

EVOLUTION OF LATE CRETACEOUS–PALAEOGENE SYNOROGENIC BASINS IN THE PIENINY KLIPPEN BELT AND ADJACENT ZONES (WESTERN CARPATHIANS, SLOVAKIA): TECTONIC CONTROLS OVER A GROWING OROGENIC WEDGE

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Abstract: The Pieniny Klippen Belt and neighbouring zones of the Western Carpathians represent an ancient accretionary wedge that developed during the meso-Alpidic (Coniacian–Eocene) tectonic epoch. After an overview of the extensive literature data, the authors present an interpretation of the synorogenic sedimentary record of these zones as being related to various environments of the foreland basin system consisting of the trench-foredeep and wedge-top depositional areas. The peripheral trench-foredeep depozones migrated from the South Penninic–Vahic oceanic realm towards the Oravic continental fragment in an intra-Penninic position, where the synorogenic deposits were laid down with coarsening- and thickening-upward trends before being overthrust by the propagating orogenic wedge tip. The development of wedge-top, piggyback basins (Gosau Supergroup) was controlled by the dynamics of the underlying wedge, composed of frontal elements of the Fatic and Hronic cover nappe systems of the Central Western Carpathians (Austroalpine units). Several compressional and extensional events are documented in the complex sedimentary and structural rock records within the wedge and related basins. The successive transgressive-regressive depositional cycles and corresponding deformation stages are interpreted in terms of a dynamic accretionary wedge that maintained the critical taper only transiently. The supercritical taper states are reflected in regression, shallowing and erosion in the wedge-top area, while the trench was supplied with large amounts of clastics by various gravity-flow types. On the other hand, the collapse stages tending to subcritical wedge taper are indicated by widespread marine transgressions or ingressions in the wedge-top area and a general deepening of all basins to bathyal conditions. Accordingly, the evolution of the entire trench-foredeep and wedge-top basin systems was principally controlled by the complex interplay of the regional tectonic evolution of the Alpine-Carpathian orogenic system, local wedge dynamics and eustatic sea-level fluctuations.

Key words: Western Carpathians, Oravic units, Gosau Supergroup, synorogenic sediments, palaeotectonic interpretation, geodynamic evolution.

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INTRODUCTION

The Western Carpathians evolved as a complex collisional orogenic system, related to two suture-like zones that experienced a long-term polystage structural history and extensive shortening, resulting in the superposition and juxtaposition of units derived from sometimes distant palaeogeographical settings (e.g., Plašienka *et al.*, 1997; Putiš *et al.*, 2009). Remnants of ophiolite-bearing mélanges and high-pressure units (Meliata-Bôrka nappes) that are thought to represent Upper Jurassic (Neo-Cimmerian) subduction complexes related to the closure of the Neotethyan oceanic branch occur in the southern Western Carpathian zones. South of these occurrences, units with a South Alpine-Dinaridic affinity, currently affiliated with the Internal West-

ern Carpathians (e.g., Froitzheim *et al.*, 2008) appear. Northwards, the Central Western Carpathians are composed of a Palaeo-Alpidic (Cretaceous) nappe stack of thick- and thin-skinned thrust sheets that represent an eastward continuation of the Austroalpine units of the Eastern Alps (e.g., Schmid *et al.*, 2008).

The Central and External Western Carpathians are separated by a narrow, structurally complex zone associated with the Pieniny Klippen Belt. North of it, the External Carpathians (Flysch Belt) represent the “Tertiary” (Eocene to Lower Miocene) accretionary complex, composed of numerous thrust sheets of Cretaceous to Miocene sedimentary complexes, scraped off their original, mostly oceanic base-

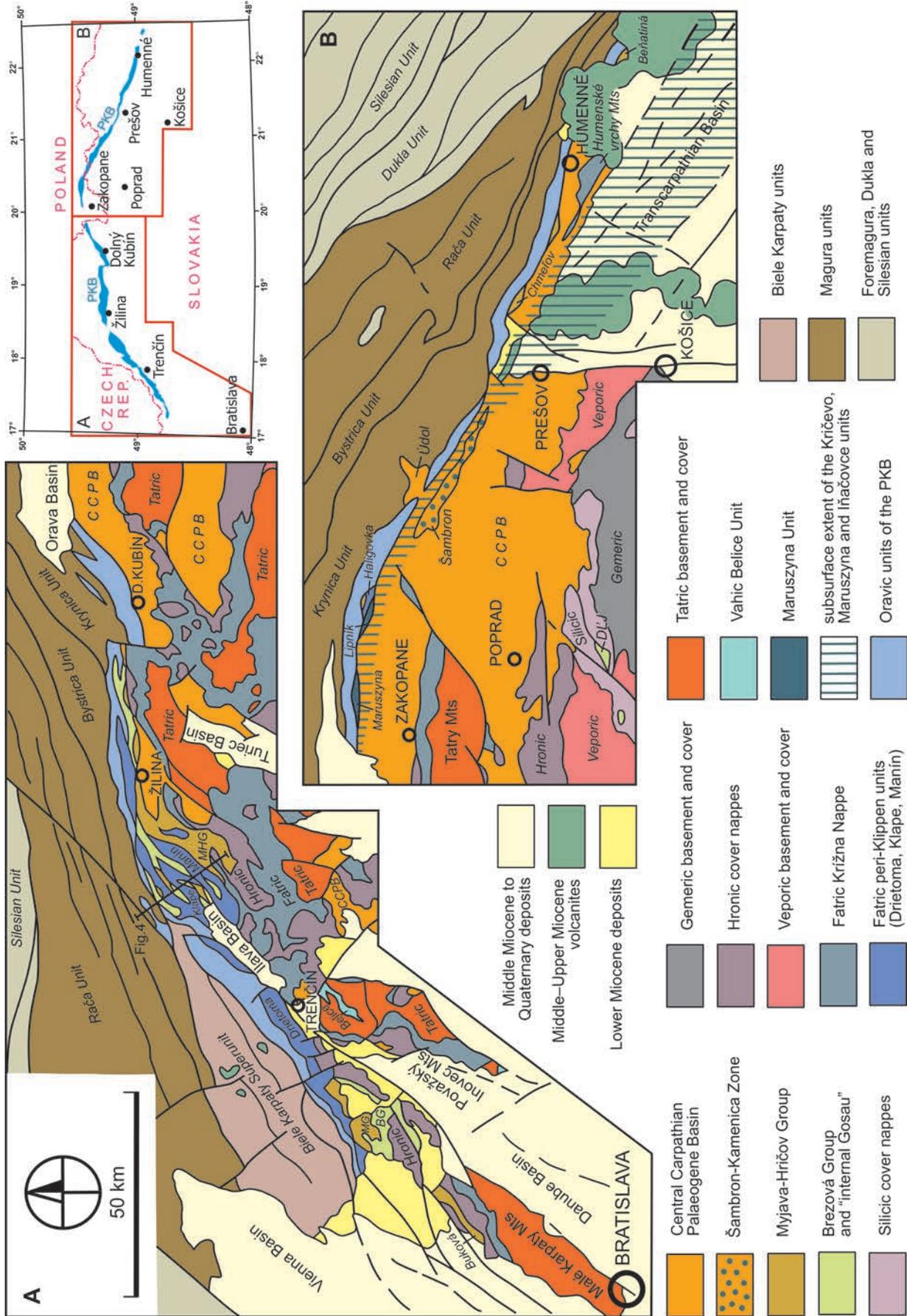


Fig. 1. Tectonic sketch map of zones along the Pieniny Klippen Belt. **A.** Western segment. **B.** Eastern segment. Inset shows their position in the Western Carpathians. Abbreviations: PKB – Pieniny Klippen Belt; BG – Brezová Group; MG – Myjava Group; MHG – Myjava-Hričov Group; DLJ – Dobšinská Ladová Jaskyňa; CCPB – Central Carpathian Palaeogene Basin.

ment under-ridden below the Central Carpathian thrust stack (e.g., Oszczytko, 2006).

The formation of the Klippen Belt was accompanied by a variety of complex tectonic processes, which commenced with the Late Cretaceous subduction of the Ligurian-Vahic oceanic domain. Subsequently to its closure, collision of the Central Carpathian orogenic wedge with the Oravic ribbon continent, from which the typical Klippen Belt sedimentary nappes were detached and stacked, took place during the Early Palaeogene. This Meso-Alpidic epoch (Coniacian–Lutetian), lasting about 50 Ma, was decisive for the shaping of not only the Klippen and Flysch belts, but also the ultimate tectonic edifice of the entire Western Carpathians and their current position in the European Alpidic mountain system. Finally, during the Late Palaeogene and Early Miocene, the Klippen Belt and related zones were additionally narrowed and transpressionally lengthened up to their present complex form, while the Central Western Carpathians experienced extension and the formation of new sedimentary basins in a fore-arc position.

In this paper, the authors mainly consider the “Senonian” (i.e., Upper Cretaceous from the Coniacian onward) and “Lower Palaeogene” (i.e., Paleocene to Middle Eocene) synorogenic sedimentary complexes of the Pieniny Klippen belt and neighbouring units. The aim is to give an overview of the present geological knowledge about these zones and to formulate an updated evolutionary tectonic model for the Meso-Alpidic epoch. In particular, the authors show that sediments of this age, presently juxtaposed in mutually complex structural relationships, were originally different parts of the evolving syntectonic basin system. The Oravic and Vahic units were located in a lower-plate position and their synorogenic sediments, typically with coarsening- and thickening-upward trends and with terrigenous clastic material derived predominantly from the overriding thrust sheets, were deposited in the peripheral trench-foredeep type furrows. On the other hand, the coeval wedge-top piggyback basins, developed on top of the accretionary wedge of the upper plate tip, are represented by Gosau-type basins and exhibit strong influences imposed by the structural development of the underlying wedge.

GEOLOGICAL SETTING

The Pieniny Klippen Belt (PKB¹) is a structural zone, only several km wide, but up to 600 km long, shaped mainly by Paleocene to Eocene thrusting and by superimposed Late Eocene–Early Miocene wrench tectonics (Fig. 1). It separates the Cenozoic accretionary complex of the External Western Carpathians (EWC – Flysch Belt) from the Cretaceous basement/cover thrust stack of the Central Western Carpathians (CWC – Austroalpine units). The PKB includes only Jurassic to Palaeogene sediments detached from an unknown, completely subducted substratum. The PKB sedimentary successions exhibit very variable lithology and complex internal structure. During long-term detailed research, numerous lithostratigraphic and tectonic units repre-

sented different and partially unrelated palaeogeographic settings were distinguished. Juxtaposition of rock complexes of originally distant provenances, extreme shortening and lateral dispersion within a very narrow zone invokes to consider the PKB as a suture, even though the ophiolite complexes do not contribute to its present surface structure. In general, the PKB is often characterized as a block-in-matrix structure, or megabreccia formed by isolated blocks of “klippen” composed of competent Middle Jurassic to Lower Cretaceous limestones surrounded in a soft matrix of the “klippen mantle”, consisting of Lower Jurassic and Upper Cretaceous to Palaeogene shales, marls and flysch formations. However, the original fold-and-thrust structure with three superimposed nappe units (see below) are still readily recognized locally, e.g. in the Pieniny Mts. (Birkenmajer, 1986; Plašienka and Mikuš, 2010). The most comprehensive overviews of the PKB geology of their times were compiled by Uhlig (1890, 1904, 1907), Andrusov (1938, 1968, 1974), Scheibner (1967), Książkiewicz (1977), Birkenmajer (1977, 1986) and Mišík (1997); recently by Plašienka in Froitzheim *et al.* (2008), Schlögl *et al.* (2008) and Plašienka (2010, 2012a).

At present, two types of pre-Upper Eocene unit are distinguished within the PKB in a broader sense (PKB *s.l.*). The narrow, complex and in places discontinuous northern strip is composed of the PKB units in its strict sense (PKB *s.s.* – Fig. 1). These were derived from an independent palaeogeographic domain, known as the Pienidic or Pieninic units in the older literature, but renamed as the Oravic domain (Oravicum) by Mahel’ (1986). The Oravic domain represents an intra-oceanic (“intra-Penninic”), rifted continental crustal fragment, separated by two branches of the Alpine Atlantic Ocean from the North European Platform to the north and the Austroalpine-Central Carpathian realm to the south. In the south, it was bounded by the Middle Jurassic–Cretaceous, South Penninic oceanic domain (Ligurian-Piemont-Vahic-Iňačovce, see below), and from the north by the Jurassic? – Cretaceous – Palaeogene, North Penninic oceanic zone (Valais-Rhenodanubian-Magura) – see e.g., Schmid *et al.* (2008, p. 12–13). The Oravic successions were deposited in various marine environments on and in the vicinity of an intra-oceanic continental fragment, known as the Czersztyn Ridge. In mid-Cretaceous time, the Oravic domain was partly overridden from the south by the frontal elements of the CWC cover nappes, particularly of supposed Fatric affiliation (Drietoma, Manín, Klape units in the western and the Haligovce Unit in the eastern PKB part; cf. discussion in Plašienka, 1995a, 2012a). The Fatric Superunit is a large-scale cover nappe system, chiefly represented by the Križna Nappe in the CWC. This was detached from a wide basinal area, which was created by Early Jurassic rifting between the current Tatric and Veporic thick-skinned thrust sheets (cf. Prokešová *et al.*, 2012 and references therein). Presently, the frontal Fatric units are adjacent to the PKB *s.s.* and largely share its structure and deformation history. Informally, they are also named the “non-Oravic PKB units” to stress their pre-emplacement differences in composition and evolution, compared to the “true” Oravic,

1 For abbreviation explanations see Appendix

TIMESCALE	MAGURA SUPERUNIT	BIELE KARPATY SUPERUNIT	ORAVICUM			VAHICUM	SAVA-SZOLNOK BELT					
	KRYNICA UNIT	JAVORINA UNIT	ŠARIŠ UNIT	SUBPIENINY U.	PIENINY UNIT	BELICE UNIT	ŠAMBRON UNIT	KRIČEVO UNIT	IŇAČOVCE U.			
MIOCENE	Burdigalian	Lužice Formation	Čausa Formation				Prešov Fm	Burkalo Fm	gap			
	Aquitanian		Kremná Fm									
OLIGOCENE	Chatthian	Magura Formation	ÚDOL SUCCESION				Huty Formation	Lazovo Formation	gap			
	Rupelian		Malcov Formation									
EOCENE	Priabonian	Beloveža Formation	Kuželov Fm	variegated shales	gap	Šambron Fm	Dulovo Fm	Nacina Ves Fm				
	Bartonian								MARUSZYNA SUCCESION			
PALEOCENE	Lutetian	Szczawnica Formation	Svodnice Formation	Proč Formation	gap	variegated shales	Bajlovo Formation	Lesné Formation				
	Ypresian								Nivnice Formation	?		
LATE CRETACEOUS	Thanetian	Haluszowa Fm	Javorina Fm	Jarmuta Fm	Jarmuta Fm	variegated marls	Horné Belice Formation	Iňačovce Formation				
	Selandian								Szczawica Formation	Romano Formation		
LATE CRETACEOUS	Danian	Malinowa Formation	Kaumberg Formation	Malinowa Formation	Jaworki Formation	Sromowce Fm	Kričevo Formation	Iňačovce Formation				
	Maastrichtian								Jarmuta Fm	marly limestone		
	Campanian								variegated shales			
	Santonian								variegated shales			
LATE CRETACEOUS	Coniacian	Malinowa Formation	Kaumberg Formation	Malinowa Formation	Jaworki Formation	Snežnica Fm	Kričevo Formation	Iňačovce Formation				
	Turonian								Lazy Fm	variegated shales		

Fig. 2. Integrated Upper Cretaceous to Lower Miocene lithostratigraphy of the trench-foredeep basins of the Western Carpathian Penninic units and overstepping formations.

i.e., PKB *s.s.* units. The zone in the Middle Váh Valley in western Slovakia, where the “non-Oravic” units predominate, was distinguished as the “peri-Klippen zone” by Maheľ (1980). Both the proper (Oravic) PKB *s.s.* and the peri-Klippen zone constitute the PKB *s.l.* (or Považie-Pieniny Belt; Plašienka in Froitzheim *et al.*, 2008), which is up to 20 km wide in the Middle Váh Valley (Figs 1A, 4).

During the latest Cretaceous to Early–Middle Eocene stacking period of the Oravic units, only the Jurassic and younger formations were detached from their substratum that was underthrust below the outer edge of the mid-Cretaceous stack of the CWC basement and cover nappes. The decoupled successions were then sequentially thrust outwards in a piggy-back manner and created the original Lower Palaeogene fold-and-thrust belt that was later thrust over the rear parts of the developing EWC accretionary wedge (Biele Karpaty and Magura units). In this backstop position, the PKB *s.l.* experienced further strong deformation, including out-of-sequence thrusting, transpression-transension, backthrusting and complex block rotations. As a result, the locally very complicated, tectonically induced block-in-matrix structure originated, which in places largely obliterated the original fold-thrust structures.

Within the PKB *s.l.*, the Upper Cretaceous (“Senonian”) and Palaeogene sediments occur in three considerably differing developments and tectonic positions: 1) Coniacian to Lower–Middle Eocene hemipelagites and syn-orogenic clastics in the Oravic units of the PKB *s.s.* (Púchov-Jarmuta Group in the sense of Mello, 2011) that compose continuous sedimentary successions with underlying Jurassic through Cretaceous strata; 2) Coniacian to Middle

Eocene sediments, which create a post-nappe cover, superimposed on the frontal elements of the Central Carpathian thin-skinned thrust sheets (Fatric and Hronic nappe systems) and are included in the Gosau Supergroup; 3) Bartonian to Oligocene strata ranging up to Lower Miocene in places that mostly seal, or are partially still involved in the complex PKB structures.

Other Upper Cretaceous and Palaeogene sediments also occur within boundary zones adjacent to the PKB *s.l.* on both sides. From the outer side, these are deposits of the Biele Karpaty and Magura superunits of the EWC Flysch Belt (e.g., Potfaj, 1993; Stráník *et al.*, 1997; Picha *et al.*, 2006; Oszczytko and Oszczytko-Clowes, 2009). The EWC units are not dealt with in detail in the present paper, however. On the inner side in western Slovakia, Upper Cretaceous syn-orogenic deposits occur in the Vahic Belice Unit as an internal, structurally independent part of the South Penninic accretionary complex. In eastern Slovakia, a somewhat similar structural position is occupied by the Iňačovce-Kričevo Unit (Fig. 1B). These units are treated in more detail below. In all areas, the Central Carpathian Palaeogene Basin (CCPB, known also as the Podhale Basin in Poland) represents an overstepping complex that seals all the pre-Bartonian structures in the CWC.

UPPER CRETACEOUS AND LOWER PALAEOGENE DEPOSITS OF THE VAHIC AND ORAVIC UNITS

The Vahic and Oravic units represent the Western Carpathian counterparts of the Alpine Upper and Middle Pen-

nic units, respectively (*sensu* Schmid *et al.*, 2004). Alternatively, the Oravic units might be correlated with the Margna-Sesia *alias* Cervinia continental fragment located within the Ligurian-Piemont Ocean, which was rifted off the Austroalpine margin (cf. Froitzheim *et al.*, 2008; pp. 1157–1158) and is still a part of the Upper Penninic nappe system. The common characteristics of all these zones are: 1) Early Jurassic widespread rifting and Middle Jurassic breakup of the southern branch of the Alpine Atlantic (Ligurian-Piemont-Tauern-Ybbsitz-Vahic oceanic tract), followed by distinctive Upper Jurassic pelagic facies, such as radiolarites and Maiolica-type limestones; 2) continuous marine, deep-water sedimentation throughout the Cretaceous; 3) commencement of the synorogenic clastic sedimentation in the Late Cretaceous times – during the Cenomanian–Turonian–Coniacian in the inner oceanic zones, and during the latest Cretaceous–earliest Palaeogene in the outer zones partly underlain by attenuated continental crust (the Czorsztyn Ridge and its slopes); 4) Late Cretaceous to early Palaeogene development of the subduction-related accretionary wedge, composed of sedimentary units and in places peels of ophiolites that had been detached from the oceanic crust and/or fragments of continental crust during their underthrusting below the Central Carpathian (Austroalpine) nappe stack.

Vahic (South Penninic) domains

During the Late Jurassic and Cretaceous, the outer CWC Tatric margin faced the eastern branch of the Ligurian-Piemont oceanic realm named the Váh Ocean in the Carpathians (Maheľ, 1981). As was inferred by Plašienka (Plašienka *et al.*, 1994, 1995; Plašienka, 1995a, b, c, 2012a), the Vahic oceanic domain is represented by the Belice Unit occurring in the Považský Inovec Mts. in western Slovakia, some 10 km SE of the surface exposures of the PKB (Fig. 1A). The onset of shortening in the Belice trench basin and subduction of the Vahic lithosphere is recorded in the synorogenic clastic sedimentation that started during the Coniacian–Santonian (Kullmanová and Gašpariková, 1982). Upper Cretaceous clastics were deposited in front of the convergent Tatric margin and were later scraped off their underthrust substratum, piled up in an accretionary complex and overridden by the Tatric (Infratatric) Inovec basement nappe.

The Belice Unit is composed of two formations. The Oxfordian–Lower Cretaceous eupelagic Lazy Fm (radiolarites, Maiolica limestones and Palombini-type shales) is overlain by the Horné Belice Fm (Fig. 2), which is hundreds of metres thick Coniacian–Campanian sequence of deep-marine clastics (Plašienka *et al.*, 1994; Plašienka, 1995c). The lower, Coniacian–Santonian part consists of thin-bedded distal calcareous turbidites and thick-bedded sandstones with lenses of polymictic conglomerates, deposited in the middle and outer parts of a submarine turbidite fan fed from sources on its inner – CWC margin (Plašienka *et al.*, 1994). The upper, Campanian to possibly Lower Maastichtian sequence comprises purple-red marly shales, greenish-grey calcareous sandstones, pebbly mudflows and olistolith-bearing chaotic breccia bodies, composed dominantly of material derived from the overlying Infratatric

Inovec Nappe. These sediments represent typical proximal turbidites with breccia debris flows deposited along a trench-slope hinge (Marschalko in Plašienka *et al.*, 1994). Sediments of the Belice Unit were affected by very low- to low-grade metamorphism and by several penetrative deformation stages recording processes of thrusting-related burial and subsequent exhumation, supposedly within a growing accretionary wedge (Plašienka, 1995c; Korikovský *et al.*, 1997; Putiš *et al.*, 2008, 2009).

One of the possible subsurface extensions of the Vahic units in western Slovakia was encountered by the SBM-1 Soblahov borehole, which penetrated a sedimentary complex of unknown provenance below the Manín (or Belá-Vysoká) Nappe near the town of Trenčín (see Kullmanová, 1978; Maheľ, 1985). This unspecified unit is several hundred metres thick and includes a strongly imbricated complex of dark, slightly metamorphosed shales of Jurassic to Lower Cretaceous age, with layers of breccias, conglomerates, sandstones and limestones, which are intercalated with slices of Upper Cretaceous globotruncanid-bearing variegated marls. The borehole was located about 10 km NE of the surface exposures of the Belice Unit. The strata penetrated by it can be partly correlated with the unit with regard to age and lithology. This indicates that the frontal Tatric elements moved far northward, probably out-of-sequence in part, beyond the northern Tatric edge in that area (Plašienka, 1995a, b).

The eastern Slovakian analogue of the South Penninic-Vahic complexes is the Iňačovce-(Kričivo) Unit (Soták *et al.*, 1993, 1994; Plašienka *et al.*, 1995), which was penetrated by several deep boreholes in the pre-Miocene basement of the East Slovakian Neogene Basin. The Iňačovce Unit was most comprehensively characterized in the paper by Soták *et al.* (2005). In earlier publications, it was variously named as the Pozdišovce-Iňačovce, Iňačovce-Kričivo, or only Kričivo (Kričivo, defined from the Ukrainian territory) Unit (e.g., Kruglov, 1971; Slávik, 1976; Sviridenko, 1976; Leško and Varga, 1980; Grecula *et al.*, 1981; Ďurica, 1982; Soták *et al.*, 1993, 1994, 2000), combining various complexes occurring only in the subsurface basement of the Transcarpathian Depression at the boundary of the Western and Eastern Carpathians. Since these complexes are known only from limited borehole data, there are still great uncertainties about their composition and mutual relationships. At present, only the Iňačovce Unit appears to be satisfactorily defined in terms of its lithostratigraphy, metamorphism and deformation structures.

According to Soták *et al.* (2005), the Iňačovce metasedimentary complexes consist of several lithostratigraphic units late Palaeozoic (?) to Eocene in age (Fig. 2). Dark grey phyllitic slates, arcose sandstones and occasional carbonates are possibly of Permian age (Planderová and Slávik, 1977; Pozdišovce Fm – Soták *et al.*, 2005), while light crystalline limestones with foraminifers and variegated phyllites of the “Quartenschiefer” type represent the Triassic (Soták *et al.*, 1994; Bunkovce Fm – Soták *et al.*, 2005). This lower complex might represent an analogue of the detached Middle Penninic nappes of the Alps (Schmid *et al.*, 2004). The upper complex, probably Jurassic to Cretaceous, includes dark metapelites, greenschists, calcareous and graphitic

phyllites of the “Bündnerschiefer” affinity (Iňačovce and Rebrin fms – Soták *et al.*, 2005). Metapelites and sandstones with Middle Eocene nummulites are the youngest stratigraphically determined rocks (Soták *et al.*, 1993, 1994; Nacina Ves and Lesné fms – Soták *et al.*, 2005). Bodies of serpentinites occur in the upper parts of several boreholes, occasionally amygdaloidal metabasalts and hyaloclastites also were drilled.

All rock complexes of the Iňačovce Unit were affected by low-grade metamorphic overprint and penetrative ductile deformation. The peak metamorphic conditions of 500–700 MPa and 350–400°C were reached approximately 30 Ma ago, as indicated by K-Ar dating of illite concentrates (Biroň *et al.*, 2000b; Soták *et al.*, 2000, 2005). The cooling and exhumation-related zircon fission-track dating provided ages of around 20 Ma. The structural evolution progressed from underthrusting and tectonic burial recorded by penetrative, bedding-parallel metamorphic foliation and minute intrafolial isoclinal folds, superposed by layer-parallel shortening with development of crenulation up to transposition cleavage and high-strain, non-coaxial shear zones. The exhumation process is documented as progressively more brittle structures, such as kink folds, extensional shear bands, normal faults, mineralized veins, fractures and cataclastic zones (Soták *et al.*, 2000, 2005). This tectono-metamorphic evolution was interpreted in terms of subduction-related underplating of the Iňačovce Unit below the outer margin of the CWC block during the Late Eocene and its exhumation from depths of below 15 km by the core-complex-style extensional unroofing during the Early–Middle Miocene, simultaneously with the opening and subsidence of the eastern Slovakian part of the Neogene Transcarpathian Basin (Soták *et al.*, 2000, 2005).

The Kričovo (Krichevo) Unit, which is known from deep boreholes that reached the pre-Neogene substratum of the Ukrainian part of the Transcarpathian Basin, shows some different characteristics compared to the Iňačovce Unit, particularly the missing metamorphic overprint and ultramafic bodies, and presence of macrofossils (e.g., Jurassic ammonites). For this reason, Soták *et al.* (2005) proposed to differentiate between the Iňačovce and Kričovo units. Both might represent the same depositional realm, but their subsequent tectono-metamorphic history was diverse. According to Sviridenko (1976), the Kričovo zone comprises (Fig. 2): 1) Triassic carbonates, variegated shales, sandstones and mafic volcanites; 2) Jurassic fossiliferous marlstones and crinoidal limestones; 3) Cretaceous, up to 1,000 metres thick complex of dark shales, marls and limestones with subordinate intercalations of sandstones and siltstones and also with passages of variegated shales and marls (Kričovo and Romano fms); 4) calcareous shales, siltstones, sandstones and gravelites with Middle Eocene nummulites (Dulovo Fm); 5) variegated claystones, siltstones, sandstones and tuffite intercalations (Middle–Upper Eocene Bajlovo Fm); and 6) Lower Oligocene menilite-type black shales and sandstones (Lazovo Fm). However, affiliation of the Triassic and Jurassic rocks to the same unit as the Cretaceous and Palaeogene strata is questionable in this strongly imbricated zone that is probably composed of several units with different palaeogeographic and tectonic affiliations.

It was inferred that the Iňačovce, Kričovo and related units continue from the subsurface of the Transcarpathian Depression to the Pannonian Basin basement along the Mid-Hungarian (Zagreb–Zemplín) fault zone *via* the Szolnok Unit up to the Dinaridic Sava Zone (Schmid *et al.*, 2008).

Oravic (intra-Penninic) domain

At present, three large-scale thrust units are distinguished within the PKB *s.s.* (Oravicum) from bottom to top: the Šariš, Subpieniny and Pieniny nappes. They include several local subunits and/or successions (e.g., Plašienka, 2012a). The innermost Pieniny Nappe (the terms Pieniny and Subpieniny are used in sense of Uhlig, 1907) was derived from a basinal area to the south of the Czorsztyn Ridge. It contains several Jurassic–Cretaceous, slightly differing successions (Pieniny *s.s.*, Kysuca, Branisko, possibly also Nižná – e.g., Andrusov, 1938, 1974; Birkenmajer, 1977, 1986; Józsa and Aubrecht, 2008), dominated by deep-water pelagic strata and terminated by Turonian–Santonian sandy turbidites and conglomerates composed of partly “exotic” material (Snežnica and Sromowce formations; Figs 2, 6A). This coarsening-upward synorogenic sequence developed in the foreground of the Fatric Klappe Nappe, which provided the majority of the clastic material, including the “exotic” components. As inferred by Plašienka (1995a, 2012a), the exotic material was most probably resedimented from the mid-Cretaceous, Upohlav-type conglomerates of the Klappe Unit.

The Pieniny Nappe overthrusts the Subpieniny Unit, which was derived from the Czorsztyn Ridge and its southern slopes and includes several successions. In addition to the most typical Czorsztyn succession, characterized by comparatively shallow-marine Middle Jurassic to Lower Cretaceous strata interrupted by several gaps, it includes also some slope-derived, “transitional” successions with mixed features of the Czorsztyn and Pieniny-type successions (Niedzica, Pruské, Czertezik). The Upper Cretaceous strata are mainly composed of red pelagic *Globotruncana* marlstones of the *couches rouges* facies, known under the informal term “Púchov marls” in the PKB (Stur, 1860). Synsedimentary submarine lava flows of within-plate alkaline basalts document the protracted extensional tectonic regime in the Czorsztyn swell area during the Late Cretaceous (Bučová *et al.*, 2010; Spišiak *et al.*, 2011), while the onset of convergence is heralded by the Jarmuta Fm, the Maastrichtian (up to Danian?) sequence of calcareous turbidites (Fig. 2). The upper part of the Jarmuta Fm includes bodies of chaotic breccias, the Gregorianka Breccia Member (Nemčok *et al.*, 1989; redefined by Plašienka and Mikuš, 2010) in the eastern PKB and the Záskanie Breccia (Marchalko *et al.*, 1979) in the Orava region. The breccias are composed of material derived exclusively from the overriding Pieniny Nappe (Fig. 6C).

The outer- and lowermost Oravic element of the PKB is the Šariš Unit. It was differentiated only recently (Plašienka and Mikuš, 2010; Plašienka *et al.*, 2012; Plašienka, 2012a) as strongly dismembered Lower Jurassic to Middle Eocene sedimentary complexes that formerly were collectively assigned either to the “klippen mantle”, or to the innermost elements of the Magura Superunit in eastern Slovakia. The

term Šariš Unit unifies several locally defined elements of hitherto unclear affiliation: the “Kopanice facies” (Picha *et al.*, 2006) and Fodorka Unit (Salaj, 1995) in western Slovakia, the Grajcarek (Birkenmajer, 1970, 1977, 1986) and/or Hulina Unit (Sikora, 1974) in the Polish PKB and the Fakľovka Unit in the Slovakian Pieniny Mts. (Oszczypko *et al.*, 2010). Further east (the Šariš sector of the PKB), the northern strip of the PKB is built of Paleocene to Lower Eocene calcareous turbiditic sandstones, which were in the past referred to as the “calcareous Magura facies” (Matějka, 1959), or the Kyjov and Lackovec “series” with close relationships to the Magura Unit (Pesl and Menčík, 1959; Stráník, 1965, 1967), united as the “Zemplín Belt” by Andrusov (1965) and assigned by him to the Magura Unit. On the other hand, Leško (1960) considered this unit as an independent element of the PKB (“Inovce development”), composed mainly of calcareous sandstones of the Proč Fm (Leško and Samuel, 1968). Later Nemčok (1980; Nemčok *et al.*, 1989) unified the Palaeogene Proč Fm with the lithologically identical Maastrichtian Jarmuta Fm, both forming the klippen matrix, and considered the entire PKB to represent a gigantic olistostrome with all klippen as olistolites. Recently, Plašienka and Mikuš (2010) and Plašienka *et al.* (2012) documented the structural independence of the Proč and associated formations and defined the entire Jurassic to Palaeogene succession as the Šariš Unit, which is the third first-order Oravic tectonic unit of the PKB.

All these units are characterized by their most typical element, the Maastrichtian? – Paleocene – Lower/Middle Eocene Proč Fm (Leško, 1960), which is united with the Jarmuta Fm in Poland. The Proč Fm is composed of calcareous turbidites, slide bodies and mass-flow breccias (Milpoš Breccia Mb – Plašienka & Mikuš, 2010), containing material that principally originated from the overriding Subpieniny Nappe (Fig. 6E). Moreover, numerous klippen resting within the breccias and sandstones of the Proč Fm are sedimentary olistoliths. Besides these syn-orogenic clastics, the Šariš Unit includes a more-or-less continuous, but strongly condensed and dismembered Jurassic to Cretaceous deep-water pelagic succession (Fig. 2). These formations were frequently deposited below the CCD, for example, as were the Jurassic radiolarites and Upper Cretaceous red pelagic shales (CORB) of the Malinowa Fm containing, exclusively agglutinated foraminifers (DWAf). According to Kruglov (1971, 1974), the Vuľchovčik (Vulkhovchik) Fm is an eastward analogue of the Proč Fm in the Ukrainian PKB.

In summary, the sedimentary records of the terminal synorogenic formations in the Oravic units indicate their sequential thrusting: first, around the Cretaceous/Palaeogene boundary, the Pieniny Unit overrode the Jarmuta basin of the Subpieniny Unit that was in turn thrust over the Proč basin of the later Šariš Unit during the Paleocene–Early Eocene. Subsequently the Šariš Unit overthrust the internal zones of the Magura Superunit, along with all overlying elements. In this perspective, the progressively outward younging syn-orogenic clastic formations represent the migrating peripheral foredeep basins, with coarsening-upward trends that were fed by material derived from the advancing fronts of the overriding nappes. Therefore the ages of these sediments are considered as indicative of the timing of the

thrusting events and their propagation within the Oravic Nappe stack of the PKB.

GOSAU-TYPE BASINS IN THE WESTERN CARPATHIANS

The Gosau basins, filled with Upper Cretaceous to mid-Palaeogene deposits (Gosau Group or Supergroup), were defined in the Northern Calcareous Alps (NCA) as a basin system developing on top of the “pre-Gosauian”, eo-Alpine Bajuvaric-Tyrolic-Juvavic nappe system, composed mainly of Mesozoic carbonates (e.g., Faupl *et al.*, 1987; Wagneich and Faupl, 1994). At present, the Gosau sediments occur in synform structures, interpreted either as inverted extensional grabens controlled by subcrustal erosion due to the underthrusting of topographic elevations carried by the subducted Penninic oceanic lithosphere, possibly the mid-oceanic ridge (Wagneich, 1995), a Tauern continental fragment (Kázmér *et al.*, 2003), or in the western NCA as syn-thrusting, piggyback growth basins (Ortner, 2001). In general, the sedimentary fill of the Gosau basins was differentiated into the Lower Gosau Subgroup (Late Turonian–earliest Campanian), composed of terrestrial carbonate conglomerates and nearshore sandstones and marlstones. After an erosional intra-Gosauian unconformity, the Upper Gosau Subgroup includes Campanian to Lutetian deep-sea, hemipelagic and calcareous turbiditic deposits, locally including reef-derived debrites (Faupl *et al.*, 1987; Wagneich, 2001). In the eastern NCA part, these sediments occupy several synclines, partly differing in evolution (Giesshübl, Glinzendorf and Grünbach synclines from N to S). Towards the east, the NCA nappes and the Gosau synclines continue into the subcrop of the Neogene Vienna Basin (e.g., Wessely, 1992) and reappear again on the surface in the northern part of the Malé Karpaty Mts. (e.g., Salaj and Priehodská, 1987; Wagneich and Marschalko, 1995). Further eastward, scattered occurrences of Coniacian–Eocene formations can be traced along the southern boundary of the PKB in the Middle Váh Valley in western Slovakia, in southern Poland and also in the eastern Slovakian PKB sector, in a belt that is often referred to as the “peri-Klippen zone”.

These Gosau complexes, which are related to the Upper Austroalpine cover nappe systems of the NCA (Bajuvaric-Tyrolic-Juvavic) and outer CWC zones (Fatric-Hronic), are sometimes referred to as the external Gosau basins (e.g., Willingshofer *et al.*, 1999). In contrast, the internal, or Central Alpine Gosau basins (Wagneich and Faupl, 1994), occur in the inner zones of the Eastern Alps underlain by crystalline basement units (Kainach and Krappfeld basins). These basins exhibit a short, but intense subsidence during the Campanian, which was coeval with the cooling ages and exhumation of adjacent metamorphic domes by orogen-parallel extension in sinistral-wrench corridors (Neubauer *et al.*, 1995; Willingshofer *et al.*, 1999). Thus the origin of the Central Alpine Gosau basins was related to the extensional collapse of the Austroalpine lithosphere, overthickened as a result of the mid-Cretaceous thrusting.

In the Western Carpathians, remnants of the internal Gosau sediments are related to the highest, Silicic cover

TIMESCALE	NORTHERN MALÉ KARPATY MTS				MIDDLE VÁH VALLEY				EASTERN SLOVAKIA		
	Surovín succession	Stará Turá succession	Bradlo succession	Buková succession	Hoštíná succession	Podmanín succession	Hričov succession	Domaníža succession	Údol succession	Beňatina succession	
Oligocene/Miocene	Burdigalian	Lužica Formation				Čausa Formation					Miocene basins
	Aquitanian	gap				gap				Čelovec Fm	
Oligocene	Chatthian	gap				gap				Malcov Formation	Podtatrá Group
	Rupelian	gap				gap				Huty Formation	
Eocene	Priabonian	gap				gap				Borové Fm	Podtatrá Group
	Bartonian	gap				gap				Borové Fm	
Eocene	Lutetian	Jablonka Formation	Jablonka Formation	Priepastné Formation	Buková Formation	gap				Haligovka succession	Myjava-Hričov Group
	Ypresian	Dedkov vrch Formation	Lubina Formation	Kravárikovci Formation	Jelenia hora Formation	Šafranica Formation	Súľov Formation	Súľov Formation	Súľov Formation	Súľov Formation	
Paleocene	Thanetian					Jablonové Fm			Jablonové Fm	Myjava-Hričov Group	
	Selandian					Hričovské Podhradie	Mojtín bauxite carb. breccia				
Late Cretaceous	Danian				Bartalová Breccia					Brezová Group	
	Maastrichtian	Poliánka Formation	gap	Bradlo Fm	Vápenková sk.	Ihršte Formation	Hradisko Fm				Gosau Supergroup
Late Cretaceous	Campanian			Podbradlo Fm	Kržíža Breccia	Púčov Formation	Hrabové Formation	gap		Brezová Group	
	Coniacian	Košariská Formation		Košariská Formation					bioclastic limestone		Gosau Supergroup
Late Cretaceous	Santonian	not exposed		Hurbanova dol.	gap	Rašov Formation	Žadovec Formation			CWC	
	Turonian			Ostriež Fm							
				Pustá Ves Fm		KLAPE UNIT	MANÍN UNIT				

Fig. 3. Unified Upper Cretaceous–Palaeogene lithostratigraphy of the wedgetop-forearc basin system and overstepping Lower Miocene formations in zones associated with the PKB.

nappe system of the inner CWC zones (Vepor-Gemer Belt and the Slovak Karst Mts. – cf. Fig. 1B). These are mostly carbonate conglomerates and breccias, freshwater limestones with coal seams, and terrigenous clastics filling the karst cavities. The largest preserved exposure, near the Dobšiná Ice Cave, includes also marine sediments, Campanian rudist-bearing bioherms and globotruncanids-bearing variegated marlstones (e.g., Havrila in Mello, 2000). However, some other small remnants of the Senonian deposits, scattered within the CWC, are indications of the original greater extent of the internal Gosau basins (see Mišík, 1978). These occurrences were probably continuous with the Upper Cretaceous Gosau-type deposits in the Hungarian Transdanubian Range and Uppony Mts. of the Internal Western Carpathians (e.g., Wagneich and Siegl-Farkas, 1999; Haas, 2012), but these are beyond the scope of the present paper.

Malé Karpaty Mountains

The most complete Western Carpathian Gosau complexes are preserved in the northern Malé Karpaty Mts. (Fig. 1A). On the basis of some differences in lithostratigraphy, several Upper Cretaceous and Palaeogene successions have been distinguished there (Samuel *et al.*, 1980; Salaj and Began, 1983; Salaj, 1987; Salaj and Priečovská, 1987; Salaj and Michalík, 2000). The general division includes two main lithostratigraphic units, the Coniacian–Maastrichtian Brezová Group and the Paleocene–Eocene Myjava Group (Fig. 3). In its southern part, the Brezová Group rests transgressively on the Triassic carbonates of the Hronic superunit. Overlapping some remnants of pre-transgressive freshwater limestones and conglomerates (Pustá Ves Fm), the Coniacian transgressive cycle begins with terrestrial carbonate conglomerates and breccias (Valchov Mb of the Os-

triež Fm), overlain by marine calcareous sandstones (Baranec Mb) and neritic marls (Štverník Mb). The Santonian marlstones, calcareous sandstones and minor conglomerates are followed by a Lower Campanian sequence of variegated marlstones rich in planktonic globotruncanids of the Košariská Fm (“Púčov marls” of Stur, 1860), indicative of deepening conditions. These correspond to the Nierental Fm of the Alpine Upper Gosau Subgroup (Wagneich *et al.*, 2011). The Púčov-type hemipelagic marlstones are overlain by mixed siliciclastic-calcareous, mostly turbiditic sandstones (Podbradlo Fm, Middle–Upper Campanian), at least 500 m thick. This shallowing-upward cycle is terminated by the Maastrichtian shallow-marine, sandy-bioteritic limestones, passing into calcareous turbidites basinwards (N-ward with respect to present coordinates), where they interdigitate with hemipelagic marls (Bradlo Fm, e.g., Salaj and Michalík, 2000; Fig. 6D). This sequence crosses the Cretaceous/Palaeogene boundary without interruption in the northern basal part of the area (Surovín succession – Salaj, 1987), whereas the absence of coeval sediments in the south is evidence of emergence.

The next cycle, differentiated into several formations, starts with Selandian–Thanetian conglomerates and calcareous sandstones with in part resedimented algal-coral reefs (Mišík and Zelman, 1959; Scheibner, 1968; Köhler *et al.*, 1993 – Kambübel Limestone, Kravárikovci Fm), intercalated with and followed by Lower–Middle Eocene basinal hemipelagic marls and limy turbidites altogether up to 1,000 m thick (Priepastné Fm – Salaj, 1987).

In more northern zones, adjacent to the PKB *s.s.*, only the youngest Cretaceous and Palaeogene deposits are exposed. The formations are of deeper-water origin and thicker, by comparison with the southern developments. The Stará Turá succession (Salaj, 1987) contains only the Palaeogene

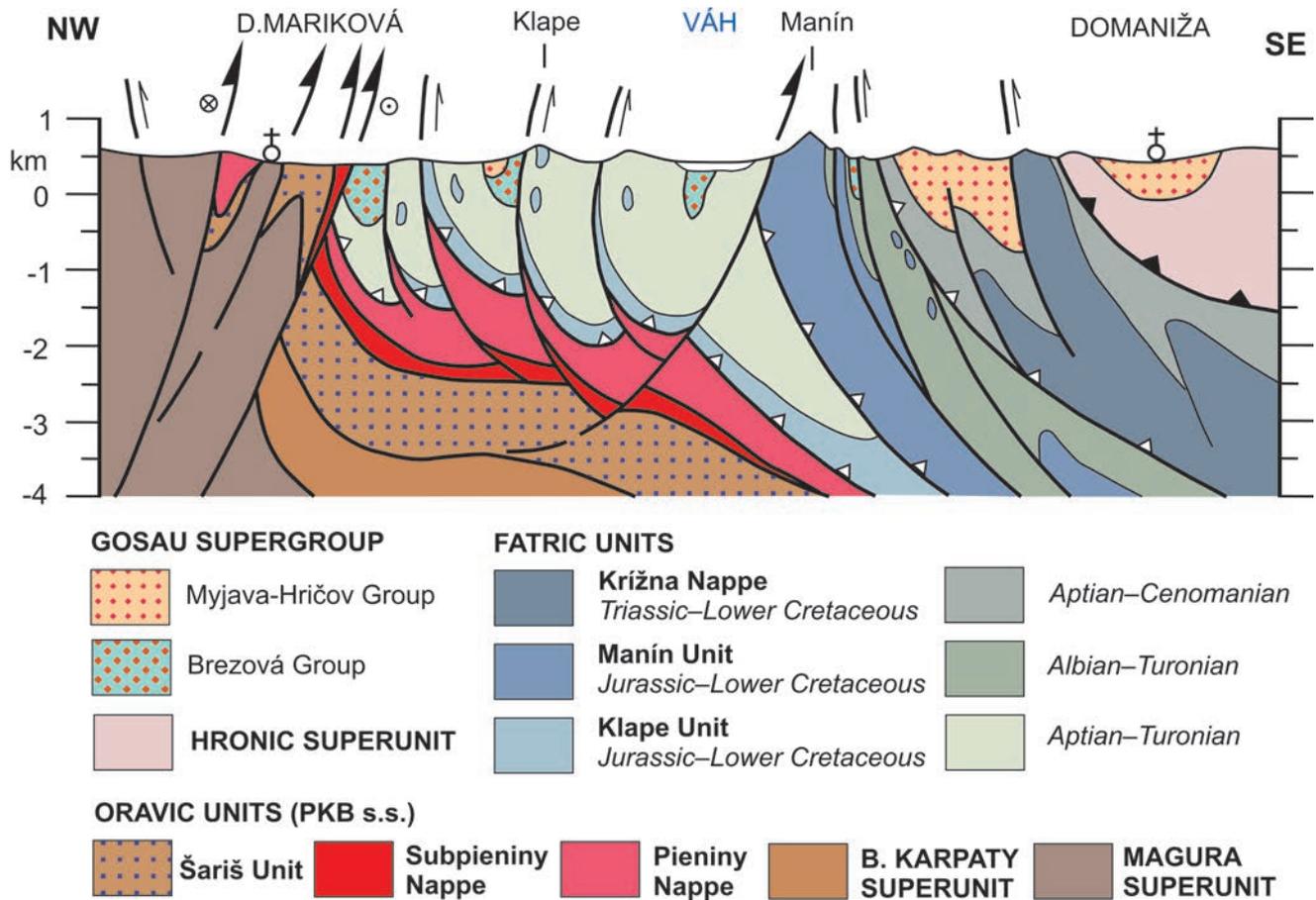


Fig. 4. Geological cross-section of the Pieniny Klippen Belt and adjacent zones in the Middle Váh Valley. For its location, see Figure 1A.

Myjava Group, consisting of Thanetian–Ypresian Lubina Fm, a complex of basal conglomerates, calcareous turbidites and marlstones, pebbly mudstones and blocks of reef limestones, up to 1,000 m thick (Fig. 3). The adjacent Surovín succession includes Campanian–Maastrichtian marlstones and distal calcareous turbidites (Košariská and Polianky fms), followed by a shallowing-upward sequence of biotrititic limestones and sandstones with resedimented reef blocks (Dedkov vrch Fm, Paleocene–Ypresian). Then, during the Lutetian, the basin subsided rapidly to bathyal depths, with the sedimentation of variegated pelagic claystones and fine-grained sandstones (Jablonka Fm). Along the contact with the PKB, narrow slices with Bartonian *Globigerina* marls and dark shales occur (Samuel, 1975).

Middle Váh River Valley

In the Manín zone of the peri-Klippen belt of the Middle Váh Valley (Fig. 1A), the “Senonian” deposits (the upper part of the Podmanín Group *sensu* Kysela *et al.*, 1982; adapted here as the Podmanín succession; Fig. 3) consist of Coniacian to Santonian shallow-marine sandstones with crab burrows and silty claystones with sandy slump bodies containing a littoral fauna (Žadovec Fm); Lower Campanian variegated marls of the *couches rouges* facies (Hrabové Fm); Upper Campanian to Maastrichtian calcareous sandstones with exotic conglomerates (Hlboké Fm); and Upper Maas-

trichtian to Danian? bioclastic (*Orbitoides*-bearing) limestones, sandstones and conglomerates with scattered rudist reef bodies (Hradisko Fm). It is noteworthy that calcareous turbidites show palaeotransport from the north (Marschalko and Kysela, 1980) indicating the existence of intrabasinal sources for the clastic material, which in part was recycled from older conglomerate formations and was partly derived from coeval, shallow-marine biogenic sources.

In the Middle Váh Valley, the Coniacian to Lower Eocene sediments occur also as the fillings of three synclines that separate individual slices of the Klapce Unit, which is another “non-Oravic” unit of uncertain position occurring in the peri-Klippen zone. Plašienka (1995a, 2012a) assigned it, along with the Manín Unit, to the Fatric (Křížna) nappe system (Fig. 4). The Klapce Unit is first of all characterized by thick prisms of mid-Cretaceous (Albian to Turonian) deep-water, coarse clastic deposits, dominated by the “exotic”, so-called Upohlav-type conglomerates (“Klapce Flysch”; see e.g., Mišík and Reháková, 2004, and references therein). These are unconformably overlain by the Upper Cretaceous–Lower Eocene Hoština succession (Salaj, 1994, 2006; Mello, 2011). The Hoština succession (partially redefined here; Fig. 3) includes basal polymict conglomerates of the Coniacian–Santonian Rašov Fm (Fig. 6B), locally with *Hippurites* reef bodies, followed by a deepening- and fining-upward sequence of calcareous turbidites (Late Santonian) and variegated marlstones of the *couches rouges* fa-

cies (Lower Campanian Púchov Fm *sensu* Mello, 2011). Upper Campanian to Maastrichtian sediments are represented by the comparatively shallow-water *Inoceramus* marls, *Orbitoides* limestones, blocks of rudist-bearing biohermal limestones, calcareous sandstones and conglomerates (Ihršte Fm). The Lower Palaeogene (Paleocene–Ypresian) strata are composed of shallow water bioclastic and sandy limestones with reef bodies and carbonatic conglomerates (Šafranica and Kravárikovci fms).

The peri-Klippen zone in the Middle Váh Valley includes, in addition to the Klape-Manín zone with its Gosau-type complexes, also Palaeogene deposits situated in partially independent structures. They were known informally as the “peri-Klippen Palaeogene”, later named the “Myjava-Hričov-Haligovka zone” (Scheibner, 1968), “Považie-Hanušovce zone” (Samuel, 1972), but recently they were formally assigned to the Myjava-Hričov Group (Mello, 2005, 2011).

Stratigraphically, the Myjava-Hričov Group contains strata of the Paleocene to Middle Eocene age (Fig. 3). In addition to the sediments of this age described above and affiliated with the Hoština succession, the largest extent of the Myjava-Hričov Group appears in a variably wide zone, rimming the Manín Unit in the SE (Fig. 1A). In a narrow zone flanking the Manín Unit, the Paleocene to Lower Eocene sediments were assigned to the Hričovské Podhradie Fm (Mello, 2005, 2011). They represent a new sedimentary cycle, although a gradual transition from Maastrichtian deposits was indicated in places (e.g., Salaj *et al.*, 1978), but not definitely confirmed; a hiatus was observed at the base of the Danian (Hansen *et al.*, 1990). The formation is composed of variegated claystones and marlstones, laterally interfingering with calcareous turbiditic sandstones and conglomerates with numerous resedimented blocks of lower Thanetian bioherms and patch-reefs (Kambühel Limestone), as well as olistoliths of Urgonian limestones. The sandstones laterally pass into shallow-marine biodetritic and sandy limestones of the Jablonové Fm (Thanetian–Ypresian; Fig. 6F). These are overlain by the coarse-grained carbonate breccias and conglomerates of the Lower to Middle Eocene Súľov Fm.

Further to the SE, in the area of CWC built of Fatric and Hronic nappes, the Súľov Fm represents a new transgressive cycle. In the Mojútín area, there are preserved remnants of pre-transgressive phenomena, such as indications of karstification, with bauxite pockets and blocky carbonate breccias, overlain by remnants of limestones of the Jablonové Fm. However, the Súľov Conglomerate usually directly oversteps the Cretaceous formations of the Fatric Křížna Nappe and, in a majority of places, the Triassic and Jurassic carbonates of the Hronic nappes. In the Prečín-Domaníža-Žilina synform (Figs 1A, 4), the Súľov Conglomerate attains a great thickness of up to 800 m and is almost exclusively composed of poorly sorted carbonate material, derived from the Triassic formations of the Hronic units, predominantly dolomites (Marchalko and Samuel, 1993). Higher up, a deepening- and fining-upward sequence of nummulitic limestones, calcareous turbiditic sandstones, conglomerates with blocks of reef limestones, and finally bathyal variegated claystones and sandy turbidites occur (Lower–Middle Lutetian Domaníža Fm).

In the Malé Karpaty Mts., southward of occurrences of

the Brezová and Myjava groups, a succession analogous to that of the Súľov-Domaníža area covers the Triassic carbonates of the Hronic nappes in the Buková synform (Fig. 1A). The Buková succession (Fig. 3) begins with pre-transgressive terrestrial carbonate breccias (Bartalová Breccia – Michalík, 1984; Polák, 2012), of presumably latest Cretaceous–Paleocene age. The Upper Paleocene–Lower Eocene transgressive sequence is composed of carbonate conglomerates, sandstones and algal-coral bioherms (Jelenia hora Fm, Buček in Polák, 2012), followed by deep-sea dark calcareous claystones and siltstones up to 500 m thick, with sporadic turbiditic sandstone beds and conglomerate lenses (Lutetian Buková Fm). In the same synform, but in an unclear contact with the underlying formations, also a much younger (Kiscelian, i.e., Rupelian) turbiditic shaly-sandy, strongly folded sequence occurs (Hrabník Fm – Marko *et al.*, 1990).

Recently, another deep-water Upper Cretaceous–Middle Eocene succession was encountered by drilling in the Hornonitrianska kotlina Depression (Soták *et al.*, 2013). The succession consists of marine red beds of possibly latest Cretaceous age, followed by basal Paleocene calcareous sandstones and bioturbated siltstones, Selandian–Thanetian sandstones, silty marlstones, conglomerates and slump bodies with fragments of Kambühel-type biohermal limestones, and Lower to Middle Eocene grey and yellow marlstones. This discovery is surprising, because the locality lies some 40 km to the SE of the PKB and therefore it can hardly be regarded as a “peri-Klippen” development. On contrary, it indicates that not only the PKB and adjacent zones were flooded by the Paleocene–Eocene deep sea, but that so too were at least some of the more inner parts of the CWC.

The eastern prolongation of the Manín-Klape synclines, filled with Upper Cretaceous to Lower Eocene deposits, can be found in the Varín (Kysuce) PKB sector NE of Žilina, adjacent to the mid-Cretaceous flysch complexes of the Klape Unit. There, between Teplička nad Váhom and Nededza villages, the succession consists of Coniacian–Santonian conglomerates, Campanian–Maastrichtian variegated “Púchov marls” (Gbeľany Fm – Kantorová and Andrusov, 1958), sandy-bioclastic limestones with large foraminifers of Thanetian–Ypresian age, and variegated shales with Lutetian agglutinated foraminifers (Samuel and Haško, 1978). The Paleocene–Eocene sediments, described as the “Varín development” of the Považie-Hanušovce Belt by Samuel (1972), can be followed eastwards in a narrow discontinuous belt along the southern PKB boundary, up to Terchová and Zázrivá villages (Scheibner, 1968; Samuel and Haško, 1978). At present, they are generally referable to the lower Palaeogene Myjava-Hričov Group.

Northern and eastern PKB sectors

In the Orava region, the sediments of the Brezová or Myjava Group are not present in their original position, but occur as clasts within the younger Palaeogene sediments of the CCPB, hence witnessing a destruction of a large peri-Klippen Gosau-type basin also in this area (Köhler and Gross, 1994). The pebbles and boulders include, among others, unique Campanian *Orbitoides*- and rudist-bearing biohermal limestones (Mišík *et al.*, 1968), Maastrichtian calcareous

sandstones with *Orbitoides* and conglomerates, Danian coral-algal reef limestones, Thanetian bioclastic limestones, and Eocene algal-coral and nummulitic limestones (Scheibner, 1968; Mišík *et al.*, 1968; Köhler and Gross, 1994).

Birkenmajer (2000) described the Rusinowa Conglomerate Fm on the northern slopes of the High Tatra Mts., which according to his interpretation should be a relic of the Upper Cretaceous Gosau Group, unconformably overlying the Triassic strata of the Fatric Križna Nappe. Although the age of these conglomerates might be questionable (cf. Jurewicz, 2005), the possible Gosau-like deposits were reported also north of the Tatra Mts. in the vicinity of the PKB. In the subcrop of the Podhale Basin, Upper Cretaceous (?) conglomerates and sandstones were drilled between two slices of the Manín-type Križna Unit (Baňska IG-1 borehole – Wieczorek and Barbacki, 1997; Wieczorek and Olszewska, 1999).

In the Polish Pieniny sector of the Klippen Belt, between Maruszyna and Szaflary villages, a narrow and short slice follows the boundary between the Klippen Belt and the CCPB (Podhale Basin – Fig. 1B). This unit was named the Maruszyna succession (Kostka, 1988, 1993; Dudziak and Kostka, 1989). It is a deep-water hemipelagic succession that contains Maastrichtian marly limestones, Middle Paleocene variegated marls and shales, Upper Paleocene to Lower Eocene red marls, and Middle Eocene soft blue-grey claystones (Fig. 2). The Maruszyna succession was correlated with the Myjava development, in western Slovakia (Alexandrowicz and Birkenmajer, 1978), because it is considerably different from the coeval deposits of the PKB proper. In fact, it also differs from the Brezová and Myjava-Hričov groups in its lack of conglomerates and, particularly, in the scarcity of shallow-water limestones and reef bioherms and detritus from them. For this reason and owing to an analogous structural position and lithostratigraphic content, the Maruszyna Unit and possibly also the “southern” Haligovce development (Lipník Unit, see below) are tentatively regarded as lateral counterparts of the Kričovo Unit, sliced along the PKB-CWC boundary.

In the Slovakian Pieniny Mts., the large Haligovka Klippe occurs with a distinctive lithologic composition (Fig. 1B), forming spectacular cliffs, towering over Haligovce village. The Haligovce Unit is considered to be an analogue of the Manín Unit of western Slovakia, mostly on the basis of the Urgonian-type limestones, which are so characteristic for the Manín Unit. In addition, this view is confirmed also by the type of uppermost Cretaceous to Eocene strata of the Haligovce area. The Gosau-type succession of the Haligovce Unit (Fig. 3) includes variegated marlstones, *Orbitoides* and algal sandstones (Maastrichtian; Köhler and Buček, 2000), overlain by biogenic limestones with Thanetian large foraminifers and algal-coral patch reefs, and Paleocene–Lower Eocene carbonatic nummulitic conglomerates (lithologically similar to the Súľov Fm) interfingering with calcareous sandstones (Žilina Fm) with reef olistoliths (Matějka, 1963; Scheibner, 1968; Potfaj and Rakús in Janočko, 2000; Köhler and Buček, 2005). South of the Haligovka Klippe, at the contact with the CCPB formations, a narrow slice occurs that is formed of pelagic Upper Cretaceous to Eocene sediments, similar to those of the Maruszyna succession, described by Matějka (1963) as the “southern Hali-

govce Palaeogene development”. It is composed of variegated, calcite-poor shales with pebble mudstones, containing material from Paleocene reefs (Stráňík, 1967; Scheibner, 1968). On a preliminary basis, the authors regard this occurrence as an independent unit, related to the Maruszyna Unit on one side and the Kričovo Unit on the other. It is designated hereafter as the Lipník Unit, named after Lipník Brook in Haligovce village, where these sediments are exposed in numerous outcrops.

The easternmost occurrences of Fatric units (Križna Nappe *s.l.*) in the Western Carpathians are in the Humenské vrchy Mts. (south of Humenné town in Fig. 1B), as an inlier of Mesozoic strata among the sediments of the Central Carpathian Palaeogene Basin (CCPB), close to the southern PKB boundary in eastern Slovakia (Fig. 1B). The Humenné Unit consists of several post-Eocene, S-verging imbricated slices, composed of Mesozoic (Middle Triassic to Cenomanian) sediments (Jacko and Schmidt, 1994; Žec, 1997). The lithostratigraphy of the Jurassic to Lower Cretaceous strata closely match that of the Vysoká succession, i.e., a swell-type, partly shallow-marine development of the Fatric units, including Urgon-type limestones. The deep MLS-1 Podskalka borehole (Maheľ, 1986) encountered several slices underlain by the Upper Cretaceous to Palaeogene sediments, which were tentatively assigned to the Iňačovce-Kričovo Unit of the Penninic origin (Soták *et al.*, 1997). According to Soták *et al.* (1997), these circumstances are analogous to those of western Slovakia, where the SBM-1 Soblahov borehole drilled various Jurassic to Senonian complexes of unknown provenance below the Fatric Manín (or Belá) Unit (see above).

The eastern Slovakian exposures of the Fatric units occurring near the PKB are also accompanied by special types of Palaeogene sediments that are similar to those of the western Slovakian Myjava-Hričov Group in general and to the Domaniža succession with the Súľov Conglomerate in particular (Fig. 1B). These carbonatic conglomerates with material, derived from the CWC Fatric-Hronic nappe complexes, are exposed in close proximity to the PKB units on one side (e.g., the Chmeľov–Radvanovce area, where they contain also blocks of Paleocene reefs; Marschalko, 1975; Marschalko *et al.*, 1976), or are located above the CWC units on the other side (Humenské vrchy Mts.). The easternmost Slovakian exposures of the PKB (Podhorod' area, near the Slovakian-Ukrainian border) are from its southern side accompanied by the Beňatina succession (Leško, 1960; Leško and Samuel, 1968; Potfaj and Rakús in Žec, 1997), which includes Súľov-type carbonatic conglomerates, upwards interfingering with Middle Eocene variegated shales (Kružice Fm – Fig. 3).

UPPER PALAEOGENE TO LOWER MIOCENE DEPOSITS OF THE PIENINY KLIPPEN BELT AND ADJOINING ZONES

Strata of this sequence encompass the time interval from the late Middle Eocene (Bartonian) to the Early Miocene (Eggenburgian, i.e., early Burdigalian). After the late Lutetian break in sedimentation, a new Bartonian–Oligo-

cene sedimentary cycle is represented by the Podtatra Group (Gross *et al.*, 1984; Gross, 2008). It is the infilling of the extensive Central Carpathian Palaeogene Basin (CCPB), which ultimately covered most of the CWC area (Fig. 1). The CCPB is generally classified as a forearc basin that developed above the outer zones of the CWC Cretaceous thrust system, south of the PKB, i.e., inward with respect to the deforming EWC accretionary wedge (e.g., Tari *et al.*, 1993; Soták *et al.*, 2001; Kázmér *et al.*, 2003).

In the northern part of the Pružina-Domaniža-Žilina synform of the Middle Váh Valley, sediments of the Podtatra Group disconformably rest on the Lutetian Domaniža Fm (Mello, 2005, 2011) – Fig. 3; whereas further to the east their distinctly transgressive position above the Mesozoic complexes of the Hronic and Fatric nappes may be observed. The basal part is composed of carbonatic sandstones, conglomerates, breccias and nummulitic limestones of Bartonian–Priabonian age (Borové Fm). The overlying deepening-upward sequence is formed by the upper Priabonian–Lower Oligocene (lower Rupelian or Kiscelian) Huty Fm (Fig. 3). Its lower part includes predominantly calcareous, in part variegated shales, siltstones and fine-grained sandstones, then *Globigerina* marls, black manganese and calcite-poor shales, menilitic cherts, and finally siliciclastic sandstones and greywackes with layers of siltstones, mudstones and coarse-grained conglomeratic mass-flows (the Pucov and Tokáreň mbrs; Gross *et al.*, 1984; Soták, 1998; Janočko and Jacko, 1999; Soták *et al.*, 2007; Vojtko *et al.*, 2010; Starek *et al.*, 2012). During the late Rupelian, the basin was filled with extensive lobes of turbiditic sandstones (Zuberec Fm) and then with Chattian–Aquitainian (Egerian) thick-bedded to massive sandstones with subordinate conglomerates and claystone intercalations (Biely Potok Fm). Comprehensive overviews of the CCPB and its deposits can be found e.g., in Gross *et al.* (1984, 1993), Nemčok *et al.* (1996), Soták *et al.* (2001), Janočko (2002), Janočko and Elečko (2003), Gross (2008), and Soták (2010).

In a narrow anticlinal zone that follows from the SW trend of the neighbouring PKB between the towns of Stará Ľubovňa and Sabinov in NE Slovakia, a distinctive sedimentary complex, the Šambron Fm, is exposed (Figs 1B, 2). It is generally assigned to the CCPB. This is characterized by three megarhythms of thick bodies of polymict conglomerates and boulder beds, interbedded with distal turbidites that are dominated by dark shales and mudstones; the cumulative thickness is 800–1,400 m (Marschalko, 1975). Chaotic conglomerate/breccia debris flows, pebbly mudstones, slumps and olistolites indicate a high-energy depositional setting undergoing active deformation. The source area should have been a highly elevated subaerial zone, composed of crystalline basement and Mesozoic cover complexes of CWC affinity. Palaeocurrents indicate derivation of the clastic material from the NE to E (Marschalko, 1973, 1975; Marschalko *et al.*, 1976) and from the SE (Janočko *et al.*, 2003). Accordingly, the source area was located on the CWC edge in the vicinity of the PKB, but still to the south of it, since no material of PKB provenance was encountered in the pebbles. The conglomerates also contain clasts of Bartonian nummulitic limestones, recycled from the Borové Fm (Buček, 2001). The age of the Šambron Fm is problematic; Marschalko

(1973) and Soták *et al.* (2001) indicated a Bartonian–Priabonian age for it, while others (e.g., Gross, 2008) include the Šambron Beds in the Lower Oligocene Huty Fm.

Another phenomenon of this area, which is important from a palaeotectonic point of view, is the occurrence of serpentinitic sandstones (Soták and Bebej, 1996). These occur in a higher stratigraphic position than the Šambron Fm, in the Upper Oligocene part of the Huty Fm and/or the Zuberec Fm, which is composed of thin-bedded, “zebra” type turbidites (Soták and Bebej, 1996). Moreover, the whole Šambron-Kamenica Zone is exceptional with regard to the enormous amount of Cr-spinels in the heavy-mineral concentrates (up to 80%, Soták *et al.*, 1996). According to Lenaz *et al.* (2009), geochemically these spinels mostly represent the Alpine-type, ocean-island peridotites and basalts, while Spišiak *et al.* (2001) indicated their derivation from ophiolitic ultrabasites (both Iherzolites and harzburgites). Obviously, the eastward located source area must have included obducted or mélangé-type ophiolite complexes, which were tentatively correlated with an imbricated part of the Iňačovce-Kričovo Unit in the peri-Klippen zone (Soták and Bebej, 1996; Soták *et al.*, 1996). These authors designated the peri-Klippen part of the CCPB as the “perisutural” basin related to the Magura trench basin, whereas Leško and Varga (1980) correlated it directly with the “Ligurian” Peninic units, such as the (Iňačovce)-Kričovo and Szolnok units. Farther east in the Humenské vrchy Mts. area, the polymict Memík conglomerates of probably Upper Eocene–Lower Oligocene age also include a significant amount of serpentinite clasts (around 20%), which most likely were derived from the neighbouring Iňačovce-Kričovo Unit (Soták *et al.*, 1990, 1991).

Besides being drilled by several deep boreholes during exploration for hydrocarbons in the Lipany area (Nemčok *et al.*, 1977; Leško, 1983; Kullmanová and Rudinec, 1988; Rudinec, 1990), the Šambron Fm is exposed in a topographically and structurally elevated zone, known as the Hromoš-Šambron-Kamenica Zone (e.g., Nemčok, 1979; Plašienka *et al.*, 1998; Soták *et al.*, 2001). This is an intensely folded and imbricated, SWS-verging antiformal thrust stack (Plašienka *et al.*, 1998), which was driven by backthrusting of the Magura Krynica Unit that affected also the PKB structure in this area during the Early–Middle Miocene (Plašienka and Mikuš, 2010; Plašienka *et al.*, 2013). Owing to backthrusting, the Šambron Fm was exhumed from considerable depths of at least 5 km (Soták *et al.*, 1996, 2001; Biroň *et al.*, 2000a; Hrušický *et al.*, 2001). It might be inferred that the Šambron coarse clastics do not represent part of the CCPB Podtatra Group, but form an upper structural stage of the Maruszyna-Lipník-Šambron-Kričovo Unit (Šambron-Kričovo Belt *sensu* Grecula *et al.*, 1981), which was later covered by the Oligocene Huty and/or Malcov fms (see Fig. 1B). In an analogous position, conglomerate-rich deposits similar to the Šambron Fm occur also in the southern proximity of the PKB in the Pieniny Mts. (Szaflary Beds in Poland). Being affected by backtilting-backthrusting, the Szaflary Beds are also distinctively deformed in that area (the “peri-Pieniny flexure” of Mastella, 1975).

In addition to the Šambron conglomerates, the rugged, tectonically controlled morphology during the Late Eocene

transgression is demonstrated also by numerous bodies of subaerial and subaqueous mass flow, namely conglomerates and breccias scattered around the CCPB (locally known as the Pucov, Terchová, Markušovce, Tokáreň, or Vajsková conglomerates). These are related to the development of alluvial-fan deltas and hyperpycnal flows, supplied by short feeder systems from small drainage areas that were steep and of variable relief (Starek *et al.*, 2012, 2013).

A further upper Palaeogene complex related to the PKB in eastern Slovakia was known as the “Ujak facies” development or series (Matějka, 1959; Stránik, 1965; Oszczytko *et al.*, 2005), or the “Ombron Group” (Nemčok *et al.*, 1990), more recently redefined as the Údol succession (Plašienka and Mikuš, 2010 – Figs 1B, 2, 3). Formerly, the Middle Eocene variegated, calcite-poor shales also were assigned to it, which the authors now consider to belong to an older, Lower Palaeogene sedimentary cycle. The Údol succession includes the Upper Eocene to Lower Oligocene *Globigerina* marls and menilitic shales, and the Oligocene marly shales with turbiditic sandstones and pebbly mudstones (Malcov Fm). The Údol succession unconformably overlies different units of the PKB and forms an interconnecting element between the coeval flysch-dominated sedimentary basins of the EWC Flysch Belt and the CCPB of the CWC (Oszczytko *et al.*, 2005; Plašienka and Mikuš, 2010). Importantly, numerous authors noticed that deposition of Upper Eocene strata over the PKB units was preceded by strong tectonic deformation of the latter, which was designated as the “Illyrian” or “Pyrenean” phase (e.g., Stránik, 1965; Leško and Samuel, 1968; Nemčok, 1971). Nevertheless, the Údol succession, together with the underlying PKB and adjacent zones of the CCPB and Magura unit, was also affected by intense post-Oligocene deformation (Plašienka *et al.*, 1998, 2013).

Relics of deformed Eggenburgian (lower Burdigalian) conglomerates, sandstones and claystones occur in several places adjacent to the PKB – Figs 1, 2, 3). In the westernmost area, around the Branč Castle near Myjava, these sediments seal the nearly vertical imbricated structures of the underlying PKB units, but still they were tilted and partly involved as lenses in a strike-slip shear zone along the northern PKB boundary. Similarly in the Middle Váh Valley, the Lower Miocene sediments of the Trenčín and Ilava depressions were involved in the latest stages of deformation together with the underlying units of the peri-Klippen zone. In eastern Slovakia, the comparatively thick Eggenburgian deposits (Prešov and Čelovce fms) also unconformably overlie the folded CCPB sediments. They developed in pull-apart basins along the boundary between the PKB and the East Slovakian Neogene Basin (Kováč *et al.*, 1995; Baráth *et al.*, 1997) and were later moderately, but clearly deformed by additional backthrusting of the PKB and Magura units during the late Early–Middle Miocene.

In the northern proximity of the Pieniny sector of the PKB, the Lower Miocene deposits occur in a piggyback position above the Palaeogene strata of the EWC Magura Nappe (Cieszkowski, 1992; Kremná Fm – Oszczytko *et al.*, 2005; Fig. 2). Along a steep fault contact, the Miocene sediments are immediately adjacent to the PKB units there. According to Oszczytko and Oszczytko-Clowes (2010,

2014), the Kremná Fm occurs also in tectonic windows within the PKB of the Małe Pieniny Mts. This information would indicate a very young, late Early to Middle Miocene age for the final thrusting along the eastern PKB – Magura interface. Recently, it was documented that also some typical deep-marine clastic “flysch” formations (e.g., the Magura Fm), considered for decades to be Eocene–Oligocene, are at least partly of Lower Miocene age (Oszczytko-Clowes *et al.*, 2013).

INTERPRETATION – PRINCIPAL EVOLUTIONARY PHASES OF THE LATE CRETACEOUS–PALAEOGENE BASINS OF THE PIENINY KLIPPEN BELT AND SURROUNDING ZONES

Depositional phases and palaeogeography of the Gosau basins

The most complete “Senonian” through Eocene successions of the Gosau-type basins are exposed in the northern part of the Malé Karpaty Mts. and in the Manín-Klape Belt of the Middle Váh Valley and adjacent CWC zones to the south. In general, seven sedimentary sequences, which represent the development phases of the Gosau basins, can be distinguished there (Fig. 5).

Phase I (latest Turonian?–Coniacian–Early Santonian, ca. 90–85 Ma). The sequence includes pre-transgressive freshwater limestones and breccias, then continental and marine basal carbonate-dominated or polymict conglomerates (Rašov Fm, Valchov Mb), followed by hemipelagic marls, olistostromes with a littoral fauna and reef bodies, and calcareous turbidites (Ostriež Fm).

Phase II (Late Santonian to Middle Campanian, ca. 85–75 Ma). Terrigenous and shallow-marine biogenic sources gradually became inactive and instead variegated hemipelagic marlstones of the *couches rouges* facies were deposited (Púchov, Hrabové and Košariská fms).

Phase III: (Middle Campanian to Cretaceous/Palaeogene boundary, ca. 75–65 Ma). Sediments are represented by neritic marls, shallow-water bioclastic limestones, tempestites, calcareous sandstones and conglomerates with exotic pebbles and blocks of rudists-bearing bioherms (Ihrište, Bradlo and Hradisko fms).

Phase IV (Danian to early Ypresian (ca. 65–50 Ma). The lower, Danian part of this stage is poorly reflected in the sedimentary record, partly not present at all (a gap due to emergence or eroded later), partly composed of terrestrial conglomerates. The Selandian–Ypresian time span is first of all characterized by shallow-marine deposits, rich in coarse terrigenous material (Jablonové Fm) and more frequently by fragments of destroyed biogenic build-ups (Kambühel reefs).

Phase V (late Ypresian–Lutetian (ca. 50–40 Ma). The base of this new transgressive cycle involves coarse-grained carbonate breccias and conglomerates with blocks of reef limestones of the upper Ypresian to lower Lutetian Súľov Fm, which are followed by calcareous turbiditic sandstones and bathyal variegated claystones (Domaniža Fm). Loose ends of an analogous basin occur also along the SW margin of the eastern Slovakian PKB.

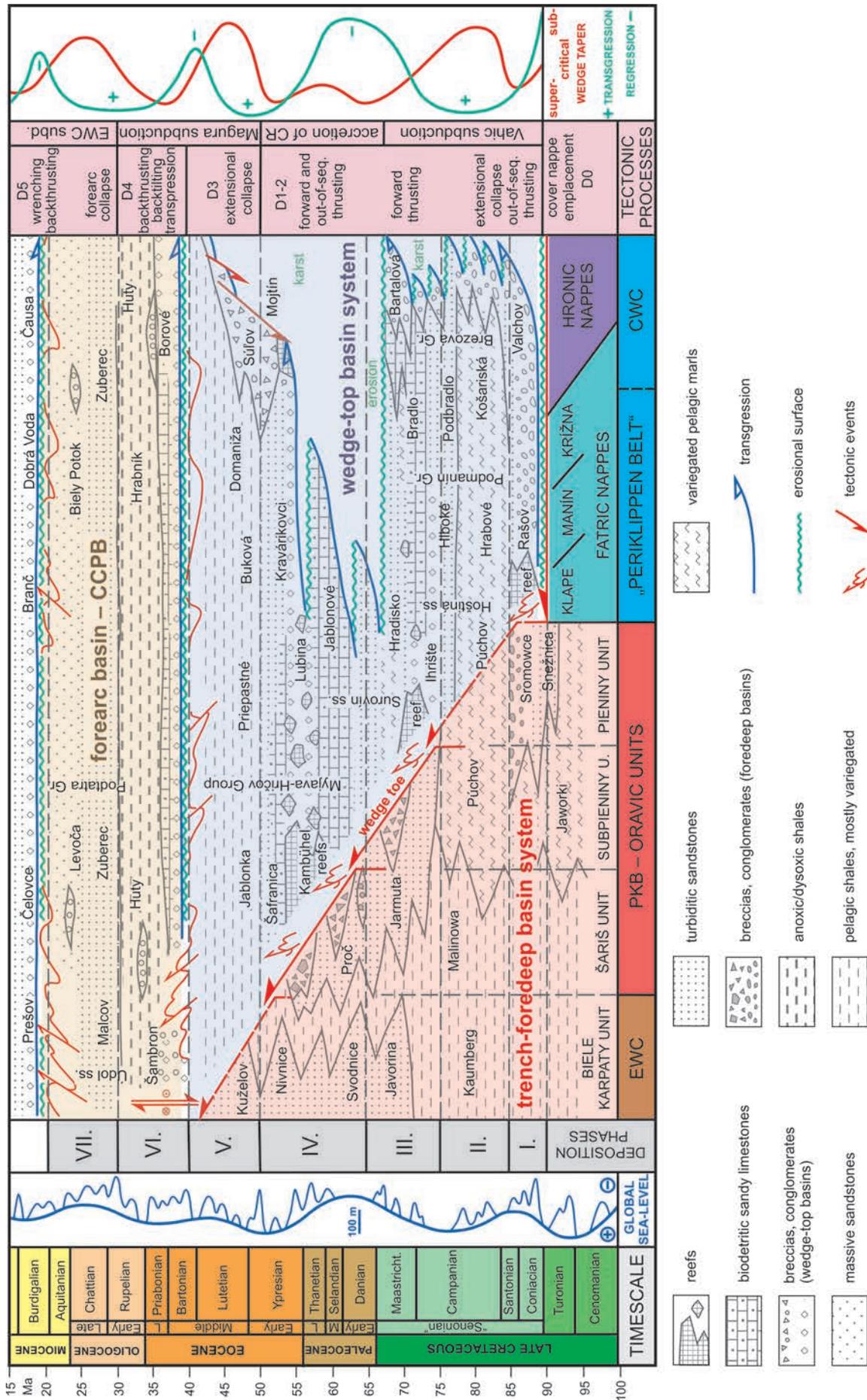


Fig. 5. Synopsis of sedimentary and tectonic evolution of Upper Cretaceous to Lower Miocene sedimentary complexes, connected to the PKB and adjacent zones. The scheme combines data from western and eastern Slovakia. Names denote the indicative lithostratigraphic units described in the text. Note that the Vahic and related units are not considered in this scheme (see Plašienka, 1995a, b, 2012a). The sea-level curve is according to Haq *et al.* (1988). CR – Czorsztyn Ridge.

Phase VI (Bartonian to early Rupelian (40–30 Ma). After the upper Lutetian gap, a new transgressive cycle is represented by a sequence of continental to shallow-water calcareous clastics and nummulitic limestones (Borové Fm) at the base of the extensive Central Carpathian Palaeogene Basin (CCPB), which ultimately covered most of the CWC area. The northern periphery of the CCPB underwent strong subsidence and massive input of coarse-grained terrigenous material (Šambron Fm). During the late Priabonian–early Rupelian starved, dysoxic to anoxic basins (Huty Fm, menilitic shales) were influenced by the input of occasional bodies of coarse mass-flow debrites, derived from the basin margins (Pucov Mb).

Phase VII: late Rupelian to Aquitanian (late Kiscelian–Egerian; ca. 30–20 Ma) – the terrigenous input into the CCPB increased gradually, but considerably and the basin was probably overfilled during the earliest Miocene (Zubrec and Biely Potok fms). However, the CCPB represented by the stages VI and VII is not considered as a constituent of the Gosau basin system and will not be treated in detail here, since the CCPB as a forearc-type basin corresponds to a new, fully independent evolutionary stage of the entire Western Carpathians with a geodynamic background different from the Coniacian–Lutetian Gosau basins.

It is inferred that these sedimentary sequences correspond to the growth phases of synorogenic basins developing in a convergent regime that was controlled by far-field tectonic stresses and local deformation stages in concurrence with the sea-level fluctuations. This concept is based on the following symptomatic features: a) the start of the Gosau-type deposition at the Turonian/Coniacian boundary means construction of a completely new basin system in the wedge-top area, as revealed for instance by an abrupt change in the palaeocurrent directions of gravity flows in comparison with the underlying mid-Cretaceous turbiditic systems (Manín-Klape zone – cf. Marschalko, 1986); b) coarse basal clastics of each transgressive cycle contain only local material, including e.g., the “exotic” pebbles redeposited from the mid-Cretaceous conglomerates of the Klape unit, or Urgonian limestones in the Manín zone; c) scattered, but frequent blocks of bioherms (Coniacian–Santonian, Maastrichtian, Thanetian–Ypresian), which are coeval with or slightly older than the host mass-flow deposits, point to a transient presence of marginal reefs that were destroyed or drowned during processes of basin evolution; d) the evolutionary stages of the Gosau basins distinguished above are arranged into transgression-subsidence-regression cycles that were supposedly controlled mainly by the structural development of the underlying orogenic wedge.

Important clues about the palaeogeography of Gosau basins come from the provenance studies of clastic material and heavy-mineral spectra. Petrofacies analysis of Upper Cretaceous sandstones and conglomerates of the Klape-Manín zone was performed by Marschalko (1986; Marschalko and Kysela, 1980). Quartz-carbonate lithic arenites contain important amount of calcareous littoral biodebris, while conglomerates are classified as “exotic”, i.e., containing a large quantity of various sedimentary, metamorphic and magmatic rocks of uncertain provenance (for review see e.g., Mišík and Sýkora, 1981; Mišík and Marschalko,

1988; Mišík and Reháková, 2004). In addition, the conglomerates contain blocks of older mid-Cretaceous conglomerates and Turonian neritic Orlové sandstones with oyster banks, as well as carbonate clasts of local origin, including synchronous, reef-derived clasts and Urgon-type limestones in the Manín zone (Marschalko, 1986). Already Birkenmajer (1988), in part Salaj (1990) and later also Plašienka (1995a, 2012a) proposed a recycling model of “exotic” pebbles in the Senonian and Palaeogene conglomerates, whereby most of their material was resedimented from mid-Cretaceous conglomerates of the Klape Flysch. A slightly higher proportion of carbonate clasts, compared to the older conglomerates, is explained by newly added clasts of mostly Maiolica-type limestones. According to the authors own observations, the Coniacian–Santonian Rašov conglomerates of the Klape-Manín zone are bimodal, mixed from two distinct, though still local sources. Unlike the perfectly rounded redeposited “exotics”, the newly added limestone clasts are smaller in size and subangular, indicating transport of relatively short duration (Fig. 6B).

Comprehensive information about the composition and provenance of heavy minerals is available from the clastic formations of the Eastern Alpine Gosau basins (e.g., Wagneich and Faupl, 1994; Winkler, 1996; Wagneich, 2001). Recently, Stern and Wagneich (2013) summarized data from the eastern part of the NCA, from the subcrop of the Vienna Basin and from its eastern margin in the northern Malé Karpaty Mts. (Brezová-Myjava succession). As well, they provided new detailed information about the mineral chemistry of garnet, chrome spinel and tourmaline across various lithostratigraphic successions of the Gosau basins. In general, the Lower Gosau Subgroup of the Giesshübl, Glinzendorf, Grünbach and Studienka synclines is dominated by chrome spinels, derived from harzburgite-type peridotites, while the garnets contain increased content of pyrope and grossularite molecules and are interpreted as representatives of the metamorphic soles of obducted ophiolite nappes in the inner NCA zones. Starting from the Campanian, the Upper Gosau Subgroup exhibits an abrupt decrease of ophiolite-derived material to a total lack of it in the Palaeogene formations, and an increase in the proportion of almandine-rich garnets coming from low- to medium-grade metamorphic zones, exhumed in the central Austroalpine basement zones (Stern and Wagneich, 2013). However, this distinct trend is only partly discernible in the Brezová-Myjava area, where the heavy-mineral assemblages are impoverished, with a dominant stable zircon-rutile-tourmaline association, and particularly with a high tourmaline content (Salaj and Priečovská, 1987; Wagneich and Marschalko, 1995). Garnets are rare in the lower part and then increase upsection, while chrome spinels are variably present up to the Paleocene, though generally decreasing in amount upwards. A high ZRT index and partly well rounded grains indicate a possible contribution of recycling from the underlying mid-Cretaceous clastic formations (Klape Flysch), including the chrome spinels (Salaj and Priečovská, 1987).

Unfortunately, few data about the heavy-mineral composition are available from the Gosau complexes in the Middle Váh Valley. Wagneich and Marschalko (1995) reported a high chrome spinel content (up to 65%), smaller amounts

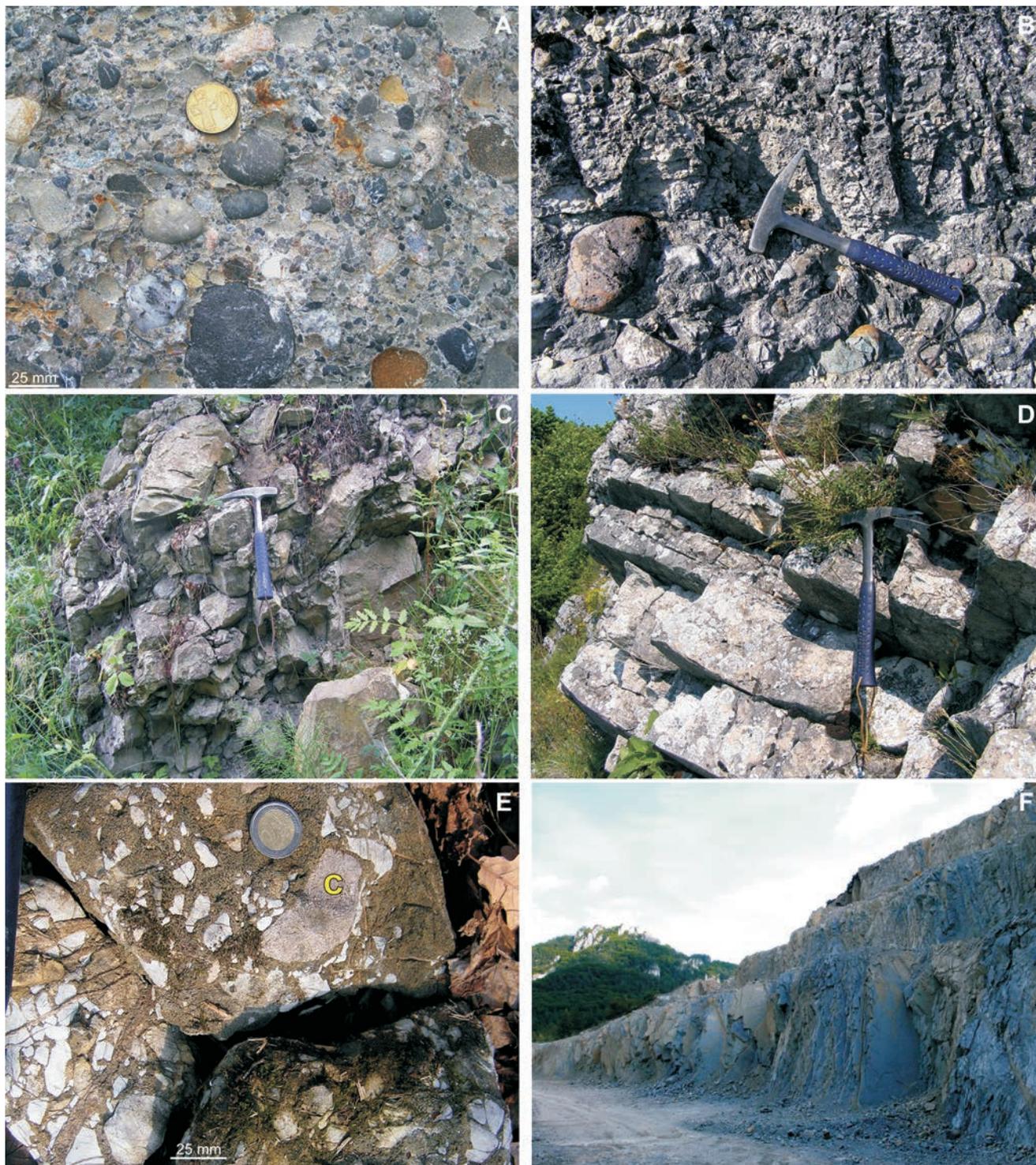


Fig. 6. Field photographs of some formations mentioned in the text. **A.** “Exotic” conglomerate of the Sromowce Fm (Santonian, Oravic Pieniny Unit, Oravský Podzámok village, Orava region) with siliciclastic sandy matrix. **B.** Conglomerate of the Rašov Fm (Coniacian–Santonian, Gosau Supergroup, Hoštiná Succession, Holiš Hill above Nimnica village, Middle Váh Valley); note its bimodal composition with scattered, perfectly rounded large “exotic” pebbles and smaller subangular carbonate clasts, the sandy matrix is rich in calcareous biogenic detritus. The next pictures are arranged in a way to compare the foredeep deposits (left column) with the coeval wedge-top basin sediments (right column). **C.** Gregorianka Breccia Mbr of the Jarmuta Fm (Maastrichtian?, Oravic Subpieniny Unit, Gregorianka – Hlboký potok Creek near Jarabina village, eastern Slovakia), angular clasts are composed of the Maiolica-type limestones. **D.** Sandy-bioclastic limestones, Široké Bradlo Mbr of the Bradlo Fm (Late Campanian–Maastrichtian, Brezová Group, Bradlo-Hrombaba Hill, Brezovské Malé Karpaty Mts.). **E.** Polymictic sandy breccia of the Proč Fm (Paleocene?, Šariš Unit, Vršatec Klippen area); angular clasts are dominated by the Maiolica-type limestones, c – clast of Jurassic crinoidal limestone. **F.** Calcareous sandstones and fine-grained conglomerates of the Jablonové Fm (Thanetian, Myjava-Hričov Group, quarry near Jablonové village, Middle Váh Valley); in the background rock cliffs built by carbonate conglomerates of the Súľov Fm (Ypresian–Lutetian). All photos by D. Plašienka, except for F, taken by J. Bučová.

of garnets and traces of blue amphiboles from the Campanian turbidites in the Klape zone. The “Senonian” deposits of the Manín zone show ubiquitous chrome spinels, upward increasing garnet content and some chloritoid in addition to the stable zircon-tourmaline-apatite assemblage. Since the underlying and neighbouring Albian–Turonian Klape Flysch complexes are very rich in chrome spinels (Jablonský *et al.*, 2001), it cannot be excluded that they were largely redeposited into the “Senonian” sediments, along with some blue amphiboles. The garnets might have been derived, as in the Alps, from exhuming Eoalpine metamorphic complexes in the inner CWC zones (Veporic metamorphic complex – cf. Janák *et al.*, 2001; Jeřábek *et al.*, 2012). Their chemistry is not known, however.

Foreland basin classification and evolution

In terms of the foreland basin typology introduced by DeCelles and Giles (1996), the Western Carpathian Gosau-type piggyback basins may be regarded as “wedge-top” depozones that developed inboard the actively deforming orogenic wedge composed of the frontal CWC elements. By definition, wedge-top basins are characterized by coarse alluvial and fluvial deposits laid down in subaerial settings, or marine fine-grained shelf sediments, mass flows to deep-water clastics and hemipelagites near the conjunction with the trench or foredeep. The trench-foredeep and wedge-top basin system taper onto both the foreland area and the hinterland orogenic wedge (DeCelles and Giles, 1996). Furthermore, wedge-top basins are characterized by frequent unconformities, soft-sediment deformation and growth structures related to the deformation regimes operating in the underlying wedge. All these features can be recognized in the Gosau basins that developed along the outer CWC margin during the Late Cretaceous and early Palaeogene. However, the particular structural mechanisms operative during piggyback basin formation might have been different to some extent along the strike of the accretionary wedge. For instance, Ortner (2001) described the Gosau Muttekopf Basin in the western NCA part as a typical compressional growth basin, which developed in response of active thrusting within the underlying fold-thrust belt of the NCA (Ortner, 2003). On the other hand, most of the Lower Gosau basins in the central and eastern NCA developed as pull-aparts controlled by the dextral transpression/transension tectonic regime, triggered by oblique subduction of the Penninic Ocean (Wagreich, 1993, 1995; Wagreich and Decker, 2001). Taking into account structural data from the Middle Váh Valley, the Western Carpathian Gosau basins share some characteristics of both of these basin types.

In general, the triangular depression generated by flexural downbending of the lower plate in front of the advancing orogenic wedge is termed trench, if developed on oceanic crust, and foredeep, if formed on foreland continental crust. In the case under consideration, both of these types of frontal depression originated sequentially: first the trench trough during subduction of the Vahic oceanic lithosphere in front of the CWC orogenic wedge (e.g., the Belice Unit), then the prograding foredeep developed in fronts of Oravic thrust sheets that were serially detached from an intra-oceanic continental frag-

ment, and finally a new trench resulted from subduction of the Magura Ocean. Thus, for the sake of simplicity, the authors mostly use the combined term trench-foredeep.

The trench setting is characterized by clastic sedimentation with a thickening-and-coarsening-upward trend, as the trench depocentre deepens and approaches the tip of the upper plate accretionary wedge that supplies the trench with progressively more coarse erosional debris. The clastic material is transported to the trench by various types of gravity flow and redistributed along the trench axis, usually by turbidity currents forming the typical “flysch” deposits. Subsequently, depending on the local conditions, the trench sediments are either partly detached and accreted to the wedge tip, or underplated below the wedge. Occasionally, the trench deposits may be subducted completely, especially if they are comparatively thin, owing to a deficiency of clastic material.

The term foredeep is most commonly used for flexural depressions developing during the closing stage of orogenesis, when thick and strong foreland continental lithosphere collides with the orogenic wedge. As convergence ceases, the foredeep deposits become increasingly shallow-water and eventually continental, as seen in the transition from “flysch” to “molasse” in classical concepts (e.g., the Molasse Zone of the Alps). However, this cannot be applied in situations when only a small continental fragment is accreted to the orogenic wedge (e.g., the Oravic continental ribbon, or the Briançonnais domain), or when shortening affects intracontinental extensional basins. In these circumstances, the foredeep deposits, along with parts of the underlying pre-orogenic successions, are deformed as they are detached from their underthrusting basement substratum and accreted to the advancing orogenic system. Consequently, no distinct shallowing is observed and the synorogenic sediments correspond rather to trench-type deposits.

In the Western Carpathians, the coupled peripheral trench-foredeep (lower plate) and wedge-top (upper plate) basin system in the sense of DeCelles and Giles (1996) can be recognized for the entire Late Cretaceous–Palaeogene period (Fig. 5). The first couple (**Phase I**) is represented by the Coniacian–Santonian basins (ca. 90–85 Ma), the peripheral foredeep with the Snežnica and Sromowce fms and the Belice trench basins that developed as the synorogenic depocentres of the later Pieniny Unit and Belice Unit, respectively, while the wedge-top, piggyback basin with the typical, conglomerate-dominated Valchov and Rašov fms occupied the upper plate position on top of the frontal parts of the prograding orogenic wedge. Nevertheless, both positions share some analogous features, for example, conglomerates composed of local – intrabasinal material, typically recycled from the mid-Cretaceous “exotic” formations of the Klape Unit (the Sromowce, Rašov and the lower part of the Horné Belice fms), or carbonatic when transgression reached the innermost CWC zones, rich in Triassic carbonates (Hronic units – Valchov Fm). However, important differences also exist – the Rašov-type conglomerates are rich in shallow-marine bioclastic material, including rudist reef bodies, which are virtually absent from the foredeep conglomerates of the same age (cf. Fig. 6A, B). This difference obviously resulted from different positions within the convergent zone and separated accommodation areas: deep-wa-

ter turbiditic clastic fans or aprons with coarsening-upward debrites in the case of peripheral trench-foredeep, *versus* a system of shallow-marine, fining-upward, probably narrow wedge-top depressions rimmed by short-lived bioherms. Also the palaeocurrent directions are opposite outward, indicating the existence of an elevation between the foredeep and wedge-top basins, which provided the coarse clastic material, including the resedimented “exotics”. This damming elevation, which was at least partially subaerial, is interpreted as the frontal imbricated thrust stack of the prograding and actively deforming wedge, or as a ramp anticline of the thin-skinned fold-thrust system.

During the Late Santonian–Early Campanian (**Phase II**, 85–75 Ma), the wedge-top basins subsided, clastic sources were flooded, biogenic build-ups were drowned and the input of bioclastic, as well as terrigenous material ceased. Instead, mostly red pelagic marlstones (CORB) were deposited. Besides the global sea-level rise, gravitational collapse of the overthickened accretionary wedge might have contributed to the excess subsidence of the wedge-top basins. The clastic input was reduced also in the remnant Belice lower-plate trench basin and came to an end in the Pieniny foredeep basin. In the foreground Oravic zones, only distal sandy turbidites were intercalated with hemipelagic marlstones in the Czorsztyn Ridge area (later Subpieniny Unit), while the Šariš sedimentary area subsided below the CCD and was almost devoid of clastic supply (Malinowa Fm).

The next **Phase III** embraces the time period from the mid-Campanian to the Cretaceous/Palaeogene boundary (75–65 Ma). In the wedge-top basins, this regressive sequence started with a renewed input of clastic material, either recycled from older polymict sandstones and conglomerates, or newly added biodetritic material from intrabasinal sources. The Upper Campanian to Lower Maastrichtian strata are rich in conglomerates, calcareous sandstones, bioclastic limestones and resedimented bioherms. The original positions of the latter are unknown, but SE-oriented palaeocurrent vectors of calcareous turbidites in the Manín zone (Marschalko and Kysela, 1980) indicate that they should have been located in the Klape zone or along its northern margin. The wedge-top basin with the typical Bradlo and Ihrište fms is coupled with the concomitant complexes of the foredeep basin of the later Subpieniny Unit, which is first of all represented by calcareous turbidites and tectono-sedimentary breccias of the (Jarmuta Fm, Gregorianka Breccia). Unlike the wedge-top basin system, shallow-marine biogenic detritus is very scarce there. Instead, clastic material derived from the overriding Pieniny-Fatric thrust system, now representing the developing thrust wedge, is present (cf. Fig. 6C, D). Accordingly, the wedge-top and foredeep basins of the convergent system were again separated by a subaerial(?) structural high, composed of frontal imbricates of the Pieniny Nappe. The inner (southern) side of this elevation probably was rimmed by the shallow-marine biostromes and bioherms that provided bioclastic detritus for the wedge-top Gosau basins to the SE. The more distant foreland areas (later Šariš and Biele Karpaty-Magura units) subsided considerably during the Senonian to abyssal depths, characterized by non-calcareous sedimentation of oceanic red-beds (Kaumberg and Malinowa fms). During the latest

Cretaceous, the temporary, but widespread inversion of the EWC (Flysch Belt) basins is indicated by the massive input of clastic material distributed in extensive systems of Upper Campanian to Paleocene turbidite fans. Their terrigenous clastic material was derived either from the hinterland CWC orogenic wedge, or from the foreland intrabasinal structural highs, such as the Silesian Ridge (for review see e.g., Oszczytko, 1992, 2006; Picha *et al.*, 2006). During the Maastrichtian, the remnant Vahic oceanic basin was closed, as indicated by the coarse, chaotic, trench-type deposits of the Belice Unit directly overridden by their sources, basement-cover complexes of the Tatric Inovec Nappe (Plašienka *et al.*, 1994; Putiš *et al.*, 2008; Plašienka, 2012a).

The Paleocene–Early Eocene **Phase IV** (65–50 Ma) is dominated by shallow-marine deposits again, particularly by reef buildups of mainly Thanetian age in the wedge-top basins. The Lower and Middle Paleocene deposits are mostly missing; probably they were eroded before the strata of the fourth cycle were deposited. There also is evidence of emergence, erosion and karstification. (e.g., Salaj, 2002; Mello, 2011). As in the previous stages, reefs occur only as redeposited fragments, as olistoliths in calcareous turbidites and as slump bodies. This would indicate active compressional tectonics, whereby the ephemeral marginal reefs were destroyed soon after they came into being. Contemporaneously, the peripheral foredeep migrated outwards into the Proč basin of the later Šariš Unit, which was supplied with clastics derived from the frontal elements of the overriding Subpieniny Nappe and the piggyback Pieniny Unit (cf. Fig. 6E, F). Deposition of the Proč Fm terminated during the Lower–Middle Eocene, as a consequence of being overthrust by the higher Oravic nappes.

In **Phase V** (ca. 50–40 Ma), the wedge-top system subsided to bathyal depths and eventually below the CCD, as evidenced by the prevalent deposition of calcite-poor variegated shales during the Lutetian (Jablonka, Priepastné and Domaniža fms). The same process of subsidence and decrease in clastic input occurred also in the EWC basins (e.g., the Beloveža Fm – cf. Fig. 2). Ultimately, the Lutetian deep sea covered large areas of the PKB, including the peri-Klippen zone and the outer CWC zones. Owing to normal faulting and the formation of steep fault scarps, the inner marginal zones of this pelagic basin were fed with large amounts of unsorted, Súľov-type carbonatic material derived from the Triassic complexes of the Hronic units. These deposits are dominant in the Middle Váh area, but occur also eastwards all along the PKB, up to Ukraine.

During the Middle Eocene, the sequential accretion of the EWC thin-skinned thrust sheets was initiated. During the initial stage, nappes of the Biele Karpaty Superunit were stacked and overthrust by the PKB units. Subsequently, during the Late Eocene and Oligocene–Egerian, all other units of the Magura and later also the Silesian-Krosno superunits were progressively included in the growing EWC accretionary wedge. In the meantime, the hinterland CWC region collapsed and subsided to create the extensive and deep CCPB. This is tectono-sedimentary **Phase VI**, which begins with transgressive carbonate clastics and shallow-marine bioclastic limestones of Bartonian–Priabonian age (Fig. 5). Then, during the Oligocene, the basin subsided

rapidly to be filled with shales and mudstones, indicative of poorly oxygenated conditions. The Oligocene, up to lowermost Miocene sequence exhibits an upward increase in the amount of mixed siliciclastic-calclastic input (**Phase VII**). The upper-plate position, large areal extent covering almost the entire CWC, extensive subsidence with up to 5,000 m of mostly deep-water sediments, as well as an extraordinary quantity of deposited clastic material make this basin a distinctive feature of the Western Carpathians, which has no analogues in other segments of the European Alpides. Consequently, a special crustal-scale process allowing exceptional subsidence must have operated during the opening and evolution of this basin. It was crustal thinning, either as a corollary of subcrustal erosion (e.g., Kázmér *et al.*, 2003), or more probably due to the extensional collapse of the overthickened CWC crust and the pull of the retreating subduction of the EWC oceanic lithosphere.

DISCUSSION – GEODYNAMIC BACKGROUND AND TECTONIC MODEL OF THE “SENONIAN”–PALAEOGENE– EARLY MIOCENE BASINS OF THE PIENINY KLIPPEN BELT AND ADJOINING ZONES

Meso-Alpidic tectonic evolution of the Western Carpathians – principal events

The tectonic evolution of the Late Cretaceous–Palaeogene basins and their deposits is closely related to the development of the Western Carpathian orogenic wedge. The history of the foundation and evolution of the Western Carpathian orogenic system, as described e.g., by Plašienka *et al.* (1997), Froitzheim *et al.* (2008) and Putiš *et al.* (2009), began by collisional events after the closure of the Neotethyan Meliata Ocean in southern Carpathian zones during the Late Jurassic (160–150 Ma). After an episode of retro-wedge activity (present Internal Western Carpathians) during the latest Jurassic–earliest Cretaceous, the pro-wedge of the CWC grew by progradational stacking of the basement and cover thrust sheets throughout the Cretaceous. The stacking process started by thrusting of the Gemeric thick-skinned sheet in superposition over the Veporic basement-cover complexes during the Early Cretaceous (Lexa *et al.*, 2003; Jeřábek *et al.*, 2012; ca. 140–120 Ma – Hurai *et al.*, 2008). By mid-Cretaceous times (110–90 Ma), shortening transferred to the Veporic/Fatric interface, whereby the attenuated Fatric crust underplated the Veporic wedge, whilst the Fatric sedimentary cover was detached and thrust over the foreland Tatric basement and cover during the Late Turonian (ca. 90 Ma – Plašienka, 2003; Prokešová *et al.*, 2012). During the Late Cretaceous and Early Palaeogene (80–50 Ma), the overthickened supra-Veporic thrust stack collapsed by orogen-parallel extension to exhume the Veporic metamorphic dome (cf. Janák *et al.*, 2001; Jeřábek *et al.*, 2012; Vojtko *et al.*, 2013).

Following the Late Turonian (ca. 90 Ma) emplacement of the Fatric and subsequently also the Hronic nappes, shortening relocated to the northern Tatric edge. It was in-

ferred that the frontal elements of the Fatric cover nappes (Klape, Manín, Drietoma) glided beyond the northern Tatric edge in superposition above the oceanic Vahic (South Penninic) crust (Plašienka, 1995a, b, 2012a). During its Late Cretaceous subduction, these frontal Fatric and Hronic nappes behaved as a “false” accretionary complex, being affected by out-of-sequence thrusting and imbrication with the underlying Vahic complexes and overlying Gosau sediments of the wedge-top basins. The Vahic subduction probably commenced between the latest Turonian and the Santonian and continued at least until the Maastrichtian in Western Slovakia, where it was terminated by collision with the Oravic Czorsztyn Ridge in an intra-Penninic position (Belice Unit – Plašienka *et al.*, 1994; Plašienka, 2012a). Accordingly, the Vahic subduction lasted in the time span approximately between 90–85 and 70–60 Ma, similar to the subduction of the South Penninic Piemont oceanic domain in the Eastern Alps (Arosa Zone, Platta Nappe, Matrei Zone, Ybbsitz Klippen Belt, Kahlenberg Nappe; see Schnabel, 1992; Homayoun and Faupl, 1992; Faupl and Waggreich, 2000; Kurz *et al.*, 2001; Schmid *et al.*, 2004; Froitzheim *et al.*, 2008; Handy *et al.*, 2010). However, data from more eastern areas indicate that the eastward prolongation of the South Penninic oceanic zones (Iňačovce remnant basin) remained unlocked until the Eocene (Soták *et al.*, 1994, 2005). This information and structural data from western Slovakia indicate an oblique dextral collision between the CWC system and the Czorsztyn Ridge. Supposedly, the Oravic domain, as an elongated continental ribbon centred by the Czorsztyn Ridge, was oriented NW–SE to W–E (e.g., Picha *et al.*, 2006; Golonka *et al.*, 2000; for an alternative view see Aubrecht and Túnyi, 2001; Golonka *et al.*, 2006). On the other hand, the outer, eastward convex oroclinal arc of the CWC was stretching in a roughly N–S direction (e.g., Csontos and Vörös, 2004; Grabowski *et al.*, 2010) and moved to the north to NW, in unity with the buttressing Adria microplate (e.g., Handy *et al.*, 2010). As a result, their encroachment was propagated from west to east, causing a dextral transpression within the collision zone during the Palaeogene (cf. Fig. 9). As a result, an eastward-opened oceanic remnant basin was left for continuing deposition in the later Iňačovce and Kričovo units (see Soták *et al.*, 1994, 2005) and presumably also in its westward wedging-out extension, the combined Maruszyna-Lipník-Šambron unit. In this interpretation, the Vahic (Belice), Maruszyna-Lipník-Šambron-Kričovo and Iňačovce units are all representatives of the Carpathian Upper Penninic units, derived from the eastern branch of the Ligurian-Piemont Ocean (Alpine-Carpathian Atlantic *sensu* Missoni and Gawlick, 2011).

After the incipient collision following the closure of the Váh Ocean in the present western Slovakian area, deformation and thrusting of Oravic units commenced by the latest Cretaceous and continued until the mid-Eocene (Fig. 5). As argued previously, foreland-propagating sequential thrusting is recorded as the synorogenic, progressively coarsening-upward clastic sediments, supplied by material eroded from the overriding thrust-sheet toes (Plašienka and Mikuš, 2010; Plašienka, 2012a).

In contrast, the Late Cretaceous to Middle Eocene Gosau basins developed as wedge-top depressions in con-

junction with post-emplacment imbrication and subsequent extensional events within the CWC Klape-Manín nappe system, acting then as an accretionary wedge. The seven sedimentary sequences of the Gosau-type basins distinguished above persisted for about 5 to 15 Ma each, but the cyclicity seen in them did not entirely coincide with the global eustatic sea-level fluctuations (Fig. 5). For instance, there is a good positive correlation between the Campanian eustatic sea-level rise and the inferred contemporaneous wedge-top collapse and coastal onlap (Phase II). The cumulative effect of these two simultaneous, but unrelated processes brought about intense subsidence and open-marine hemipelagic sedimentation of variegated, CORB-type deposits. Correlation between the sea-level lowstand and partial emergence and erosion of the wedge can be postulated for the Late Maastrichtian–Selandian period (upper phase III and lower phase IV). However, a negative correlation with the global sea-level curve applies for the other stages. The transgressive Phase I is related to the sea-level low-stand, and the Lutetian drop of the eustatic curve coincides with maximum flooding of the wedge-top area, with pelagic sedimentation commonly occurring below the CCD (Phase V). A similar situation occurred also during the Oligocene (Phase VII).

For this reason, it is inferred that the seven depositional stages identified above were dominantly controlled by the local tectonic processes operating within the prograding Western Carpathian orogenic wedge. In contrast, only two general cycles have been recognized in the eastern NCA. The Lower Gosau Subgroup is characterized by predominant terrestrial to shallow-marine sedimentation, which was followed by a short emergence event and then by rapid subsidence of the Upper Gosau Subgroup, with a gradual transgression invading even more southern NCA zones. In this scheme, the Campanian–Maastrichtian to lower Palaeogene formations of the NCA show uninterrupted deep-water hemipelagic deposition, whereas the shallow-water biodebitris (e.g., the Kambühel reefs) was derived from the inward-migrating southern shore. Such a pattern is then consistent with the subcrustal-erosion tectonic model proposed by Wagreich (1995).

The architecture of the Western Carpathian Gosau basins appears to be different. No emergence and erosion was detected at the Santonian/Campanian boundary; rather a gradual deepening is recorded. Shallow-marine biogenic and terrigenous detritus is common throughout, often coarse-grained and apparently derived from intra-basin sources. It is concentrated at certain time levels that are interpreted here as the culminations of the regressive-transgressive depositional cycles represented by the evolutionary stages described above. As interpreted from the sedimentary record, each cycle included two main phases: 1) basin inversion, regression and shallow-marine, biogenic and/or clastics-dominated sedimentation, finally up to partial emergence and erosion of earlier sediments; 2) marine transgression or ingression, drowning of terrigenous and biogenic sources of clastic material, deep-water hemipelagic and turbidite sedimentation. Only the first, Lower Senonian cycle is different in part, as it began the whole depositional succession of the wedge-top basins with terrestrial sedimentation followed by marine transgression. Supposedly, these

two phases reflect contrasting tectonic regimes operating within the underlying, actively deforming accretionary wedge.

Structural evolution of the PKB and adjacent zones

While reconstructing the structural evolution and operating stress fields, the tectonic affiliation of any unit studied must be considered with caution. This particularly applies for the distinction between the “non-Oravic” units transported to the PKB area from distant palaeogeographic zones and the Penninic (Vahic-Oravic-Magura) units along with the post-emplacment Gosau-type sedimentary cover, i.e., units that acquired their structural record in post-Turonian times only. The former units (Drietoma, Klape, Manín, Haligovce), generally assigned to the CWC Fatric nappe system, contain a rich transported structural record attained during their detachment and thrusting from the homeland to the present position. In general, this early structural record corresponds well with that of the Fatric Krížna Nappe (Plašienka, 2003; Prokešová *et al.*, 2012), especially in the lithologically variable Manín unit. However, it is sometimes very difficult to distinguish it from the post-emplacment deformation elements formed in the present peri-Klippen zone, since the geometry of both structural associations has in part similar characteristics, being controlled by equally oriented palaeostress fields. Taking into account some possible distinctive features, such as the ductility of the structures (higher in the Fatric units, e.g., low-grade pressure solution foliation, shearing-related cleavages, elongated objects and stretching lineation, tight to isoclinal folds), a distinction may be tentatively made between the pre- and post-emplacment structures in the Fatric units (see also Maheľ, 1989). Consequently, the pre-emplacment (pre-Coniacian, or pre-Gosau) deformation elements are here assigned to the non-genetical deformation stage D₀ recorded exclusively in the Fatric units.

Regrettably, the predominantly brittle mesoscopic structural record for the entire Late Cretaceous–Palaeogene–Early Miocene period also is poorly defined, since only the overall W-E to gradually NWN-SES shortening with either compressional, or transpressional regimes is interpreted from palaeostress analyses along the entire PKB (e.g., Marko *et al.*, 1995; Pešková *et al.*, 2009; Bučová *et al.*, 2010; Mikuš, 2010; Vojtko *et al.*, 2010; Šimonová and Plašienka, 2011; Plašienka, 2012b). This orientation would correspond to the foreland-propagating thrusting and nappe stacking, revealed by the general geometry of fold-thrust structures in the PKB and adjacent zones (Andrusov, 1938, 1974; Książkiewicz, 1977; Birkenmajer, 1986; Jurewicz, 1994). Besides the purely compressional regime, dextral transpression associated with this palaeostress orientation was documented in several parts of the PKB, regardless of position in its recent arcuate shape (e.g., Ratschbacher *et al.*, 1993; Nemčok and Nemčok, 1994; Bučová *et al.*, 2010; Plašienka, 2012b).

However, assuming a general CCW block rotation of the Western Carpathian domain by some 50° during the late Early Miocene (Márton *et al.*, 2013 and references therein), the horizontal compression axis should be corrected to

roughly NWN–SES to SW–NE for the Palaeogene. During the Miocene, also the palaeostress field rotated clockwise, triggered by the eastward shift of the collisional zone along the front of the Carpathian orogen (e.g., Marko *et al.*, 1995).

Plašienka and Mikuš (2010) and Plašienka (2012b) reconstructed the early stages of the tectonic evolution of the Oravic PKB units in eastern Slovakia with reference to the interpretation of sedimentary-stratigraphic data and structural elements (bedding, cleavage, folds and shear bands). Supplemented by the data from western Slovakia, a modified model is presented here. The oldest compressional deformation stage D₁ is represented by pressure solution cleavage oriented at high angles to the bedding in competent limestones, especially those of the Subpieniny unit. The cleavage shows a genetic relationship to the SW–NE-trending mesoscopic F₁ folds. The D₁ 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. Assuming the stacking succession of the three Oravic units, the D₁ stage progressed in a piggy-back manner from higher to lower thrust sheets during the Paleocene and Lower Eocene. The late, W–E-trending F₁ macroscopic folds, subsequent and slightly oblique to the mesoscopic F₁ folds, are related to out-of-sequence thrusting in the rear of the developing thrust wedge. In the innermost CWC zones, this compressional stage brought about exhumation and cooling through the zircon and apatite fission-track (ZFT and AFT, respectively), partial annealing zones of the CWC basement complexes, covering a wide span of ages between 55 and 40 Ma (Kováč *et al.*, 1994; Danišík *et al.*, 2004, 2011; Vojtko *et al.*, 2013; Králiková *et al.*, 2014a, b).

The poorly documented D₂ event is represented by “cross folding”, with both macroscopic and mesoscopic folds and related cleavages oriented in a NW–SE to N–S direction. However, the kinematic significance and the relative timing of this folding are uncertain, possible relationships with the PKB arc formation might be inferred.

The D₃ deformation stage is registered as 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. Taking into account the data from western Slovakia, this event can be related to the Lutetian extensional collapse in particular. However, the CWC rigid buttress probably remained in a compressional regime with basement exhumation, surface uplift and erosion, as indicated by the absence of Lutetian sediments and also by the ZHe and AFT data from the Nízke Tatry Mts. (Danišík *et al.*, 2011). Hence the D₃ event denotes an extensional episode of the wedge toe only during the generally compressional Paleocene–Eocene tectonic regime.

Shortening with a NW–SE to N–S axis was renewed in the D₄ stage. In the Middle Váh Valley, it is recorded as backthrusting-backtilting of the PKB *s.l.* units, whereby most of strata were steepened to overturned towards the south (Figs 4, 8G, H). Generally, SE- to S-vergent backthrusting is particularly well expressed in NW Slovakia, in the Varín and Orava PKB sectors, trending W–E to SW–

NE, respectively (e.g., Marko *et al.*, 2005; Pešková *et al.*, 2009, 2012). This deformation stage culminated in dextral transpression with eastward-increasing manifestations in the northern and particularly in the eastern PKB branch (Fig. 9), which attained the structural appearance of a typical dextral wrench corridor (Ratschbacher *et al.*, 1993; Nemčok and Nemčok, 1994; Plašienka, 2012b). This stage is related with late Middle Eocene to Early Oligocene compression, revealed also by the AFT data from the basement highs along the southern flanks of the CCPB, clustering at around 40 Ma (Kováč *et al.*, 1994; Danišík *et al.*, 2004).

During deformation stage D₅, the complex relationships of the PKB and Magura units originated. In the Pieňiny Mts., the Oravic units of the PKB were thrust towards the N–NE over the youngest, Lower Miocene deposits of the innermost Krynica Subunit of the Magura Belt (Oszczypko and Oszczypko-Clowes, 2010, 2014). However, farther eastward (Šariš PKB sector, Čergov Mts.), the Krynica Subunit was thrust back over the PKB and this accounts for its narrowing and even disappearing from the surface for a short section NW of Prešov (Fig. 1B). This late SW–NE shortening event also affected the inner structure of the PKB as well as the adjacent part of the CCPB (Šambron-Kamenica anticlinal zone; Plašienka *et al.*, 1998). Subsequently, the eastern PKB branch trending 120° SE attained its present linear form, bounded by steep fault boundaries on both sides. These faults are clearly post-Oligocene in age (Plašienka *et al.*, 2013). They correspond to oblique-slip, reverse-dextral backthrusts.

At the same time, the western, SW–NE trending PKB branch experienced a sinistral transpression-transension, which persisted until the Early–Middle Miocene (Kováč and Hók, 1996; Pešková *et al.*, 2009; Bučová *et al.*, 2010; Šimonová and Plašienka, 2011). This stage was followed by the late Early Miocene (post-Eggenburgian) CCW block rotation of the Western Carpathian domain and then, during the Middle Miocene, by the general back-arc extension related to the opening of the large sedimentary depressions of the Pannonian Basin system (see e.g., Kováč, 2000, and references therein). Contemporaneously, large-scale basement exhumation and uplift of the CWC “core mountains” occurred.

Application of the critical taper concept

The evolution of accretionary to orogen-scale wedges and fold-thrust systems is well known from the structural development of both ancient (e.g., Price, 1988, 2001; Platt, 1986; Plesch and Oncken, 1999) and modern field examples (e.g., Lallemand *et al.*, 1994; Maltman, 1998; Bonnet *et al.*, 2007), as well as from analogue (e.g., Persson and Sokoutis, 2002; Soto *et al.*, 2006; Bonnet *et al.*, 2008; Sieniawska *et al.*, 2010; Konstantinovskaya and Malavieille, 2011; Rauch, 2013) and numerical (e.g., Koons, 1989; Willet, 1992; Willet *et al.*, 1993; Burbridge and Braun, 2002; Simpson, 2011) modelling. The generalized models (e.g., Chapple, 1978; Davis *et al.*, 1983; Dahlen, 1990) predict that the wedge geometry and its internal deformation are preferably controlled by the overall shape of the wedge, which is a function of lithology and the mechanical properties of materials

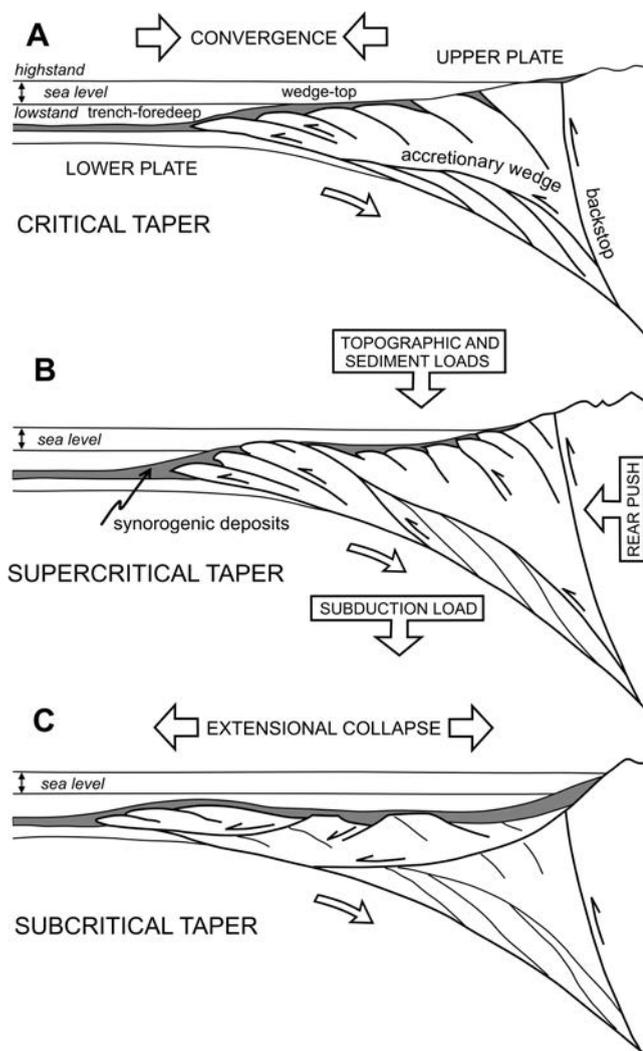


Fig. 7. Terminology and dynamic controls of the peripheral trench-foredeep and wedge-top basin systems (see text for details). **A.** Steady-state wedge maintaining critical taper. **B.** Unstable overthickened wedge with supercritical taper. **C.** Extended, subcritical wedge taper. Synorogenic sediments are shown in grey.

within the wedge, the pore fluid pressure, and the strength of the basal décollement. In an equilibrium state, the wedge maintains its critical taper through a balance between the internal compressional deformation, which tends to increase the taper angle, and the slip along the basal detachment that enables relaxation of excessive compressional stresses within the wedge. Alternatively, the dynamic wedge may keep the critical taper only transiently and thickens by accretion of material to its tip and sole until the critical taper angle is exceeded (supercritical wedge). Beyond this limit, the wedge becomes gravitationally unstable and undergoes extensional collapse. The ensuing extensional thinning causes a decrease of the taper angle (subcritical wedge), which is then compensated by accretion of new material and finally leads to repeated wedge thickening (Fig. 7). As a result, the wedge may propagate like a caterpillar in motion by means of an alternation of compressional and extensional events (cf. Patacca and Scandone, 2001; Palladino, 2011).

The critical wedge theory can also explain many characteristics of the Gosau basins that developed at the toe of

the Western Carpathian orogenic wedge. In view of this, the previously mentioned two phases of the regressive-transgressive sedimentary cycles are expressed by: 1) regression and inversion of piggy-back basins, their potential emergence and ultimately local erosion were caused by the surface uplift generated by the build-up of compressive stresses within a wedge, its internal shortening and ensuing thickening; 2) transgression and rapid subsidence of the wedge-top basins occurred after the overthickened wedge had surpassed the critical taper and internal strength limits and underwent an extensional collapse. On the basis of this reasoning, the following tectonic scenario is proposed for the evolution of the synorogenic basins that are differentiated according to the depositional stages recognized above (Figs 5, 8, 9).

Late Turonian, ca. 90 Ma (Phase 0, Fig. 8A). This was the emplacement event of the Fatric (Klape, Manín, Křižna – deformation stage D₀) and Hronic cover nappe systems, with the foundation of the accretionary wedge above the Vahic oceanic crust and an initially (sub)critical taper.

Latest Turonian?–Coniacian to Early Santonian, ca. 90–85 Ma (Phase I, Fig. 8B). The subduction of the Vahic Ocean commenced and the Pieniny-Belice trench-foredeep basin with deep-marine turbidites and mass-flow conglomerates (incl. exotics recycled from the accretionary wedge toe) was established. The foredeep-trench basins were separated by an erosional wedge-toe elevation from the wedge-top growth basins (Rašov-Valchov type) with terrestrial to shallow-marine, clastics-dominated deposition (transgressive conglomerates, bioherms and biostromes), followed by gradual deepening with neritic marls and calcareous tempestites and turbidites. The wedge-top accommodation space was created by downbending, due to subduction and orogenic wedge loads, despite the sea-level fall. The wedge deformed internally by out-of-sequence thrusting and attained a critical up to gradually supercritical taper during the Early Santonian.

Late Santonian to mid-Campanian, ca. 85–75 Ma (Phase II, Fig. 8C). Subduction of the Vahic Ocean continued. Drowning and destruction of terrigenous and biogenic sources occurred owing to flooding of the wedge-toe elevation, caused by the global sea-level rise and subduction load of the Vahic lithosphere. The sedimentary successions show fining upward and sudden deepening (ingression) with oceanic red beds (variegated marlstones, CORB) in both the trench and wedge-top, Púchov-type piggyback basins, which communicated during this stage. Hence the wedge collapsed rapidly to the subcritical taper state, whereas exhumation of the overthickened axial parts of the buttressing CWC orogenic wedge (Vepor-Gemer zone) by orogen-parallel extension started, as evidenced by structural data, cooling ages and start of sedimentation in the internal Gosau basins.

Mid-Campanian to earliest Danian, ca. 75–65 Ma (Phase III, Fig. 8D). Coarsening-upward syn-orogenic sedimentation in the Vahic (Belice) trench and Oravic (Jarmuta) foredeep basins occurred, subsequently subduction of the Vahic Ocean terminated approximately at the Cretaceous/Palaeogene boundary. In accord with the descending sea-level, regression and finally local emergence is recorded in

the wedge-top basins with development of transient marginal biogenic buildups that were mostly destroyed afterwards. The subcritical wedge (Phase II) began to deform internally by out-of-sequence thrusting and attained the supercritical taper during the latest Cretaceous, then the wedge did not collapse, but the critical-supercritical taper was maintained by buttressing frontal collision of the orogenic wedge with the Czorsztyn Ridge after closure of the Vahic Ocean, whereby also the EWC basins (Biele Karpaty-Magura) were partly inverted. The wedge toe accreted the detached Oravic Pieniny Unit, whereas the Vahic Belice Unit was underplated and attached to the wedge sole by basal duplexing and/or partly involved in the subduction channel (MP-VLT metamorphism; Putiš *et al.*, 2008).

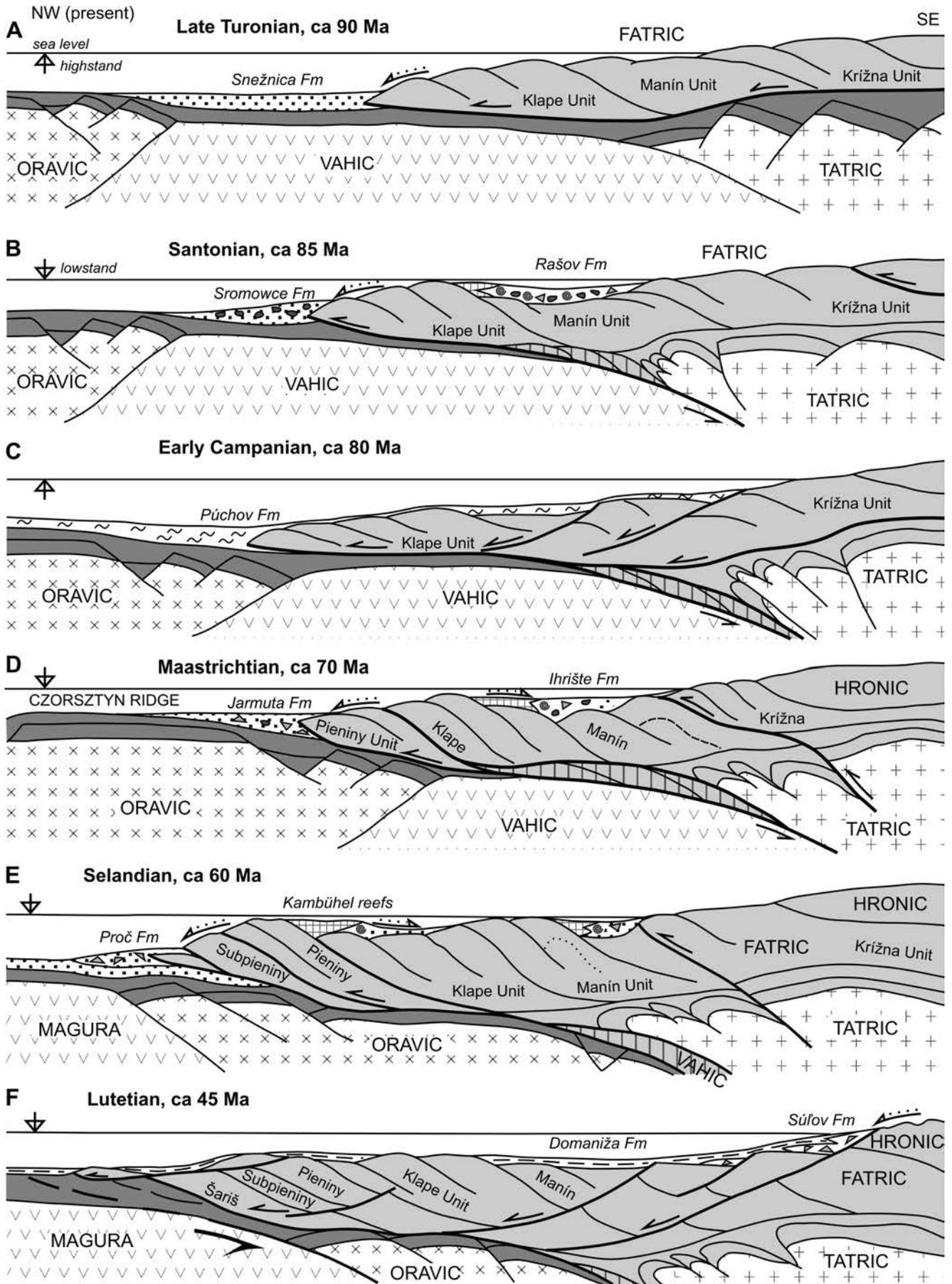
Danian to Ypresian, ca. 65–50 Ma (Phase IV, Fig. 8E). The wedge-top basins are characterized by terrestrial or shallow-marine sediments rich in terrigenous material or fragments of biogenic build-ups. The sea-level was at a low-stand during the Danian and then it rose in the Thanetian to the Ypresian high-stand, which caused a shallow transgression over the wedge. The wedge stayed in a compressional state, owing to collision and underthrusting of the Oravic continental ribbon (Czorsztyn Ridge) below the orogenic wedge buttressed by the CWC backstop. Its sedimentary cover (Subpieniny Unit) was detached and thrust over the Proč foredeep basin with coarsening-upward synorogenic turbiditic clastics and mass-flows. After being accreted at the wedge tip, the Oravic units were affected by the first structurally expressed compressional deformation stage D₁, possibly followed by “cross folding” stage D₂. Then the collisional zone experienced out-of-sequence thrusting and backthrusting, parts of the wedge and the CWC backstop were uplifted and eroded. Accordingly, the wedge was critically to supercritically tapered.

Late Ypresian to Lutetian, ca. 50–40 Ma (Phase V, Fig. 8F). There was establishment of a new subduction zone in front of the leading edge of the Western Carpathian orogenic wedge, composed of the detached Oravic units (Šariš and Subpieniny); this was the start of the Magura Ocean subduction. The EWC Biele Karpaty Superunit was scraped off and accreted at the wedge toe and internally shortened. After the loss of the frontal support, the wedge collapsed gravitationally and extended and its surface subsided (deformation stage D₃). Consequently, the wedge geometry changed rapidly to subcritical. The rear of the wedge was first (late Ypresian to earliest Lutetian) affected by input of huge masses of carbonatic scarp breccias, derived from the uplifted zone of the CWC, composed of Triassic formations of the Hronic Superunit (Súl'ov Conglomerate). Afterwards, during the Lutetian, it lengthened and slipped along the basal décollement. Therefore, its rear parts collapsed to form the pelagic basin, despite the drop in the global sea level.

Bartonian to Rupelian, ca. 40–30 Ma (Phase VI, Fig. 8G). The subduction of the Magura oceanic lithosphere accelerated and sediments from the inner parts of the Magura Basin were scraped off and accreted to the wedge toe (Biele Karpaty and Bystrica units). As a consequence, the wedge grew rapidly and attained the critical to supercritical taper again. The process of sequential accretion of the EWC

thin-skinned thrust sheets was initiated during the late Middle Eocene. At first, nappes of the Biele Karpaty Superunit were stacked and overthrust by the PKB units. Subsequently, during the Late Eocene and Oligocene–Egerian, all other units of the Magura and later also the Silesian-Krosno superunits were progressively included in the growing EWC accretionary wedge. In the CWC backstop areas, a partial inversion of the Lutetian basins, uplift and erosion of their marginal zones occurred, followed by shallow-marine transgression (Borové Fm of the CCPB), likely due to the eustatic sea level rise during the latest Lutetian–earliest Bartonian. The Iňačovce remnant basin was closed and its complexes were underplated below the NE edge of the CWC. The overall compressional tectonic regime controlled also the development of in part isolated anoxic basins during the Early Oligocene. In the western PKB branch, backthrusting-backtilting affected the rear parts of the EWC accretionary wedge, including the PKB. Compression, partial exhumation and cooling of basement complexes in the more inner CWC backstop zones are indicated by the ZFT and AFT ages. The significant dextral transpression in the eastern PKB branch was associated with disconnection of the PKB-EWC accretionary complex from the CWC zones and its SE-ward (in present coordinates) movement, relative to the NE edge of the CWC. As a consequence, the PKB-EWC system, carrying also slivers of peri-Klippen Facies units (Haligovce, Humenné) with the Súl'ov-Domaniza type of Eocene formations, was dextrally juxtaposed to the eastward widening strip of the Maruszyna-Lipník-Šambron-Kričovo units (Fig. 9). Unlike the Iňačovce Unit, the Kričovo-related units were not involved in underthrusting below the CWC thrust stack, but were accreted to its tip. In eastern Slovakia, the outer CWC edge and obducted oceanic complexes were squeezed and uplifted to provide clastic material for the marginal mass-flow deposits (Šambron Fm) during the Priabonian and Early Oligocene and serpentinite detritus for the Oligocene clastics, respectively. All these events occurred during deformation stage D₄, described above.

Late Rupelian to Aquitanian (Egerian), ca. 30–20 Ma (Phase VII, Fig. 8H) – subduction of the Magura oceanic lithosphere gradually ceased and was relocated northwards into the Silesian-Krosno sea. The wedge collapsed (including accreted Magura units) and was maintained in a subcritical state either by a missing frontal support (possible subduction retreat of the EWC oceanic zones), or by subcrustal erosion. The outer CWC and inner EWC (northern and eastern sectors) zones were affected by large-scale flooding and subsidence of the CCPB that partly communicated with the wedge-top, piggyback basins located above the accretionary wedge rear (inner Magura belt – PKB). During the earliest Miocene, subduction of the EWC basins vanished and soft collision of the WC orogenic wedge (western part) with the NEP started. The orogenic wedge was compressed to attain the critical state again. As a consequence, retro-wedge compression and partial closure of the CCPB and Malcov-Údol type basins occurred (deformation stage D₅). Nevertheless, marine basins in a piggyback position still persisted in the inner EWC zones, near the contact with the PKB. Simultaneously, MP/LT metamorphism and



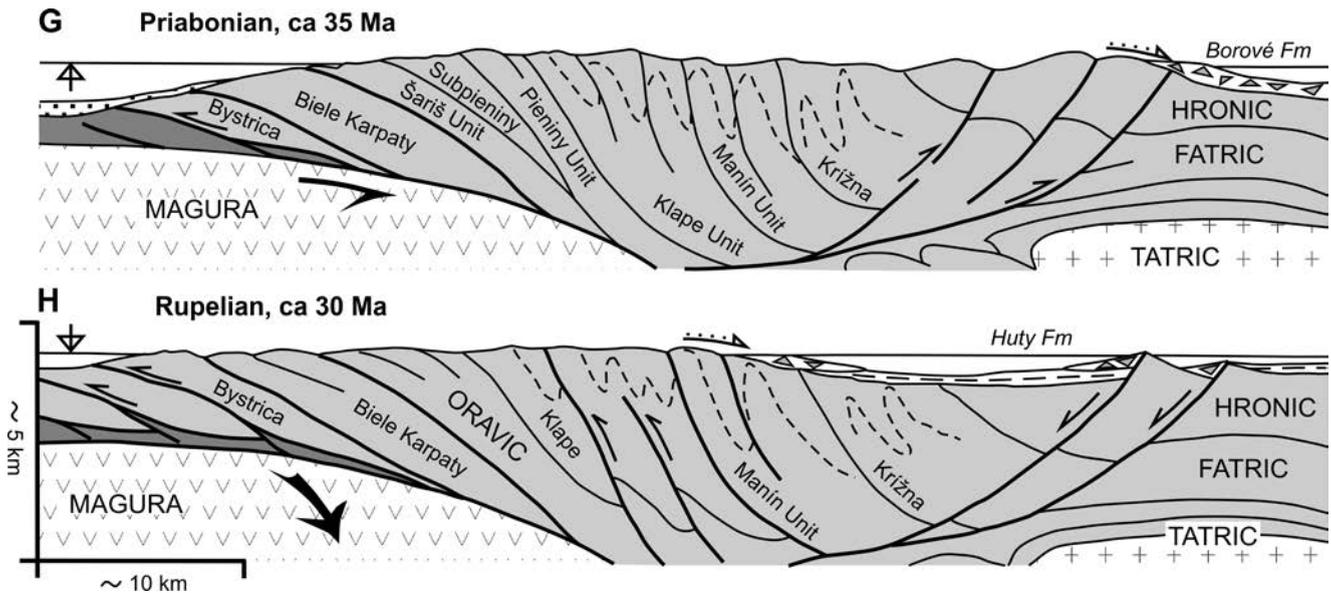


Fig. 8. Tentative evolutionary model of the trench-foredeep and wedgetop-piggyback basin system, based on situation in the Middle Váh Valley area (cf. Fig. 4). Basement complexes are hachured grey (crosses – continental crust, v-marks – oceanic crust), lower plate sediments are shown in dark grey, upper plate sediments are light grey, synorogenic sediments contemporaneous to the particular stage are hachured black, sea water is shown blank. Vertical hatching denotes the accreted Vahic oceanic sediments. **A.** Initial Phase 0, emplacement of the Fatric nappes followed by commencement of subduction of the Vahic oceanic lithosphere. **B.** Phase I, subduction of the Vahic domain, critical to supercritical wedge taper. **C.** Phase II, accretionary wedge collapse to subcritical taper state. **D.** Phase III, closing of the Vahic Ocean, incipient collision of the critically tapered wedge tip with the Oravic continental ribbon. **E.** Phase IV, gradual underthrusting of the Oravic domain below the supercritical wedge. **F.** Phase V, commencement of subduction of the Magura oceanic lithosphere, wedge collapse to subcritical taper. **G.** Phase VI, wedge growth to supercritical state (see also Fig. 9), retowedge downbending and transgression in the CWC area. **H.** Phase VII, the EWC accretionary wedge growth, collapse and extension of the backstop outer CWC zones, flooded by the CCPB sea. Not to scale.

penetrative ductile deformation affected the deeply buried Iňačovce Unit.

Burdigalian (Eggenburgian–Karpatian), ca. 20–16 Ma.

The wedge was keeping the critical taper enabling inversion of the CCPB and Early Miocene piggyback basins of the Magura zone. A new system of wedge-top, wrench-furrow type basins was established along the PKB and in the outer CWC zones. Moreover, a large-scale CCW rotation of the Western Carpathian domain was initiated by Alpine collision and subduction retreat of the outer EWC Silesian-Krosno Sea. These processes were accompanied by the initial uplift of the later CWC “core mountains” (AFT data), as well as a core-complex-style exhumation of the Iňačovce Unit.

Middle Miocene (Badenian), ca. 16–12 Ma.

Sinistral transtension in the westernmost PKB sector generated a system of pull-apart basins (Vienna Basin, Ilava-Sverepc and Orava-Nowy Targ depressions). The ensuing back-arc collapse and extension of the Pannonian Basin system were accompanied by lithospheric thinning, rifting, subsidence and extensive calc-alkaline volcanism, triggered by an eastward subduction roll-back of the Silesian-Krosno Sea.

CONCLUSIONS

During the Meso-Alpidic epoch, the Western Carpathian zones along the PKB experienced a polystage tec-

tonic evolution, as they were gradually shifted from the front of the CWC orogenic system to the rear of the developing EWC accretionary wedge. Finally, during the Early–Middle Miocene, the PKB and adjacent units were welded to the backstop CWC block, being separated from the Flysch Belt by steep reverse oblique to strike-slip faults. The Late Cretaceous–Palaeogene peripheral trench-foredeep and wedge-top basin system evolved by mutually related compressional and extensional events, documented in complex sedimentary and structural rock records. The whole story is differentiated into seven principal depositional phases, distinguished according to temporal and spatial variations in sedimentary environments, their tectonic settings, sources of clastic material, etc. The successive transgression-regression cycles are interpreted in terms of developmental tectono-sedimentary phases, controlled by a complex interplay among the regional tectonic evolution of the Alpine-Carpathian orogenic system producing far-field tectonic stresses, local wedge dynamics and eustatic sea level fluctuations. Accordingly, the seven evolutionary tectono-sedimentary phases were characterized as follows (Figs 5, 8).

I. After Late Turonian emplacement of the CWC nappe systems and the onset of subduction of the South Penninic-Vahic Ocean (Phase 0), the peripheral foredeep in the later Pieniny Unit of the PKB and the wedge-top Gosau basins were established during the Coniacian–Santonian. Both are characterized by synorogenic, coarse-grained clastic deposits with partly similar composition, but they principally dif-

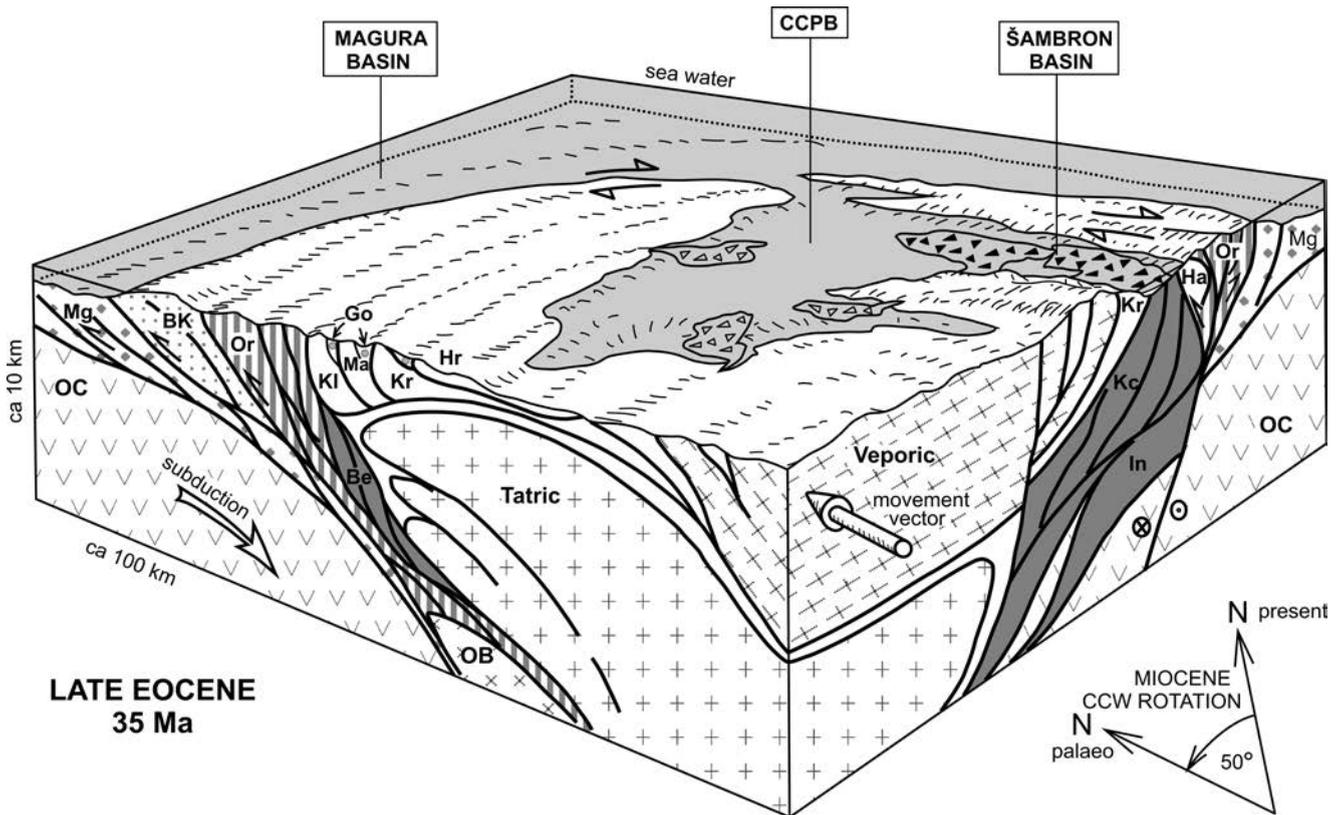


Fig. 9. Schematic block-diagram showing an overall palaeotectonic situation of the Western Carpathians during the Phase VI (Priabonian, approximately 35 Ma). Not to scale. Abbreviations: OC – oceanic crust; OB – Oravic basement; Mg – Magura units; BK – Biele Karpaty units; Or – Oravic units; Be – Vahic Belice Unit; Kc – Kričovo Unit; In – Iňačovce Unit; Kl – Klape Unit; Ma – Manín Unit; Ha – Haligovce Unit; Kr – Križna Nappe; Hr – Hronic nappes; Go – Gosau deposits.

fer in genesis; while the trench-foredeep troughs contain deep-marine, coarsening-upward sequences, the wedge was transgressed by continental to shallow-marine, fining-upward deposits.

II. During the Early–Middle Campanian, the sea level rose and the wedge collapsed gravitationally to a subcritical taper state. Therefore, a connection between the foredeep and wedge-top basinal areas was enabled. This resulted in the unified sedimentation of pelagic variegated marls and shales (CORB), in part deposited below the local CCD in the large Púchov depositional system.

III. In latest Cretaceous times, the clastics-dominated foredeep relocated outwards to the later Subpieniny Unit (Jarmuta Fm), whilst the wedge-top area was gradually uplifted, supposedly as a result of wedge compression and thickening. The regressive Bradlo and Ihrište formations are chiefly composed of bioclastic detritus, including reworked bioherms.

IV. After closure of the Váh Ocean, the wedge stayed in a compressional regime, generated by collision of the CWC with the Oravic continental fragment and its accretion to the wedge toe. The peripheral foredeep was shifted to its northern margin facing the Magura Ocean and was filled with coarse clastics with huge olistostrome bodies (Proč Fm of the later PKB Šariš Unit) during the early Palaeogene. The wedge area was compressed, uplifted, rendered emergent and eroded to some extent. The Thanetian–Ypresian, piggyback basin was influenced by shallow-marine bio-

clastic input, abundant reef olistolites and frequent gaps during the sea level rise.

V. For the period of Lutetian, the wedge collapsed and subsided to bathyal depths. The widespread and deep wedge-top basin originated and communicated also with the EWC basins and the corresponding sedimentary conditions. Its inner margin was bounded by normal faults, which supplied the adjacent peripheries with vast masses of unsorted carbonate-scarp breccias and conglomerates (Súl'ov Fm). The backstop CWC zones were still contractionally uplifted.

VI. The late Lutetian–early Bartonian episode of basin inversion was followed by a widespread Bartonian–Priabonian transgression related to the renewed sea level rise. As a result, the large forearc-type CCPB was established. Large areas of the EWC and outer CWC zones were flooded, despite the build-up of compressive stresses, back-thrusting-backtilting and dextral transpression in the eastern PKB branch. The transgressive conglomerates of the CCPB were succeeded by upper Priabonian–lower Rupelian pelagic marls and anoxic shales with huge coarse mass-flow bodies, derived from the intra-basinal cordilleras and basin margins.

VII. During the Late Oligocene and earliest Miocene, the wedge collapsed once again. The CCPB, along with the internal EWC zones, subsided considerably and was filled with large amounts of deep-marine, thickening-upward clastics.

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Appendix

List of abbreviations

AFT – Apatite Fission Tracks; CCD – Calcite Compensation Depth; CCPB – Central Carpathian Palaeogene Basin; CCW – counterclockwise (rotation); CORB – Cretaceous Oceanic Red Beds; CWC – Central Western Carpathians; DWAF – Deep Water Agglutinated Foraminifera; EWC – External Western Carpathians; Fm – Formation; Mb – Member; MP-LT – medium pressure-low temperature (metamorphism); NCA – Northern Calcareous Alps; NEP – North European Platform; PKB – Pieniny Klippen Belt; *s.l.* – *sensu lato*; *s.s.* – *sensu stricto*; WC – Western Carpathians; ZFT – zircon fission tracks; ZRT – zircon-rutile-tourmaline (ultrastable heavy mineral association).