show some close lithological and structural relationships to the Proč Fm of the Šariš Unit; therefore, both are affiliated to the Magura Superunit by some authors (e.g., Bónová et al. 2018 and references therein). Another kind of a transition between the PKB and Magura units was assumed by Jurewicz (2018) in the Polish Pieniny Mts. However, the cartographic determination of these transitional elements is problematic. The situation is even more complicated by the presence of the Lower Miocene deep-water flysch deposits occurring just next to the northern PKB limit in the Pieniny Mts (Oszczypko et al. 2005; Oszczypko-Clowes et al. 2018). Consequently, our interpretation of the presence of the Biele Karpaty (Strihovce Unit, Fig. 2x–z) in the underlier of the Oravic nappes in the eastern PKB branch should be taken as tentative only and ought to be verified by the future research.

5. The importance of dextral transpressional structures in the eastern PKB branch was accentuated and comprehensively documented in the paper by Ratschbacher et al. (1993). In the present work, we attribute a majority of these deformation structures to the fifth stage, which developed in continuity with the fourth stage. The WNW–ESE-trending fore- and out-of-sequence thrusts, folds and axial plane cleavage sets (stage 4) were modified by steeply inclined shear zones parallel to the subvertical-bounding faults, and NNW–SSE-striking Riedel shears R connecting small-scale backthrusts of the stage 5 (Fig. 4; cf. Plašienka 2012b). Hence, the eastern PKB would represent a subvertical fault-bounded planar domain deformed by dextral transpression with approximately N–S-directed shortening, vertical lengthening, W–E extension and clockwise rotation and dragging of older structures along the zone walls (Ratschbacher et al. 1993; Plašienka 2012b; Ludwiniak 2018).

   We infer that, during the fifth stage, the eastern PKB segments were uprooted from the generally SW–NE-trending fold-thrust belt (western PKB branch) and transferred along the NW–SE transform boundary of the CWC edge into the present position. As a result, a large-scale wrench corridor with characteristic flower structure, centred by the PKB, developed (Fig. 2x–z; e.g., Hrušecký et al. 2006). The main dextral strike-slip transform fault follows the southern boundary fault of the PKB, but is mostly sealed by the superimposed Oligocene sediments (Huty Fm and Údol succession in Fig. 4). It is proposed that this major wrench fault was active during the Late Eocene when it juxtaposed disconnected fragments of the CWC and PKB units with the Maruszyna–Lipník–Kričevo–Iňačovce units of a remnant oceanic domain related to then subducted South Pennine Piemont–Váh Ocean in the NW and to the Szolnok–Sava zone in the SE (see Discussion). Due to the presence of transitional elements towards the Magura belt, the northern boundary of the wrench corridor is not well defined. Most probably, it acted as a system of oblique-slip dextral-reverse faults and subsidiary thrusts within and in front of the innermost Magura element—the Krynica Unit. The regional importance of the late Middle–Upper Eocene compressional structures in the eastern Slovakian Flysch Belt, which are fading-out in the NE direction—the so-called “Illyrian” or “old Pyrenean” folding phase—was emphasized, e.g., by Książkiewicz and Leško (1959), Stráník (1965), Leško and Slávik (1969), or Nemčok (1971). This concept was based on observations of an angular unconformity between the Eocene and Oligocene flysch formations. All structures of the stage 5 were, however, modified or overprinted by additional shortening due to N–S-to-SW–NE compression.

6. The Oligocene epoch (35–25 Ma) is characterized by the general subsidence of the whole area with thick accumulations of deep-marine pelagic and clastic formations. In the CCPB in southern neighbourhood of the eastern PKB branch, these are represented by the Rupelian Huty Fm of dark shales and distal turbidites, which are SW of the ŠKZ overlain by typical flysch and then massive amalgamated sandstones of the Late Oligocene-to-earliest Miocene age. In the adjacent parts of the Krynica (inner Magura) Unit, similar sediments representing a new cycle were deposited in the Malcov piggyback basin. In between, the fold-thrust structures of the PKB were overstepped by the same deposits of the Údol succession (Ujak series in older literature, cf. Oszczypko et al. 2005) (Online Resource 1). Hence, the Oligocene sediments in this area were laid down in a broad and relatively deep basin in a forearc position above the inner (Magura) parts of the developing EWC accretionary wedge connected via the PKB with deposits of the CCPB.
7. During the seventh stage (25–15 Ma; Late Oligocene to early Middle Miocene), important additional contraction of the eastern PKB branch and adjoining zones occurred. Shortening in the N–S-to-NNE–SSW direction reactivated and strongly modified the pre-existing, particularly transpressional structures of the stage 5 and PKB boundary faults as steeply N- to NNE-dipping reverse faults. Backthrusting along the southern boundary fault affected also the neighbouring CCPB sediments by tight folds and numerous reverse and oblique faults (Mastella 1975; Plašienka et al. 2013; Ludwiniak 2018; Fig. 2x–z).

   The Šambron-Kamenica anticlinal zone (ŠKZ; Plašienka et al. 1998 and references therein) is a prominent map-scale structure of the seventh phase. Conglomerate-dominated Šambron Formation is outcropping in the anticlinal cores, while their limbs are formed by shales and distal turbidites of the uppermost Eocene—Lower Oligocene Huty Fm. Anticlines are open to tight, mildly asymmetric with steeper southern limbs (Fig. 2x, y). Their axes, as well as the bedding strikes are oriented in the WNW–ESE to W–E directions, being slightly oblique to the PKB trend (insets b and c in Fig. 4). Fold packages are arranged in three coulisse-like anticlinoria (Fig. 4), which indicates a minor dextral transpression. Structures of the ŠKZ are sealed by the Eggenburgian (early Burdigalian) sediments (cf. Soták et al. 2001; east of Sabinov in Fig. 4). The southern ŠKZ backthrust boundary seems to be connected with the southern marginal fault of the Vysoké Tatry (High Tatra) Mountains that controlled the main phase of their exhumation, cooling and surface uplift in this time period (e.g., Králiková et al. 2014; Anczkiewicz et al. 2015; Śmigielski et al. 2016).

Residual latest Oligocene—earliest Miocene (late Egerian, ca 25–22 Ma) depressions with accumulation of deep-water flysch deposits terminated evolution of the CCPB forearc basin. The depocentres are rimming the PKB from the north (Kremná Fm in the Pieniny Mts—Oszczypko et al. 2005; Oszczypko-Clowes et al. 2018), as well as from the south in the eastern part of the CCPB Podhale Basin (Środoń et al. 2006) and south of the ŠKZ (Soták et al. 2001). Supposedly, these depressions developed on the inner side of the EWC accretionary wedge in a retroarc position, i.e., in a broad basinal zone in front of S-verging backthrust of the wedge rear, which was subsequently segmented into synclinal depressions by large-scale folding. Hence, the youngest CCPB and piggyback Magura sediments are preserved just in these local synclinal zones, while they were predominantly removed by later erosion in other places.

The northern PKB boundary fault zone is not a straight line, but is composed of several asymmetric, arcuate segments with oblique-dextral NW–SE limbs passing into southward convex, N-dipping reverse faults and backthrusts (see also Jurewicz 2005, 2018; Plašienka 2012b). The most conspicuous structure of this type is the Čergov backthrust NE of Sabinov town (Figs. 2y, 4). At the same time, the Magura nappe was thrust out-of-sequence over the outer Moldavide (Dukla, Silesian-Krosno) units of the EWC (e.g., Nemčok et al. 2000, 2006; Gągała et al. 2012). This event coincides with initiation of the Pannonian back-arc extension, including the eastern Slovakian part of the Transcarpathian Basin, where fission track data on detrital zircons from the Iňačovce Unit provided ages around 20 Ma (Soták et al. 2005). According to Gągała et al. (2012), the accelerated shortening within the EWC accretionary wedge and back-arc extension in the Pannonian realm were both triggered by the onset of rapid subduction rollback of the oceanic lithosphere beneath the advancing EWC wedge.

8. The final shaping of the eastern PKB branch was achieved during the Middle to Late Miocene (15–10 Ma). The stage 8 is characterized by persisting compression in the SW–NE direction with alternating NW–SE extensional and SW–NE compressional events, which affected the Lower Miocene sediments preserved along the southern PKB boundary east of town Prešov. The easternmost PKB segment in Slovakia and Ukraine, east of the N–S trending Hornád fault system at the western side of the Transcarpathian Basin (Fig. 1), experienced an additional CCW rotation in order of 30° during the late Middle Miocene (Márton et al. 2000, 2007, 2015). This extra rotation was driven by the subduction rollback and sinistral translation of the clockwise-rotating Tisza-Dacia Megaunit along the Mid-Hungarian fault zone. As the result, the Transcarpathian Basin developed as a pull-apart depression with exhumation of the metamorphic core complex of the Iňačovce Unit at the basin bottom (Soták et al. 2005; Kováč et al. 1995, 2017; Fig. 2z). Late Middle Miocene CCW rotation was detected also in the Pieniny Mts in Poland, where the ca 11–13.5 Ma old andesite dykes also reveal a minor CCW rotation (Márton et al. 2004) postdating the general CCW rotation of the Western Carpathians. Perhaps, this local block rotation might have been caused by the drag along the SW–NE-trending sinistral strike-slip zones that generated opening of the pull-apart Orava Basin (Ludwiniak et al. 2019). Further east, a short-living (ca 14–11 Ma) but intense arc-type andesitic volcanism, preceded by felsic calc-alkaline volcanism, created a long volcanic chain stretching from the Slanské vrchy and the Vihorlat–Gutin Mts as far as northern Romania (e.g., Pécskay et al. 2006). It was generated by the ascent of partial mantle melts generated by subduction retreat followed by slab steepening and breakoff (Lexa and Konečný 1998; Konečný et al. 2002).

In general, the convergence between the foreland platform and the NE part of the Carpathian orogenic wedge ceased by the end of the eighth stage some 10 Ma ago (Kováč et al. 2017, and references therein). Thrusting processes have finished and the youngest tectonic evolution of the entire Western Carpathian area has been governed by the thermal, gravitational and geomorphological relaxations expressed by the moderate vertical movements, dominantly extensional stress field and weak seismic activity (e.g., Minár et al. 2011; Hók et al. 2016a, b; Králiková et al. 2014, 2016).

Discussion: the tectonic model

In general, the Late Cretaceous and Cenozoic tectonic processes in the Eastern Alps and Western Carpathians were governed by the convergence between the lower European plate and the upper Adriatic plate with the Austroalpine units (Alcapia in sense of Handy et al. 2010) extended along its leading edge. As subduction of the Pennine oceanic lithosphere terminated by the Late Eocene in the Alps (ca 35 Ma ago; e.g., Handy et al. 2010, 2015), the ongoing Europe–Adria convergence was accommodated by crustal stacking and lithospheric thickening that has led to the orogen-parallel extension and lateral extrusion of the AlCaPa crustal wedge (Alps–Carpathians–Pannonian domain east of the Penninic Tauern window) from the Alpine collision eastwards (e.g., Ratschbacher et al. 1991; Decker and Peresson 1996; Fodor et al. 1998). The extrusion was enhanced by the retreat of oceanic subduction of the so-called Carpathian embayment that had occupied the area of the present Carpathian arc beyond the confining bottle-neck bounds of the Bohemian spur and the Moesia platform. Hence, while the N–S collisional convergence is protracting until the recent times in the Alps, development of the Carpathian arc was governed by the Oligocene–Miocene subduction and ensuing back-arc extension, basin formation and voluminous calc-alkaline volcanism (e.g., Ustaszewski et al. 2008; Handy et al. 2015; Kováč et al. 2016, 2017 and references therein).

These boundary conditions controlled also tectonic evolution of the CWC–EWC transitional zones stretching along the PKB. East–west spatial and temporal correlation of deformation stages and their leading structures discerned above indicate that fundamental changes in the structural evolution between the western and eastern PKB branches occurred during the late Middle to Late Eocene stage 5 (Fig. 5), i.e., contemporaneously with onset of collisional processes in the Alpine regions. Thus, the 40–35 Ma time period appears to be the main turning point in evolution of by then united Alpine-Carpathian orogenic system (Handy et al. 2015 and references therein). In the Western Carpathians, this fundamental turnover can be documented by the tectonic evolution of the PKB and contiguous zones along the backstop boundary between the CWC rigid buttress and the EWC accretionary wedge.

A map-view restoration of the Late Cretaceous-to-Miocene development of the CWC vs. EWC-transitional zones is schematically depicted in Fig. 6. The crustal-scale tectonic processes, differing in the western and eastern PKB branches, are then tentatively reconstructed in Fig. 7. Figures 6a and 7a illustrate the Late Cretaceous situation at around 80 Ma ago (beginning of the second stage) when the CWC nappe structure was completed and subduction of the South Pennine Piemont-Váh oceanic lithosphere was established. The N-directed Adria push generated the SSW–NNE compression along the outer, WNW–ESE-trending Lower Austroalpine–Tatric margin of the Alcapia terrane. The Europe vs. Adria convergence triggered subduction of the Piemont–Váh oceanic lithosphere and development of the incipient accretionary wedges of the Matrei–Belice and the Peri-Klippen Manín–Klape–Drietoma units (MB and MKD in Fig. 6a, respectively). The

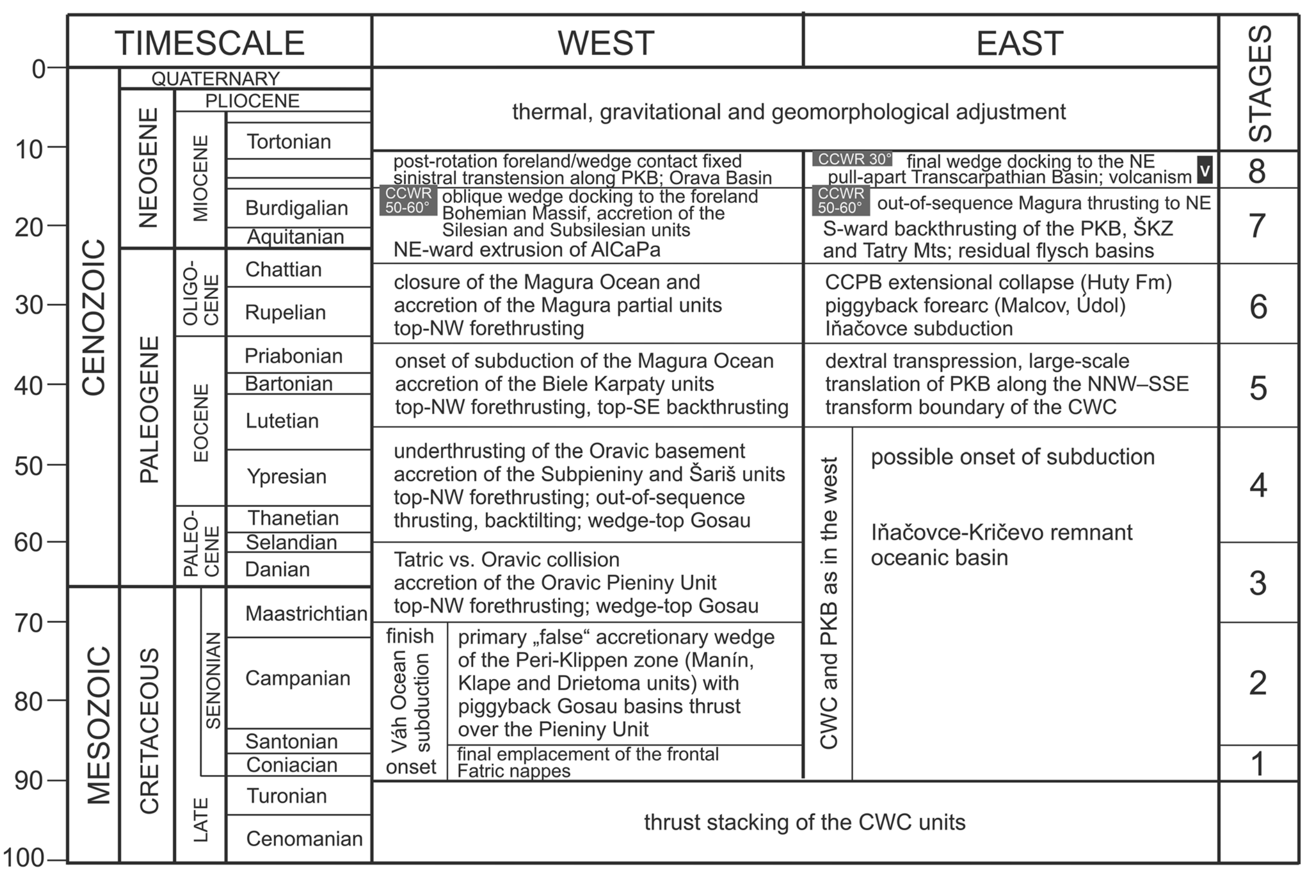
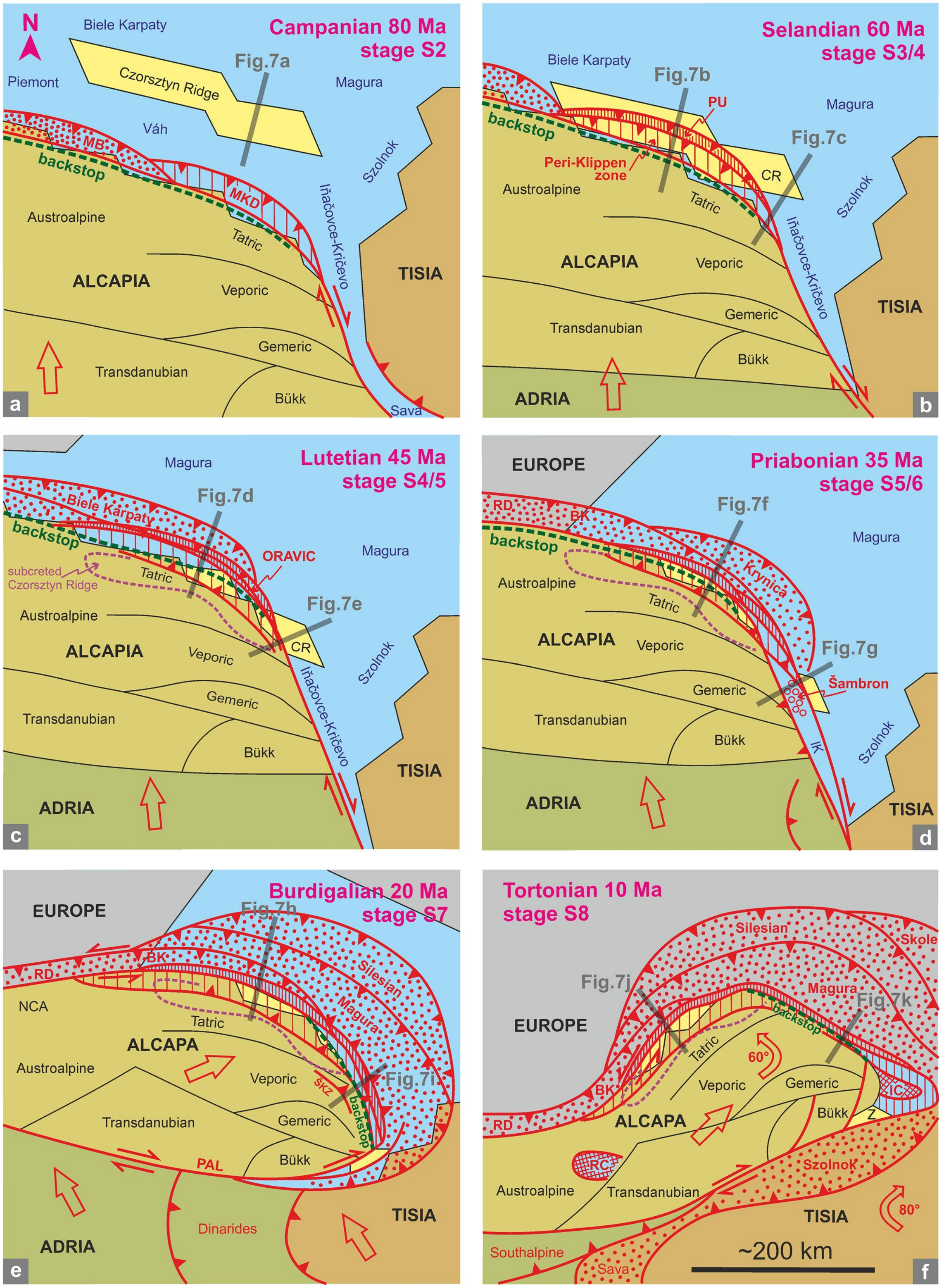


Fig. 5 Summary and west–east correlation of evolutionary tectonic stages discerned in the PKB and contiguous zones. *CCWR* counter-clockwise rotation, *V* calc-alkaline volcanism


Campanian 80 Ma
stage S2
N
Biele Karpaty
Piemont
Czorsztyn Ridge
Fig.7a
Magura
Váh
MB
backstop
MKD
Szolnok
Iňačovce-Kričevo
Austroalpine
Tatric
ALCAPIA
Veporic
TISIA
Gemeric
Transdanubian
Bükk
Sava
a
Selandian 60 Ma
stage S3/4
Biele Karpaty
Fig.7b
PU
Magura
backstop
Fig.7c
Peri-Klippen
zone
CR
Austroalpine
Tatric
Szolnok
ALCAPIA
Veporic
Iňačovce-Kričevo
Gemeric
TISIA
Transdanubian
Bükk
ADRIA
b
Lutetian 45 Ma
stage S4/5
Magura
Biele Karpaty
Fig.7d
backstop
ORAVIC
Magura
subcreted
Czorsztyn Ridge
Tatric
Fig.7e
Austroalpine
ALCAPIA
Veporic
CR
Szolnok
Gemeric
Iňačovce-Kričevo
Transdanubian
Bükk
TISIA
ADRIA
c
EUROPE
Priabonian 35 Ma
stage S5/6
RD
BK
Fig.7f
backstop
Magura
Krynica
Austroalpine
Tatric
ALCAPIA
Veporic
Fig.7g
Šambron
Gemeric
Transdanubian
Bükk
IK
Szolnok
ADRIA
TISIA
d
EUROPE
Burdigalian 20 Ma
stage S7
Fig.7h
BK
RD
Silesian
NCA
Magura
Tatric
ALCAPA
Austroalpine
Veporic
ŠKZ
Fig.7i
backstop
Transdanubian
Gemeric
PAL
Bükk
TISIA
Dinarides
ADRIA
e
Tortonian 10 Ma
stage S8
Silesian
Skole
Fig.7j
Magura
Fig.7k
EUROPE
backstop
Tatric
60°
Veporic
Gemeric
BK
IC
Bükk
RD
ALCAPA
Z
RC
Szolnok
Austroalpine
Transdanubian
TISIA
80°
~200 km
Southalpine
Sava
f

◂**Fig. 6** Evolutionary tectonic model of the PKB and adjacent zones in the context of large-scale movements and deformation of principal continental blocks in the Alpine–Carpathian regions. Oceanic domains are shown in blue, continental with yellowish–brownish or grey. For details see the text. Note that the scale and dimensions of units are approximate only. *MB* Matrei–Belice wedge, *MKD* Manín–Klape–Drietoma belt, *PU* Pieniny Unit, *CR* Czorsztyn Ridge (Oravic), *RD* Rhenodanubian, *BK* Biele Karpaty units, *IK* Iňačovce–Kričevo remnant basin, *NCA* Northern Calcareous Alps, *ŠKZ* Šambron–Kamenica fold-thrust zone, *PAL* Periadriatic lineament, *RC* Rechnitz core complex (window), *IC* Iňačovce core complex, *Z* Zemplín block

northern Alcapia margin represented the backstop boundary of the accretionary complex, while its eastern margin served as a right-lateral transfer fault zone facing the Iňačovce–Kričevo oceanic basin connected SE-ward with the then-subducted Sava Ocean. This oceanic zone developed during the Late Jurassic rifting when Adria–Alcapia and Tisia terranes were disconnected (Haas and Péró 2004; Handy et al. 2010; Császár et al. 2013).

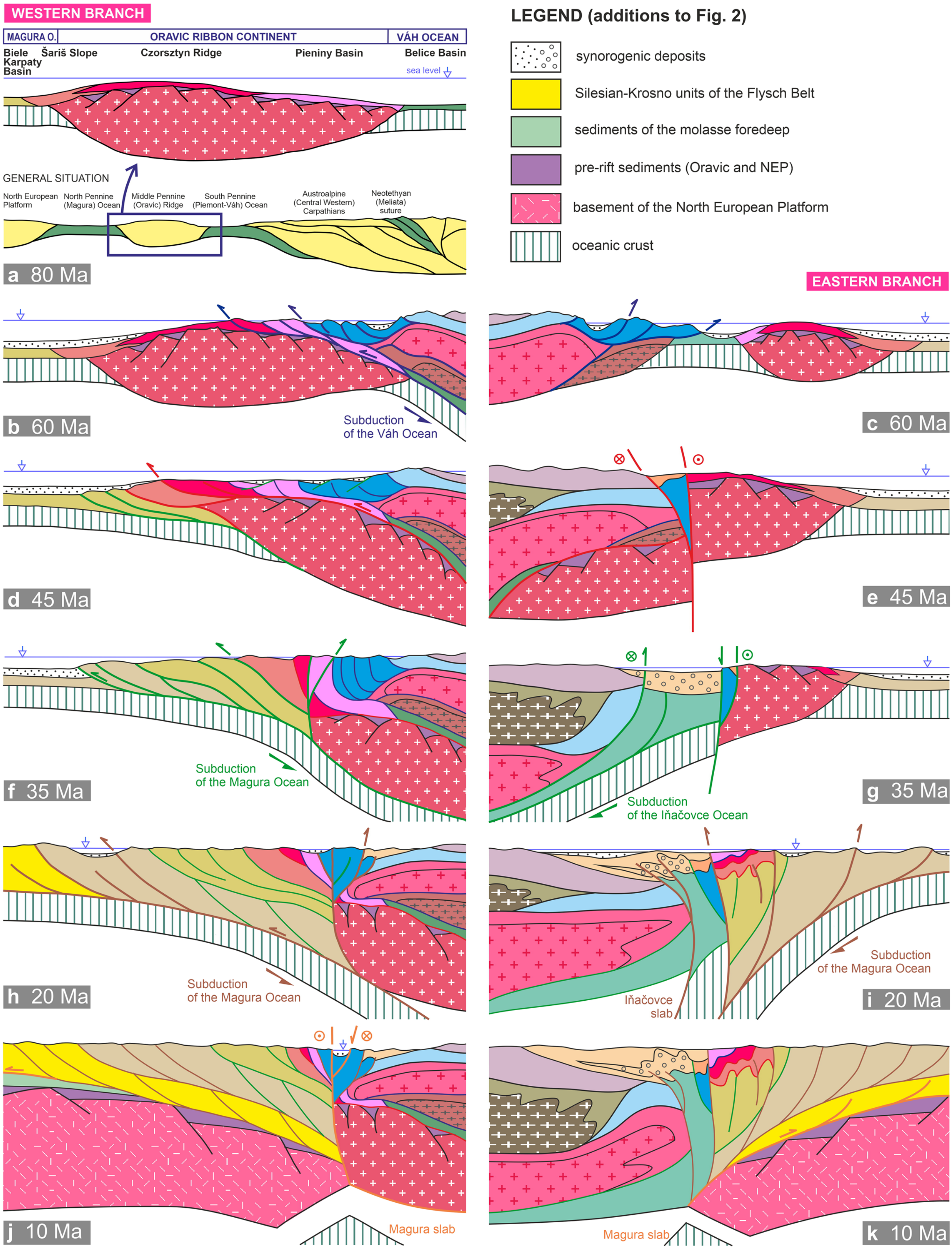
The early Paleogene state (at ca 60 Ma, transition from the stage 3–4) is depicted in Figs. 6b and 7b, c. After the earliest Paleocene collision of the Oravic continental ribbon (Czorsztyn Ridge) with the CWC orogenic wedge front (Fig. 7b), the Peri-Klippen Manín and Klape–Drietoma units overrode the Oravic Kysuca–Pieniny margin, which (Pieniny Unit) in turn overrode the ridge with the Czorsztyn-type successions (future Subpieniny Unit). However, the easternmost part of the Oravic Czorsztyn Ridge escaped this collisional event and remained surrounded by the Magura and Iňačovce–Kričevo oceanic domains (Figs. 6b, 7c).

The Eocene convergence (snapshot Middle Eocene at ca 45 Ma, turn from the stage 4 to stage 5; Figs. 6c, 7d, e), still triggered by the N-directed Adria push, caused underthrusting of the Oravic basement below the front of the CWC buttress and became its integral constituent. Rest of the Oravic units (Subpieniny and Šariš), and subsequently, also the Biele Karpaty units were accreted to the propagating wedge tip and subduction of the Magura Ocean commenced (Fig. 7d). Tentatively, the easternmost portion of the Czorsztyn Ridge was truncated and detached by the dextral strike-slip zone along the eastern Alcapia margin and began to be transferred southwards relative to the northward moving CWC part of Alcapia (Fig. 7e).

During the Late Eocene (snapshot 35 Ma, transition from the 5–6 stage; Figs. 6d, 7f, g), the Pennine oceanic branches were closed in the Alpine realm. As the result, the southern European margin began to collide with the Alcapia assembly supported by the Adriatic microcontinent from the south, whereby the Rhenodanubian Flysch Belt (RD) was thrust over the European margin (Bohemian Massif). The southernmost Magura element (Krynica Unit) was attached to the EWC accretionary wedge front, while backthrusting affected the Peri-Klippen zone beyond the backstop edge of the CWC basement units with the subcreted Czorsztyn Ridge basement (Fig. 2b–e).

In the east, the main phase of dextral wrenching occurred during the fifth phase (Figs. 6d, 7g). The broad wrench corridor was split into at least two main branches—the inherited western one that immediately followed the eastern CWC boundary changed for an oblique east-vergent thrust, whereby the adjacent parts of the Iňačovce oceanic domain were in part subducted below the CWC margin and subsequently suffered a pressure-dominated low-grade metamorphism (Fig. 7g). The eastern strike-slip branch struck into the adjacent oceanic domain and provided a passage for large-scale southward displacement of the PKB units to form its eastern branch. Stretching of the present-day eastern PKB branch for some 300 km resulted from cumulative effect of sequential detachment of Oravic units during oblique CWC vs. PKB collision and transpressional horizontal lengthening revealed by structural studies (Ratschbacher et al. 1993; Plašienka 2012b). If correct, this interpretation would also imply that the Magura and Iňačovce–Kričevo domains formed a common oceanic zone in pre-Late Eocene times, which was then truncated and separated by the right-lateral transfer fault zone bringing the PKB and attached Peri-Klippen units in between (see also Ustaszewski et al. 2008; Kováč et al. 2016).

The key role in this interpretation is attributed to the more than a thousand metres thick masses of flysch conglomerates and chaotic boulder beds of the Upper Eocene Šambron Formation cropping out in the Šambron–Kamenica anticlinal zone (ŠKZ; Figs. 4, 6d, 7g). Supplied from the north-eastern areas, the conglomerates contain material from the currently hidden sources, including the high-grade crystalline basement rocks and various Mesozoic, mainly Triassic carbonates likely of the Hronic provenance (Marschalko 1975; Marschalko et al. 1976), and Urgonian-type limestones derived most probably from the Manín (Haligovce) Unit. Accordingly, the area occupied by the PKB units now was composed of the Fatric and Hronic units of the Peri-Klippen zone and some external basement block, possibly disconnected fragment of the Oravic Czorsztyn Ridge. This situation occurred transiently during the Late Eocene to earliest Oligocene when these units were transferred along the margin of a deep wrench furrow that accumulated thick conglomerate bodies. Nowadays, these former sources seem to be destroyed completely, but a part of them might be, hypothetically, still present below the Neogene sediments of the Transcarpathian Basin and volcanics of the Vihorlat–Gutin zone further to the ESE. Thus, the Šambron conglomerates might have been deposited in a restricted wrench-fault furrow fed by unsorted mass flows derived from the Peri-Klippen Fatric and Hronic units that were passing by along the dextral wrench corridor. Supposedly, clasts of the crystalline rocks came


WESTERN BRANCH
MAGURA O.
ORAVIC RIBBON CONTINENT
VÁH OCEAN
Biele Karpaty Basin
Šariš Slope
Czorsztyn Ridge
Pieniny Basin
Belice Basin
sea level
GENERAL SITUATION
North European Platform
North Pennine (Magura) Ocean
Middle Pennine (Oravic) Ridge
South Pennine (Piemont-Váh) Ocean
Austroalpine (Central Western) Carpathians
Neotethyan (Meliata) suture
a 80 Ma
LEGEND (additions to Fig. 2)
synorogenic deposits
Silesian-Krosno units of the Flysch Belt
sediments of the molasse foredeep
pre-rift sediments (Oravic and NEP)
basement of the North European Platform
oceanic crust
EASTERN BRANCH
b 60 Ma
Subduction of the Váh Ocean
c 60 Ma
d 45 Ma
e 45 Ma
f 35 Ma
Subduction of the Magura Ocean
g 35 Ma
Subduction of the Iňačovce Ocean
h 20 Ma
Subduction of the Magura Ocean
Iňačovce slab
Subduction of the Magura Ocean
i 20 Ma
j 10 Ma
Magura slab
Magura slab
k 10 Ma

◂**Fig. 7** Conceptual cross sections outlining the structural development of the PKB and adjoining zones. For locations of cross sections, see Fig. 6, and for the legend, see Fig. 2. The left column concerns the western PKB branch, while the right column shows evolution of the eastern branch

from a basement block detached from the eastern part of the Oravic Czorsztyn Ridge (Figs. 6c, d, 7g). We hypothesize that the Zemplín basement/cover block might have been also a component of these lost source areas (Fig. 6e, f).

During the Early Miocene (stage 7, snapshot 20 Ma in Fig. 6e and cross sections 7h, i), the Adria vs. Europe convergence continued, but was partly blocked in the Alpine region by head-on collision. However, the eastern part of the convergence system remained unconstrained, since the remnant Magura oceanic domain (Carpathian embayment) was still open. This situation resulted in an eastward extrusion of the AlCaPa tectonic system from the Alpine collision, enhanced by the subduction retreat of the remaining oceanic lithosphere, which was also coeval with lithospheric extension in the Pannonian domain (Kováč et al. 2017; Gągała et al. 2012 and references therein). Hence, the movement direction of the prograding orogenic wedge changed from N–NW directed (in present coordinates) to NE-oriented. The outer units of the EWC Flysch Belt (Foremagura, Dukla, Silesian, Subsilesian, Skole) were step-by-step accreted to the wedge toe and subsequently overridden out-of-sequence by the Magura thrust sheet (e.g., Nemčok et al. 2000, 2006).

Separation of AlCaPa from the stable part of Adria along the Periadriatic lineament (PAL) and its eastward movement brought about re-arrangement of the stress field and shortening direction in the escaping block. This resulted in shifting of the main compression axis to the SW–NE direction in the eastern PKB segment, while the western segment was affected by left-lateral shearing (Nemčok and Nemčok 1994; Decker and Peresson 1996; Šimonová and Plašienka 2017). Thus, the frontal backstop edge of the western segment changed for a sinistral wrench boundary, and vice versa the eastern segment changed from the dextral wrench corridor to the frontal backstop of the eastern part of the EWC accretionary wedge (Fig. 6e).

The terminal post-docking and post-rotation situation (end of the stage 8 at ca 10 Ma; Fig. 5) is sketched in Figs. 6f and 7j, k. It followed the main phase of the Pannonian and Transcarpathian basins extension and extensive calc-alkaline volcanism in the intra-Carpathian area. The extension was accompanied by exhumation of the Rechnitz and Iňačovce core complexes (RC and IC in Fig. 6f, respectively). The misplaced inlier of the Zemplín block (Z) is tentatively interpreted as the only surface leftover of the continental fragment (Oravic Czorsztyn Ridge) that otherwise disappeared by underthrusting below the outer CWC margin.

Conclusions

Based on interpretation of wealth of structural and sedimentary rock record data, an evolutionary palaeotectonic model of the Pieniny Klippen Belt and adjoining zones is outlined. It shows that PKB began to evolve as a fold-and-thrust system of sedimentary units detached from a continental ribbon in the Middle Penninic position. Subsequently, the PKB nappe structure was strongly modified by out-of-sequence forethrusting, backthrusting and backfolding, as well as by the along-strike wrench movements. In general, eight stages of tectonic evolution, which substantially differ from the stage 5 onward in the western and eastern PKB branches, are distinguished and characterized:

- The first stage (90–85 Ma) represented the final emplacement of the Central Carpathian Fatric and Hronic nappes, the Fatric being represented by the Manín, Klape and Drietoma units presently forming the Peri-Klippen zone. In the meantime, subduction of the South Pennine Piemont–Váh Ocean started.
- During ongoing subduction (stage 2, 85–70 Ma), the frontal Fatric units occupied a position of the accretionary complex with development of piggyback Gosau-type basins in a wedge-top position.
- After subduction had finished, the Central Carpathian upper plate came into collision with the Oravic continental ribbon in the lower plate position (stage 3, 70–60 Ma). The stack of the Peri-Klippen units was thrust over the southern Oravic margin, from where the highest Oravic Pieniny Unit was detached, accreted to the wedge toe and thrust over the main Oravic area composed of the relatively shallow-water Czorsztyn-type successions.
- During underthrusting of the Oravic continental basement block below the outer Central Carpathian Tatric margin, its sedimentary cover (Jurassic to early Paleogene) was detached to form the Subpieniny and Šariš nappes that became accreted to the orogenic wedge tip (stage 4, 60–45 Ma). Oravic basement was attached to the backstop, while rear part of the accretionary wedge was affected by out-of-sequence thrusting and steepening of structures due to backtilting that influenced also sedimentation in the contemporary Gosau basins in the Peri-Klippen zone.
- Starting from the fifth stage (45–35 Ma), the western and the eastern branch of the PKB behaved differently. Related to the onset of Magura Ocean subduction, the

NW–SE shortening and accretion of the Biele Karpaty units of the Flysch Belt continued in the western branch. In contrast, the eastern branch started to develop by translation of the Oravic and Peri-Klippen units along the right-lateral wrench corridor that followed the eastern transform boundary of the Western Carpathian part of the Alcapia–Adria.

- The next stage 6 (35–25 Ma) is characterized by top-NW, step-by-step accretion of the Magura and Silesian units to the accretionary wedge toe in the western branch. Collision of the Alcapia–Adria with European margin started in the Alps, whereby the eastward extrusion of the AlCaPa wedge towards the unconstrained area of the Carpathian embayment (Magura and related oceanic realm) was initiated, enhanced by its retreating subduction. Related to this subduction retreat, the eastern area experienced Oligocene extensional collapse and subsidence of the Central Carpathian Paleogene Basin that sealed the PKB structures.
- Far-reaching rearrangement of megablocks AlCaPa and Tisia in the Carpathian area occurred in the Early Miocene (stage 7, 25–15 Ma). The eastern AlCaPa margin with affixed eastern PKB branch was affected by backthrusting in the rear of the accretionary wedge of the eastern part of the Flysch Belt, which grew by accretion of the Silesian and related units. By this time, the eastern branch changed from the right-lateral wrench boundary to convergence zone, while the western branch was affected by sinistral strike-slipping. At the end of this stage, oblique fastening of the western margin of AlCaPa to the European foreland plate was followed by the large-scale counter-clockwise rotation of the entire Carpathian part of AlCaPa.
- During the final stage 8 (15–10 Ma), gentle tying of the eastern part of the accretionary wedge with the European foreland occurred, being accompanied by the sinistral transtension in the western branch. As the convergence ceased, all large-scale horizontal tectonic movements and associated deformation in the Western Carpathian area vanished as well.

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