Paleogene palaeogeography and basin evolution of the Western Carpathians, Northern Pannonian domain and adjoining areas

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ABSTRACT

The data about the Paleogene basin evolution, palaeogeography, and geodynamics of the Western Carpathian and Northern Pannonian domains are summarized, re-evaluated, supplemented, and newly interpreted. The presented concept is illustrated by a series of palinspastic and palaeotopographic maps. The Paleogene development of external Carpathian zones reflects gradual subduction of several oceanic realms (Váh, Ilašovce-Kričevo, Szoïlnok, Magura, and Silesian-Krosno) and growth of the orogenic accretionary wedge (Pleniny Klippen Belt, Ilašovce-Kričevo Unit, Szoïlnok Belt, and Outer Carpathian Flysch Belt). Evolution of the Central Western Carpathians is characterized by the Paleocene–Early Eocene opening of several wedge-top basins at the accretionary wedge tip, controlled by changing compressional, strike-slip, and extensional tectonic regimes. During the Lutetian, the diverging translations of the northward moving Eastern Alpine and north-east to eastward shifted Western Carpathian segment generated crustal stretching at the Alpine-Carpathian junction with foundation of relatively deep basins. These basins enabled a marine connection between the Magura oceanic realm and the Northern Pannonian domain, and later also with the Dinaridic foredeep. Afterwards, the Late Eocene compression brought about uplift and exhumation of the basement complexes at the Alpine-Carpathian junction. Simultaneously, the eastern margin of the stretched Central Western Carpathians underwent disintegration, followed by opening of a fore-arc basin – the Central Carpathian Paleogene Basin. In the Northern Hungarian Paleogene retro-arc basin, turbidites covered a carbonate platform in the same time. During the Early Oligocene, the rock uplift of the Alpine-Carpathian junction area continued and the Mesozoic sequences of the Danube Basin basement were removed, along with a large part of the Eocene Hungarian Paleogene Basin fill, while the retro-arc basin depocentres migrated toward the east. The Rupelian basins gained a character of semi-closed sea spreading from the Magura Basin across the Central Western Carpathians up to the Hungarian Paleogene Basin. In the Late Oligocene, the Magura Basin connection with the Northern Hungarian Paleogene Basin remained open, probably along the northern edge of the Tisza microplate, and anoxic facies were substituted by open marine environments.

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1. Introduction

The Western Carpathians represent the northernmost segment of the Alpine-Carpathian mountain chain (Fig. 1). They consist of the Outer Western Carpathian accretionary wedge (Flysch Belt) formed during the Middle Eocene through the Early Miocene and of the Central Western Carpathians consolidated in the Late Cretaceous. These two principal parts of the orogenic system are separated by the Pleniny Klippen Belt, a narrow zone with complex structure that was dominantly affected by early Paleogene (Paleocene–Lutetian) deformation (cf. Plašienka et al., 1997a; Froitzheim et al., 2008 and references therein).

The presented model of the Paleogene palaeogeography of the Western Carpathians follows the terrane concept, in which the Central Western Carpathians, together with the geologically analogous Eastern Alps, are parts of the ALCAPA microplate that existed from the Miocene onwards (Ratschbacher et al. 1991a,b). On the contrary, the southern part of this microplate – the Northern Pannonian domain is built up by elements with Southern Alpine and Dinaridic affinity: the
Transdanubian and Bükú units (e.g., Ratschbacher et al., 1991a,b; Csontos et al., 1992; Schmid et al., 2008; Ustaszewski et al., 2010; Haas et al., 2014). According to this supposition, the boundary between the Eastern Alps and Central Western Carpathians in the north and the Southern Alps and the Northern Pannonian domain in the south is represented by the Periadriatic Fault in the Alps (e.g., Linzer et al., 2002) and by the Hurbanovo–Díósjenő Fault in the Western Carpathians (e.g., Konečný et al., 2002; Haas et al., 2014). Moreover, the palaeotectonic reconstructions take into consideration the Miocene tectonic escape of the ALCAPA microplate from the Alpine and Dinaridic realms with a movement trajectory recording several counter-clockwise rotational events ranging from 50° up to 90° (e.g., Márton and Márton, 1996; Márton et al., 1999, 2000, 2013; Márton and Márton, 2013), as well as the diminishing of various domains with oceanic and/or thinned continental crust in front of the overriding plate. The resultant mobile zones are presently represented by accretionary wedges, suture zones, and wrench zones (e.g., Ratschbacher et al., 1991a,b; Fodor et al., 1998; Tari, 2002; Nemčok et al., 2006; Oszczypko, 2006; Schmid et al., 2008; Ustaszewski et al., 2010; Haas et al. 2014). These are the flysch belts of the Alps and Outer Western Carpathians in the north, the Ilhaçovec-Kričivo Zone in the east, and the mobile belts along the Periadriatic and Mid-Hungarian fault zones in the south – the latter are situated along the transform boundary between the ALCAPA and Tisza-Dacia microplates (Fig. 1).

The aim of this paper is to review and re-evaluate the extensive published data, as well as to interpret our own results gathered during the last decades in geological, sedimentological, biostratigraphical, structural, and geochronological research in the Western Carpathians. We present an outline of the Paleogene palaeogeography and evolutionary tectonic model that attempts at unravelling not only the former extent of basins and elevated parts of the developing orogenic wedge, but also at understanding of the geodynamic background of structural evolution of the Alpine–Carpathian orogenic system as a whole. Our views are illustrated by a series of palinspastic and palaeotopographic maps for the Paleogene period.

2. Paleogene basins and their depositional systems, mobile zones, and structural evolution

Evolution of a various Western Carpathian Paleogene basins was controlled by their geodynamic position within the developing orogenic system, often in a close relationship with evolution of the Eastern Alpine, as well as the Southern Alpine-Dinaridic systems. In principle, we distinguish two broad-scale tectonic settings of the Paleogene basins, based on their position with respect to the topographic and structural evolution of the Alpine–Carpathian orogenic system as a whole. Our views are illustrated by a series of palinspastic and palaeotopographic maps for the Paleogene period.

(i) The fore-axis basin system relates to the forward advancement of the orogen that gradually incorporated rock complexes from its foreground, including the pre- and syn-orogenic basin fills. These basins developed between the stable Northern European Platform and uplifted axial parts of the Eastern Alpine-Western Carpathian orogen and included the platform shelf and its slopes (passive margin), the remnant basins with oceanic or thinned continental crust (flysch troughs) and a variety of basins located along an actively deforming margin of the overriding plate. The basins located in front of the orogenic wedge involved the lower plate trench-type and peripheral foredeep basins, the upper plate wedge-top and fore-arc basins. As the presumably oceanic basement of the lower plate was subjected to subduction, its...
off-scraped Cretaceous to Oligocene sediments underwent shortening by thrust stacking and were transformed into units of the Pieniny Klippen Belt, Alpine-Carpathian Flysch Belt and the Foredeep (Molassae Zone), and mobile zones along edges of the ALCAPA microplate (e.g., Nemčok et al., 2006; Oszczypko, 2006; Ustaszewski et al., 2010; Rauch, 2013). The upper plate, Gosau-type wedge-top basins were mainly related to the collapse stages of the propagating accretionary wedge, whereas the large Central Carpathian Paleogene Basin in a fore-arc position reflected extensional thinning of the Central Western Carpathian crust (cf. Płaśienka and Soták, 2015 and references therein).

(ii) The back-axis basin system was situated behind the uplifted axial part of the orogen. It is represented by basins which opened mostly in the Northern Pannonian domain and starting from the Late Oligocene, also in the internal parts of Central Western Carpathians, as well as by the foredeep depressions in retro-arc position in the Southern Alps and Dinarides. The complex basin evolution was connected with a range of tectonic regimes – compressional, transpressional-transtensional, and extensional (retro-arc foredeep basins, pull-apart and wrench zone furrows, and hinterland extensional basins). The time spans of the basin fills vary; with the maximal subsidence during the Paleocene, Eocene or Oligocene times. Moreover, some of these basins were later dissected by transcurrent wrench zones and transported for hundreds of kilometres during the Early Miocene (e.g., Csontos et al., 1992; Kováč et al., 1994; Csontos and Nagymarosy, 1998; Fodor et al., 1998). However, it should be noticed that the character and structural position of these basins was changing in time as the orogenic system prograded, deformed by compression and/or extension, and spread laterally. Frontal accretion, lateral dispersal, and collapse stages often occurred in a time sequence and brought about superposition of various basin types in different parts of the orogen. On the other hand, the forward and backward basins might have communicated in certain time periods, especially during the overall collapse stages.

2.1. Outer Carpathian flysch basins – the northern Penninic realm

The front of the Eastern Alpine and Western Carpathian orogen is outlined by the Alpine-Carpathian Foredeep and the Outer Western Carpathian: Rhenodanubian–Magura and Silesian–Krosno nappe groups (Fig. 1). The Cretaceous–Paleogene sediments of these units were deposited on an attenuated continental and/or oceanic crust of the Northern Penninic realm (Valais–Rhenodanubian–Magura) and on the passive margin of the Northern European Platform.

The Outer Western Carpathian thrust units are mostly composed of turbidite sediments deposited in deep-marine environment. In time of the Paleogene to Early Miocene subduction, these were gradually scraped off and stacked to form a fold-and-thrust system of the accretionary prism. The Outer Western Carpathian nappes comprise formations of the internal troughs (Magura and Fore-Magura/Dukla units) and external basins (Silesian, Sub-Silesian, Waschberg–Ždánice, and Poudzťany units).

The Outer Western Carpathian accretionary wedge is overthrust on the platform basement with the distance of more than 100 km that was documented by deep drillings and geophysical measurements (see reviews by Picha et al., 2006, Slážka et al., 2006). Autochthonous, mainly Badenian marine deposits in Poland (Oszczypko, 2006) and also the Lower Miocene marine sediments in the western sector of the foredeep were encountered beneath the nappes (e.g., Kovač et al., 1998; Oszczypko and Oszczypko-Clowes, 2003). The results of these drillings were used for balanced and restored cross-sections (e.g., Behrmann et al., 2000; Nemčok et al., 2006; Gagala et al., 2012; Beidinger and Decker, 2014 and reference therein), which allowed to estimate the widths of these basins to approximately 150–200 km during the Oligocene–Early Miocene epoch. The assumed shortening of the Magura Basin during the Eocene is similar, approximately 200–300 km (Oszczypko et al., 2015).

2.2. Oravic and Vahic domains – the southern Penninic realm

The Oravic and Vahic domains represent the Western Carpathian analogues of the Alpine Middle and Southern (Upper) Penninic zones, respectively (e.g., Froitzheim et al., 2008). The Oravic units were derived from a palaeogeographically independent intra-Penninic domain centred by a continental fragment – the Czorsztyń Ridge that was bounded from the south by the Middle Jurassic–Cretaceous Southern Penninic (Vahic) oceanic tract, and from the north by the Cretaceous–Paleogene Northern Penninic (Rhenodanubian–Magura) oceanic zone. The Oravic domain involves Jurassic to Paleogene sediments with variable lithology and complex internal structure presently ranged into three principal thrust units (from the top to bottom): the Pieniny (Kysuca), Subpieniny (Czorsztyń), and Šariš (Grajcarek) nappes (e.g., Birkenmajer, 1986; Oszczypko et al., 2012; Płaśienka, 2012). However, only the Šariš Unit involves Paleogene sediments (Płaśienka and Soták, 2015). These units appear within the Pieniny Klippen Belt.
(Fig. 1) that is a narrow, but up to 650 km long zone that was shortened during the Paleocene to Middle Eocene thrusting and was affected by superimposed Late Eocene to Middle Miocene wrench tectonics.

The Vahic Unit is the presumed Western Carpathian prolongation of the Southern Penninic oceanic complexes occurring in tectonic windows in the neighbouring Eastern Alps (e.g., the Rechnitz window). In the Central Western Carpathians it is represented by the Belice Unit in the Považský Inovec Mts. (Plašienka et al., 1994, 1997a, b; Plašienka, 2012). The Iľačovce Unit, drilled in the subcrop of the Miocene deposits of the Eastern Slovakia Basin occupies an analogous tectonic position (e.g., Soták et al., 1993, 1994, 1995, 1999), although it can be rather correlated with the Sava Zone of Dinarides (see also Schmid et al., 2008).

2.3. Paleogene basins of the Central Western Carpathians

The Paleogene basins of the Central Western Carpathians developed on top of the palaeo-Alpine consolidated orogen (Fig. 1). The Miyjava–Hričov Basin in western Slovakia was filled in Paleocene–Middle Eocene times as a continuation of the Upper Cretaceous deposition in Gosau-type basins. This basin is interpreted as a typical wedge-top basin, the development of which was dominantly controlled by the dynamics of the underlying orogenic wedge composed of the frontal Central Western Carpathian units (Fatrić, Hronic) and sequentially accreted Oravic units of the Pieniny Klippen Belt. Besides of the sea-level times as a continuation of the Upper Cretaceous deposition in Gosau-slices, or erosional remnants in Slovenia and southern Austria deformed mainly by normal and strike-slip faults. The Eocene platform east-northeast (Tari et al., 1993; Less et al., 2000). Later the basin deponenctre shifted to the east and also to the south toward the present-day Slovenia (Jelen and Rifelj, 2002), where a continuous sedimentation across the Eocene/Oligocene boundary is recorded. Global cooling in the Early Oligocene, which was associated with the first separation of the Paratethys (Baldi, 1984) resulted in deposition of anoxic clays during the Rupelian. The change in the basin configuration was roughly contemporaneous with tectonic-anadisitic magmatism along the Periadriatic and the continuing Balaton-Darnó faults (Frisch et al., 1998; Fodor et al., 1998; Benedek et al., 2004; Less et al., 2008), in which the Rupelian age of the Recsk anodesite (the north–easternmost segment of the volcanic belt) is proved (Kovács et al., 2007).

The third phase of the basin evolution started at the end of the Rupelian and is characterized by a general transgression over the eastern part of the Northern Pannonian domain and the southern zones of the Central Western Carpathians, which resulted in opening of new marine connections that terminated anoxia. Subsidence of the so-called Pétèrvására Basin started during the late Kiscellian–early Egerian (26–23 Ma). The common sedimentation area of the Northern Hungarian–Slovenian Paleogene Basin was interrupted during the Early Miocene, when the basin was separated into the northern and southern parts (Hungarian Paleogene and Slovenian Paleogene basins) by the transcurrent, Mid-Hungarian fault system (e.g., Royden and Baldi, 1988; Fodor et al., 1998; Kováč et al., 1998; Csontos et al., 1992).

2.5. Dinaridic Paleogene basins

Paleogene sediments are exposed along the eastern Adriatic coast (External, Karst Dinarides) and south of the Sava River (Internal Dinarides) in a more-or-less continuous belt (Fig. 1). In the External Dinarides, the Ypresian to early Lutetian shallow-water sediments unconformably overlie Cretaceous sediments of different age, apart from a few sites (Kras, central Dalmatia, and Herzegovinia; Čosović et al., 2006, 2008; Droben et al., 2009) where a continuous sedimentation from the Cretaceous to Paleogene took place. The beginning of shallow-water sedimentation is diachronous over the area, indicating advancing transgression from NE to SW. These sediments pass upward into basinal pelagic marls and turbidites. The oldest foredeep turbidites (flysch) are located in the north-western part and they are Early Eocene in age (Droben et al., 2012). The onset of flysch deposition in the foredeep gets progressively younger south-eastwards and offshore westwards (Tari, 2002), being of the Priabonian (Marjanac et al., 1998; Schweitzer et al., 2007) and Oligocene–Miocene age (Tari-Kováč et al., 1998). The Eocene to Oligocene strata, traditionally interpreted as the Dinaridic continental to shallow-water molasse, were deposited in a piggy-back basin which developed in the central and southern parts of Internal Dinarides (Mrinjek et al., 2012). The Jelar Breccia of uncertain age (middle Eocene–early Oligocene) is interpreted as the youngest Cenozoic sedimentary unit, while a deep-marine sedimentation continued from the Maastrichtian to Middle Eocene in the Internal Dinarides (northern and north-eastern part of Bosnia; Pamić, 1993, 1998, 2002; Čičić et al., 2008). Locally, sedimentation was interrupted and a shallow-water regime was established in the Middle Eocene (Middle to Upper Eocene breccias, calcarenites, and limestones occurring in north-western Croatia – Šimunić et al., 2000).
2.6. Paleogene mobile zones

The Paleogene mobile zones are represented by various strongly deformed tectonic units that are located along the northern, eastern, and southern edges of the ALCAPA microplate. These units are mainly represented by the Upper Cretaceous to Paleogene complexes thrust in front of the overriding plate; a part of them was metamorphosed due to a deep burial and exhumed thereafter (e.g., Schmid et al., 2008; Ustaszewski et al., 2008, 2010). The units of the mobile zones show common features in lithostratigraphy and facies development, documenting their neighbourhood in the sedimentary realm. Moreover, the present position of these units excellently mirrors geodynamic processes related to their off-scraping, thrusting, and incorporation into the growing accretionary wedges. The mobile zones in front of the Central Western Carpathians are represented by the Pieniny Klippen Belt and Outer Western Carpathian units, as well as by units located between margins of the ALCAPA and Tisza-Dacia microplates (Fig. 1). Presently, the belt of these tectonic units is composed of the Šambron Zone, Iľačovce Unit, Kríčevo Unit, Peri-Pannonian Zone, Botiza Unit, Bábča–Tijacovo Unit, Szolnok Flysch Belt, and Sava–Vardar Zone.

The units of the Iľačovce–Kričevo and Peri-Pannonian zones correspond to units of the Sava domain (cf. Pamić, 1993, 1998, 2002; Soták et al., 2001), considering their Late Cretaceous–Paleogene age, trench-type sediments (Sava Flysch), ophiolite-type rocks, long-lasting subduction (up to the Late Eocene), low-grade metamorphism, synkinematic granitic magmatism and volcanism, and foreland-forearc basin formation. Sedimentary complexes of the Szolnok Belt show partial affinities to the Pieniny Klippen Belt and Magura nappe system (Nagymaryosy and Báldi-Beka, 1993). These units represent former oceanic basins, which were subducted during the Cretaceous–Paleogene (Iľačovce Unit and Sava Zone), folded during the Oligocene accretion (Šambron–Kričevo Zone, Szolnok, and Marmarosh flysch belts), dissected by strike-slip faulting during the Late Oligocene–Early Miocene, and exhumed by detachment faulting during the earliest Miocene (Rechnitz Unit, Iľačovce Unit, and Sava Zone; Dunkl and Demény, 1997; Pamić, 2002; Soták et al., 2002; Ustaszewski et al., 2010).

2.7. Paleocene–Eocene evolution of the foredeep/wedge-top basin couples

Tectonic evolution of the Paleogene basins located along the outer margin of the Central Western Carpathians and above its frontal accretionary wedge is closely related to the evolution of the whole Eastern Alpine–Western Carpathian orogenic system after cessation of the Southern Penninic–Vahic subduction. Subduction terminated approximately at the Cretaceous/Paleogene boundary in the Eastern Alps (e.g., Mateři Zone, Ybbsitz Klippen Belt and Kahlenberg nappe; Homayoun and Faupl, 1992; Schnabel, 1992; Faupl and Wagreich, 2000; Kurz et al., 2001) and in the present western part of Western Carpathians (Froitzehim et al., 2008; Plašienka, 2012; Plašienka and Soták, 2015). However, an eastward opened oceanic remnant basin (Iľačovce–Kričevo and Sava basins) as the eastern prolongation of the Southern Penninic–Vahic oceanic zone was left for continuing deep-marine deposition between the outer Central Western Carpathian edge and the Oravic realm until the end of Eocene (e.g., Soták et al., 1994, 2005).

Two types of the Paleocene and Eocene synorogenic basins occurring in the Pieniny Klippen Belt and adjacent zones developed in response to activity of the prograding front of the Western Carpathian orogenic wedge: (i) trench-foredeep basins of the foreland Oravic area in front of the advancing wedge tip; (ii) piggy-back basins on top of the orogenic wedge (Myjava–Hriňov Group of the Gosau Supergroup). Time and space evolution of these two types of syntectonic basins exhibits close mutual relationships controlled by the wedge dynamics. According to Plašienka and Soták (2015), the peripheral trench-foredeep depozones migrated from the South Penninic–Vahic oceanic realm toward the outer Oravic domains (Šariš Unit), where the synorogenic deposits were laid down with a coarsening- and thickening-upward trend before being overthrust by the propagating orogenic wedge tip. The development of wedge-top basins was ruled by the dynamics of the underlying wedge, composed of the frontal elements of the Central Western Carpathian cover nappe systems.

2.8. The Paleogene structural record in the Central Western Carpathian complexes

The meso-scale structural record for the entire Late Cretaceous–Paleogene–Early Miocene period is poorly constrained, since only the overall W–E to gradually NW–SE shortening with either purely compressional, or dextral transpressional regimes are interpreted from palaeostress analyses along the outer Central Western Carpathian edge (e.g., Marko et al., 1995; Pešková et al., 2009; Mikuš, 2010; Vojtko et al., 2010; Šimonová and PLAŠENIKA, 2011). In the internal complexes of the Central Western Carpathians, as well as in the Northern Pannonian domain, Paleocene–Eocene palaeostress with the NW–SE to NW–NESW main compression was interpreted in present map view (e.g., Vass et al., 1993; Fodor et al., 1999; Márton and Fodor, 2003; Vojtko et al., 2010; Šükalová et al., 2012). The Paleocene–Middle Eocene transpressionally tectonic regime progressively changed to transtension here. Time brackets for this development are based on stratigraphic arguments, with an upper limit given by undeformed Upper Eocene–Oligocene formations (e.g., Marko et al., 1995; Pešková et al., 2009; Vojtko et al., 2010; Šükalová et al., 2012). However, assuming the general CCW block rotation of the Western Carpathian domain by at least 50° during the late Early Miocene (e.g., Márton et al., 2013), the horizontal compression axis should be corrected to roughly NW–SE to NE–SW for the Paleogene, in general. The palaeostress field then rotated clockwise, being triggered by the eastward relocation of the collision processes along the front of the Carpathian orogen during the Miocene.

3. Model of the Palaeogene palaeogeography and geodynamic evolution

3.1. Danian–Ypresian (~65–50 Ma)

The early Paleogene palaeogeography of the Western Carpathians assumes existence of a continuous belt of oceanic crust between the southern margin of the Northern European Platform and the northward prograding Alpine-Carpathian orogenic system (e.g., Ziegler, 1990; Oszczypko, 2006; Schmid et al., 2008; Eggert et al., 2009; Zanchetta et al., 2012; Handy et al., 2015). The northern part of the Carpathian embayment of Alpine Tethys represented the eastern prolongation of Helvetic shelf and slope facies, and corresponds to the Waschberg–Zdiánice (Pouzdřany) and Subsilesian basin system with sedimentation of variegated hemipelagic marls and thin-bedded turbidites (Picha et al., 2006). Basinal deep water facies were deposited in the Silesian and Skole basins, divided by the emerged Subsilesian Ridge (Fig. 3). Southwards, the Silesian Ridge (e.g., Golonka et al., 2006) separated the Silesian Basin from the Magura oceanic realm with deep-water sedimentation, which continued westwards to the Northern Penninic Rhenodanubian–Valais domain in the foreground of the Eo-Alpine thrust system of the Alps. During the Paleocene and Early Eocene, an increase of tectonic subsidence was detected in the whole oceanic realm of the Outer Western Carpathian basins (Poprawa et al., 2006). In front of the outer edge of the Eo-Alpine orogenic system of the Eastern Alps and the western part of Western Carpathians, the subduction of the eastern part of Southern Penninic oceanic realm terminated around the Cretaceous/Paleogene boundary (Mateři Zone, Ybbsitz Klippen Belt, Kahlenberg nappe, Vahic units – Homayoun and Faupl, 1992; Schnabel, 1992; Faupl and Wagreich, 2000; Kurz et al., 2001; Froitzehim et al., 2008; Plašienka, 2012), while the Ligurian–Piemont oceanic domain still persisted in the west (e.g., Handy et al., 2010, 2015). Similarly, in front of the eastern margin of the approximately
N–S oriented Eo-Alpine Central Western Carpathians (e.g., Csontos and Vörös, 2004), the Iňačovce–Kričev remnant oceanic basin was located (Fig. 3), and remained open until the Eocene (e.g., Soták et al., 1994, 2005). This basin was separated from the Magura oceanic realm by the Oravic domain, partly consisting of thinned continental crust represented by the submerged NW–SE to W–E oriented Czorsztyń Ridge (e.g., Picha et al., 2006).

Development of the Western Carpathian orogenic wedge was in a close relationship to the outward propagation of subduction during the more-or-less continuous consumption of oceanic lithosphere. The termination of the Southern Penninic–Vahic subduction in front of the western part of Central Western Carpathians was followed by a northward progradation of the accretionary wedge buttressed by the rigid part of the orogen. The stacking events along its outer edge were related to the incipient collision and ensuing underthrusting of an incoming continental fragment – the Oravic Czorsztyń Ridge. During the convergence, evolution of synorogenic trench/foredeep and wedge-top basins was principally controlled by the wedge dynamics, which was interpreted in terms of the critical taper theory (Plašienka and Soták, 2015). Following underthrusting, the sedimentary cover of the Czorsztyń continental ribbon was detached and thrust over the foredeep basin facing the Magura realm, and the collisional zone was
affected by out-of-sequence thrusting and backthrusting in a compressional to dextral transpressional regime. In general, the wedge was critically to supercritically tapered in this period (cf. Plašienka and Soták, 2015). Nevertheless, parts of the accretionary wedge and adjacent outer zones of the Central Western Carpathians were flooded by a shallow sea in the wedge-top Myjava-Hríčov Basin.

Following the Eo-Alpine thrust stacking and burial of the basement complexes, the internal Central Western Carpathian zones were subjected to the Late Cretaceous–Paleocene uplift and erosion. The post-orogenic collapse, exhumation, and erosion postdating the nappe stacking was documented in the whole territory of Tatra, Veporic, and Gemeric units (Kováč et al., 1994; Danišák et al., 2010; Králiková et al., 2014a,b; Plašienka et al., 2007; Králiková, 2013; Vojtko et al., 2016; Hôk et al., 1993; Plašienka, 1993, 1999; Janák et al., 2001; Jeřábek et al., 2007, 2008, 2012).

The Paleocene movement of the Adriatic (Apulian) microplate toward the north generated a build-up of compression in the Alpine, Western Carpathian and Dinaric orogenic systems (e.g., Dercourt et al., 1986; Albarello et al., 1995; Rosenbaum et al., 2002, 2004; Rosenbaum and Lister, 2005). Besides the frontal collision and gradual shortening in the Alps and in the western part of Central Western Carpathians, the Adriatic plate push simultaneously triggered the westward to south-westward propagation of the Dinaridic orogeny wedge (Fig. 3). Evolution of the entire orogenic system was accompanied by dextral wrenching along the NW–SE oriented fault systems (Tari, 2002; Schmid et al., 2008; Korbar, 2009). Such dextral wrenching was documented also along the Hurbanovo–Diošjenoj Fault (Vass et al., 1993). Owing to geological data, the fault separating the Central Western Carpathians and units of the Northern Pannonian domain can be assumed as the easternmost segment of the Periodiatic Fault active during the Paleocene–Eocene time (Fig. 3). This fault (suture) formed a boundary between the northern Alpine and Central Western Carpathians units on its northern side and the southern Alpine (Transdanubian) and Dinaridic (Bük) units on its southern side, all composed the future Miocene ALCAPA microplate. The final amalgamation of the Northern Pannonian Transdanubian Unit to the Central Western Carpathians along this boundary is documented by upper Rupelian deposits which already seal the Hurbanovo–Diošjenoj Fault (e.g., Tari et al., 1993; Vass et al., 1993; Kázmér et al., 2003).

3.2. Ypresian to Lutetian (~50–40 Ma)

Across the Paleocene/Eocene transition, the shallow-water sedimentary record is incomplete at the northern and southern shelves of the Alpine Tethys. Erosional surfaces indicate a major sea-level drop that was terminated by the Early Eocene transgression within the calcareous nanoplankton zone NP12 (Egger et al., 2009). During the Lutetian, flysch troughs of the Northern Penninic–Magura oceanic realm (Fig. 4) reached the deepest bathymetric conditions with deposition of non-calcareous clays and basinal turbidites below the CCD (Oszczypko, 1992, 2006, Oszczypko et al., 2015). This type of sedimentation took place also in the Silesian, Dukla, and Skole-Skyba basins and persisted up to the Bartonian.

Closing of the Southern Penninic–Vahic domain and shift of subduction to the leading edge of the Western Carpathian orogenic wedge composed of the detached Oravic units of the Pieniny Klippen Belt initiated establishment of a new – Magura subduction in the north-east. Subduction pull toward the trench triggered gravitational collapse of the wedge and flooding of the wedge-top area (Myjava–Hríčov Basin) in the late Ypresian to earliest Lutetian. Consequently, the wedge geometry changed to the subcritical state and the wedge-top basin subsided up to bathyal depths. Pelagic sedimentation, in part even below the CCD, is revealed by widespread calcite-poor variegated shales (Plašienka and Soták, 2015). On the other hand, the Central Western Carpathian background area remained elevated and fed the inner parts of the wedge-top basin by vast masses of carbonatic scarp breccias derived from the Triassic carbonates of the Hronic Unit (Marschalko and Samuel, 1993).

In the Late Lutetian, subduction of the Magura oceanic crust initiated offscraping of the Outer Western Carpathian Biele Karpaty Unit, which was accreted to the Carpathian orogenic wedge toe and shortened internally. Compressional growth of the accretionary wedge caused its internal deformation by shortening, thickening, out-of-sequence thrusting and backthrusting, and ensuing surface uplift of the Paleocene–Middle Eocene wedge-top basin (Myjava–Hríčov Zone), and its partial erosion in the latest Lutetian–Bartonian times. However, at the eastern and south-eastern front of the Central Western Carpathians, subduction of the Ihačovec-Kričevo remnant oceanic basin still continued (Fig. 4). Later on, gradual closing of this basin brought about continuous deformation of the accretionary complexes and partly also their underthrusting below the front of the overriding orogenic wedge (Ihačovec Unit; Soták et al., 2000).

Although a transpressional tectonic regime dominated in the growing accretionary wedge, the Lutetian lateral movements of individual segments of the Eastern Alpine-Western Carpathian orogenic system generated also widespread extension. Since the Eastern Alps moved to the N and the Central Western Carpathians to the NE–E, the extension affected particularly the zone of their junction. As a result, a subsiding zone developed above a weakened lithosphere – a marine strait that probably connected the Magura oceanic domain with the South Penninic remnant basin to the west and later also with the Dinaridic foredeep to the south (Fig. 4). Relics of this basin system occur in the western part of the Central Western Carpathians (Bánovce and Horná Nitra basins) bordered by the N–S striking Central Slovak Fault System from its eastern side following the Turiec Basin in present coordinates (Fig. 1). This boundary acted as a transtensional sinistral strike-slip fault zone (Kováč and Hôk, 1993; Hôk et al., 1995) and subsidence of the aforementioned basin depocentres (Rajec, Turiec, and Horná Nitra basins; Gross, 2008) was controlled mainly by the NW–SE oriented normal faults (in present position).

In the hinterland of the Eastern Alps, a stratigraphic gap within the Gosau Group is reported in the Carinthian area (Fig. 4). However, nummulitic marlstone and limestone were deposited in the late Ypresian (Kázmér et al., 2003; Egger et al., 2009). The Lutetian transgression from the remnant South Penninic oceanic zone situated to the west invaded eastward along the Periadriatic suture zone, and besides the Carinthian Basin it later reached also the Northern Hungarian-Slovenian Paleogene Basin. The Eocene platform carbonates unconformable overlain the Paleozoic and Mesozoic sequences of the Northern Pannonian domain, often with bauxite and coal-bearing sediments below (e.g., Kázmér et al., 2003; Tari et al. 1993). The idea that the Northern Hungarian-Slovenian Paleogene Basin communicated with the Dinaridic foredeep toward the south is supported by a similar palaeo-bioprovincial character of fossil assemblages (manifested first of all in the widespread distribution of alveolinids) in sediments of the Transdanubian Unit and Dinarides (Kecskeméti and Vörös, 1975; Drobne et al., 1977; Less et al., 2000). Moreover, the Transdanubian Unit exhibits the Southern Alpine affinity; consequently it should have been situated on the northern margin of the Adriatic (Apulian) microplate together with the Dinaridic foredeep basin (Fig. 4), where the carbonate platform was drowned and flysch deposition started during the Eocene (Tari, 2002).

3.3. Bartonian–Priabonian (~40–35 Ma)

The Bartonian–Priabonian time span is characterized by the continuing convergence of the Alpine-Western Carpathian orogenic system with the Northern European Platform resulting in the final stage of the collision in the Western Alps (Fig. 5). Push of the Adriatic plate forced closing of the whole Penninic domain there, connected with thrusting of the Alpine orogenic wedge over the Helvetic platform margin (e.g., Jilíšek, 1979; Dercourt et al., 1986; Kováč et al., 1994; Albarello
et al., 1995; Linzer et al., 2002; Rosenbaum et al., 2002, 2004; Rosenbaum and Lister, 2005; Ustaszewski et al., 2008; Handy et al., 2010, 2015).

In the north-east, the Magura oceanic crust was progressively consumed below the Western Carpathian orogenic wedge including the already accreted Pieniny Klippen Belt and Biele Karpaty units (Fig. 5). Beginning of the Magura Basin shortening is marked by the Lutetian increase in the sediment accumulation rate (Poprawa et al., 2006). This process started with deposition of the Magura-type sandstones derived from the innermost toward external zones. Finally, deposition of sandstones and calcareous marlstones was changed to deposition of weakly calcareous sandy turbidites during the Late Eocene (Oszczypko et al., 2015). Then accumulation of turbiditic facies was replaced by hemipelagic and sapropelic sediments (Globigerina Marls) at the Eocene/Oligocene boundary (e.g., Oszczypko and Oszczypko-Clowes, 2009).

Along the eastern and south-eastern edge of the Central Western Carpathians and Northern Pannonian domain, subduction of the Iliačovce-Kričev Basin basement gradually ceased. The Iliačovce Unit was underthrust below and the Kričev Unit accreted to the orogenic wedge tip, along with the Pieniny Klippen Belt. In a consequence, the active trench shifted to the Magura domain also there (Fig. 5).

Across the Lutetian/Bartonian boundary, the shortening along the northern front of Western Carpathians was associated with folding...
and thrusting of the internal zones of the Outer Western Carpathians accretionary wedge (Biele Karpaty Unit). As subduction of the Magura oceanic crust accelerated, the wedge attained critical to supercritical taper. In the western sector of the Pieniny Klippen Belt, transpressional backthrusting in the rear parts of the Outer Western Carpathians accretionary wedge and retrograde compression (Plašienka and Soták, 2015) brought about partial exhumation of the Central Western Carpathians basement complexes (e.g., Kováč et al., 1994; Králiková et al., 2014a,b).

The late Lutetian – earliest Bartonian inversion of the wedge-top basins (Myjava–Hričov Zone) was followed by a shallow-marine transgression from the Magura Sea (Fig. 5). Due to a sea-level rise, the outer Central Western Carpathians margins were flooded and carbonate clastics and biogenic limestones were deposited in the so-called Central Carpathian Paleogene fore-arc basin. After the development of carbonate ramps, an enhanced regional subsidence and progressive deepening was documented (Soták et al., 2001). The extensive basin system finally covered most of the Central Western Carpathian area (Fig. 5). The rests of uplifted internal orogenic zones supplied bodies of mass-flow conglomerates entering the accommodation space from the basin margins (Soták et al., 2001). Temporal and lateral migration of the Late Eocene–Oligocene depocentres of the fore-arc basin from west to east.
in present coordinates is in a good agreement with the proposed advancing of the Magura subduction after the final accretion of the Iľačovce-Kričev Zone (Fig. 6).

In the hinterland zones of the Eastern Alps and Central Western Carpathians, the compressional tectonic regime was still triggered by the northward translation of the Adriatic plate (e.g., Dercourt et al., 1986; Albarello et al., 1995; Rosenbaum et al., 2002, 2004; Rosenbaum and Lister, 2005; Handy et al., 2010). The retro-arc shortening brought about growing of the Southern Alpine nappe pile and thrusting events in the Dinarides (Tari, 2002; Kovács et al., 2007), which were associated with rapid deepening of the sedimentary environment of the backward basin system (Fig. 2). In the Northern Hungarian–Slovenian Paleogene retro-arc basin, located partly above the Transdanubian and Bükk units, it resulted in deep-water and turbidite sedimentation (Tari et al., 1993). The siliciclastic influx of a marginal delta system from NE during the late Bartonian to early Priabonian was documented (in present coordinates). The retro-arc basin was connected with the Dinaridic foredeep toward the south (Fig. 5).

The Late Eocene–Early Oligocene andesitic volcanic activity (37–30 Ma), which occurred along the Periadriatic Fault, was perhaps related to the break-off of the Ligurian slab and mantle upwelling between the Northern European Platform and the Adriatic microplate;

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but in the Dinarides it can be related to subduction of the Sava–Vardar or Budva–Pindos domains (von Blanckenburg and Davies, 1995; Tari, 2002; Kovács et al., 2007).

3.4. Oligocene–Early Miocene (~35–20 Ma)

Evolution of the Western Carpathians was closely related to the final stages of collision in the Alps and simultaneously to stretching of the Central Western Carpathian margin by accelerated subduction of the Magura and afterwards also Krosno realms in the east (Figs. 6, 7, and 8). Impacts of the compression and subduction roll-back brought about gradual individualization of the ALCAPA lithospheric fragment, and later initiated also its Early Miocene tectonic escape north-eastward (e.g., Ratschbacher et al., 1991a,b; Csontos et al., 1992; Kovács et al., 1994; Fodor et al., 1998).

The Oligocene palaeogeography of the Outer Western Carpathians (Figs. 6 and 7) indicates gradual ceasing of subduction of the Magura oceanic realm and continuous development of a fold-and-thrust system of the future Magura Unit (Oszczypko and Oszczypko-Clowes, 2006, 2009). During the Rupelian, as a result of regional compression, the basins of the Silesian-Krosno domain were disconnected from the World Ocean (Van Couvering et al., 1981, Oszczypko-Clowes, 2001).

This caused a basin isolation, decline in the current circulation and anoxic environment with eutrophic blooms. Dark deep-water shales were deposited with exception of the remnant Magura sub-basin, where syntectonic deposition of sandstones occurred in this time (Picha and Straník, 1999; Kotlarczyk and Uchman, 2012; Oszczypko-Clowes and Żydek, 2012). The Fore-Magura/Dukla units display a similar sedimentary facies like the Silesian-Krosno domain. Dark bituminous shales and cherts are intercalated and overlain by thick-bedded turbiditic sandstones (Ślączka and Walton, 1992; Dirnerová and Janočko, 2012). Several parts of the Magura sub-basin were tectonically uplifted and the Magura nappe system was thrust over the Fore-Magura/Dukla and Silesian sedimentary area in the Chattian (Oszczypko and Oszczypko-Clowes, 2009). The fill of individual sub-basins is characterized by thick bedded synorogenic sandy turbidites of the NP 24–25 zones (Fig. 7). The piggy-back basins above rear parts of the Outer Western Carpathian accretionary wedge (Figs. 7 and 8) provide evidence for the Early Miocene closing of the Magura Basin (e.g., Cieszkowski, 1992; Oszczypko and Oszczypko-Clowes, 2002, 2014; Oszczypko et al., 2005; Soták et al., 2012; Oszczypko-Clowes et al., 2013). However, deposition of mudstones, laminated limestones, and distal turbidites is
documented till the Late Oligocene/Early Miocene boundary (Potfaj, 1983; Cieszkowski and Olszewska, 1986).

The Oligocene palaeogeography of the Alpine-Western Carpathian mountain chain reflects culmination of compression, which led to the nappe stacking and considerable N–S shortening in the Alps. Progressing collision was followed by division of the orogen into the western and central-eastern segments by the Giudicaria bend zone (Pomella, 2010; Pomella et al., 2011). The Central Western Carpathians most probably moved also to the north, along a bend zone (Rába zone) located along the western border of this easternmost segment of the orogenic system (Figs. 6 and 7). Below the propagating front of the Central Western Carpathians, LT/MP metamorphism and penetrative ductile deformation affected the deeply buried Ihačovce Unit in the same time (Soták et al., 1993, 1994, 1995, 1999).

The movement of the Adriatic plate triggered progressive underthrusting and imbrication of the Adriatic platform, generating fold-and-thrust structures in front of the Dinaridic Western Thrust Belt (Tari, 2002) and was responsible also for uplifts along the whole Alpine chain (Figs. 6 and 7). The eastern edge of the Central-Eastern Alps, together with western part of the Central Western Carpathians, was gradually exhumed (Kováč et al., 1994; Dunkl and Demény, 1997; Fügenschuh et al., 1997; Hejl 1997; Dunkl et al., 2005; Daniščík et al., 2004, 2008; Kühlemann, 2007; Králiková et al., 2014a). Exhumation and uplift, which continued during the whole Late Oligocene–Early Miocene, brought about strong denudation of the present Danube Basin basement. According to available data, this is built up only by crystalline rocks in its central part, whereas the Mesozoic and Paleogene sediments are missing (Biela, 1978; Fusán et al., 1987; Kováč et al., 2011). This process influenced also uplift of the Transdanubian Unit in the orogen hinterland (Figs. 6 and 7). Uplift of the western part of the Northern Pannonian domain was associated with extensive erosion of the Late Eocene retro-arc basin and shift of the basin depocentre toward the east (Kázmér et al., 2003).

In contrast to the uplifted thrust stack of the Alps (together with pre-Neogene basement of the present Danube Basin), the Central Carpathian Paleogene Basin subsided on the stretched margin of the Central Western Carpathians in the east. The widening of this fore-arc basin was induced by the prograding Magura subduction pull (Fig. 6); and the basin underwent disintegration by sinistral strike-slip faults, which had the NNE–SSW to NE–SW orientation before the Miocene counter-clockwise rotation (e.g., Pešková et al., 2009; Vojtiko et al., 2010; Súkalová et al., 2012). Active faulting controlled also the continental to shallow marine deposition in several intramontane basins of the Central Western Carpathians (Marko and Vojtiko, 2006).

During the Rupelian, the accelerated subsidence in the Central Carpathian Paleogene Basin (Fig. 6), together with semi-isolation of the whole Carpathian basin system from the Mediterranean, led to a dysoxic deep-water deposition (Soták et al., 2001). During the Chattian, the collapsed orogenic wedge remained in a subcritical state either due to a subduction retreat of the Magura domain, or due to a subcrustal erosion (Wagreich, 1995; Kázmér et al., 2003). The basin subsided considerably and was filled with a large amount of deep-marine, thickening-upward clastic sediments (Fig. 7). The turbidity currents entering the fore-arc basin were composed of terrigenous material derived not only from the uplifted Central Western Carpathian basement and nappe units (Sliva, 2005), but also from the Outer Western Carpathian accretionary wedge complexes (Starek et al., 2012). The youngest turbidite fan complexes belong to the NN–1 zone; which provide sedimentological and ichnofacial features of the still deep-water environments (e.g., Soták, 1998, 2010; Starek et al., 2000; Garecka, 2005).

The Outer Carpathian provenance of a great amount of clastic material in the fore-arc basin is evidenced by the transport direction of the turbidite systems, arranged in longitudinal fans which laterally prograded from opposite sides of the Central Carpathian Paleogene Basin (Marschalke, 1964). From the north-west, a lot of terrigenous sandy material was transported from the Rhenodanubian and Magura flysch belt units toward the basin by a river discharge already during the Rupelian (Starek et al., 2013). In the opposite south-eastern part of basin, the mostly Chattian turbidite complexes document a source situated in the south-east (Figs. 6 and 7). Besides an upward increasing amount of mixed siliciclastic-calciclastic material, turbidites exhibit a peculiar feature – input of ophiolite-derived debris, like serpentinitic sandstones (Soták and Bebej, 1996) and enormous amount of Cr-spinels in the heavy-mineral concentrates (up to 80%; Soták et al., 1996). Consequently, the provenance area included obducted or mélangé-type ophiolite complexes, which were correlated with an imbricated part of the Ihačovce Unit (Soták and Bebej, 1996; Soták et al., 1996). Sources of these sediments could be therefore the uplifted accretionary wedge complex of the Ihačovce, Kríčovo, and Szolnok zones and probably, owing to its position, also the Sava Zone of the Internal Dinarides (Figs. 6, 7 and 8).

We suppose that the preserved sediments of the Central Carpathian Paleogene Basin represent only erosional remnants (Fig. 1), since the fore-arc basin system should have covered more extensive areas from the Buková Furrow in the Malé Karpaty Mts. across the Horná Nitra Basin in the west up to the Eastern Slovakia Basin in the east (Marko et al., 1990; Soták et al., 2005; Marko and Vojtko, 2006; Fordinál et al., 2012; Zlinská, 2013; Zlinská and Gross, 2013). It is most probable that a seaway connection between the Magura Basin and Northern Hungarian–Slovenian Paleogene retro-arc basin developed already during the Rupelian; which is supported by a transgression over the stretched Central Western Carpathian orogenic axis represented by the north-eastern parts of the Tatic, Veporic, and Gemic units (Vojtko, 2000; Plašienka and Soták, 2001; Soták et al., 2005).

In the hinterland of the Eastern Alps and Central Western Carpathians, the Early Oligocene compression that generated uplift and erosion of the Eocene Northern Hungarian–Slovenian Paleogene Basin resulted in important structural and geological changes. The role of the Hurbanovo–Diőszénő Fault as a continuation of the Periadriatic Fault finished (Figs. 7 and 8), and the Slovenian segment of Periadriatic Fault – the Celje fault zone developed (Fodor et al., 1998). At the same time, we suppose activation of the juvenile Rába Fault, which was forced by propagation of the Adriatic microplate, like in the case of the Giudicaria Fault (Pomella, 2010; Pomella et al., 2011), The Rupelian uplift of the Transdanubian Unit was simultaneous or followed by its eastward translation, which squeezed the weakness zone between the Eastern Alps and Central Western Carpathians (e.g., Balla, 1994). In the late Rupelian, a new depocentre of the Hungarian Paleogene Basin developed along the Hurbanovo–Diőszénő Fault. The so-called Pétervására Basin located more to the east from the previous retro-arc basin covered not only the Northern Pannonian domain units, but also the units of the southern Central Western Carpathian zones. In the basin axis, anoxic clays were deposited, while contemporaneous coarse siliciclastics at the basin margins originated from the emerged Eastern Alps and Central Western Carpathians. The maximal extension of the accommodation space was at about the early-middle Chattian (Fig. 7), while the basin’s depth started to decrease gradually from the late Chattian until the Burgdiganian (Sztań, 1995; Tari et al., 1993).

The Late Oligocene–Early Miocene evolution of the Northern Hungarian–Slovenian Paleogene Basin was influenced by the increasing activity of wrench faults systems. The faults were responsible for tectonic inversion in the northern Dinarides and tilting of the Eocene and Oligocene formations (Fodor et al., 1998; Tari, 2002), and later also for the initial disruption of the basin into two sub-basins (Fig. 8). In such a way, lateral movements along the Periadriatic and Sava-Celje fault systems disconnected units of the ALCAPA microplate (Transdanubian and Bükk units) from the Southern Alpine and Dinaridic realm, and later accommodated also its north-eastward lateral escape (e.g., Ratschbacher et al., 1991a,b; Csontos et al., 1992; Fodor et al., 1998; Rögl, 1999; Linzer et al., 2002).

The Early Miocene translation of the ALCAPA can be followed eastward along the Mid-Hungarian transect zone. The extensive
accretionary wedge complexes of the Szolnok Zone were pushed here over the margin of the Tisza microplate and, together with complexes of the Kríčovo Zone, toward the east (Fig. 8). At present, they are part of the deeply buried Szolnok Flysch Trough Unit (Csontos and Nagynarosy, 1998) and are known also form the pre-Neogene base ment of the Transcarpathian Basin, as well. The Early Miocene escape of ALCAPA initiated also a partial exhumation of the buried units of Iňáčovo accretionary wedge complexes in front of the Central Western Carpathians (Soták, 2000).

The Oligocene–Early Miocene volcanic activity (34–22 Ma) along the Periadriatic Fault in the Alps, Sava–Vardar zone in Internal Dinarides and in vicinity of the Mid-Hungarian Fault shows a number of subduction–related geochemical characteristics (e.g., Konečný et al., 2002; Kovács et al., 2007; Kovács and Szabó, 2008; Schmid et al., 2008). There are various opinions and alternative hypothesis about their origin, which can be related to subduction of the Penninic, Magura or the Budva-Pindos-Vardar oceanic plates during the Mesozoic and Paleogene.

4. Discussion

The collision zone between the Northern European Platform and Africa had a complicated geodynamic evolution characterized by presence of numerous micro-continents and micro-oceans. Their mutual positions were changing during the Mesozoic and Cenozoic as a result of complex processes of rifting, oceanic crust production, its subduction and ensuing collision of the individual crustal fragments – microplates.

The presented model of the Paleogene palaeogeography of the Western Carpathians is based on the terrane concept – microplates composed of crustal fragments of various origin and provenance (e.g., Kovács et al., 2010). Consequently, all terranes can only be classified as entities with limited existence in time and space. Accordingly, the Western Carpathians were defined as a part of the Miocene ALCAPA microplate, which embraces also the Eastern Alps and Northern Pannonian domain (e.g., Ratschbacher et al., 1991a,b; Csontos et al., 1992; Kováč et al., 1994). However, the situation was different during the Paleogene, since the southern margin of ALCAPA – the Mid Hungarian Fault did not exist yet.

On contrary, the boundary between the Alpine–Western Carpathian domain located in the north and the Southern Alpine–Dinaridic domain placed in the south was formed by the Periadriatic Fault already during the Paleogene (Fig. 3). The Periadriatic Cretaceous–Paleocene fault represents a suture zone between the northern Alpine orogenic system which was thrust over the European Platform and the nappe stack of the Adriatic plate, thrust generally to the south (e.g., Grad et al., 2009). Therefore the Hurbanovo–Diósjenő Fault dividing two crustal fragments with different provenance and vergency of thrusting; the Central Western Carpathians analogously to the Eastern Alps, and the Northern Pannonian domain with an affinity to the Southern Alps and Dinarides (Transdanubian Range and Bükk units; e.g., Csontos, 1988, 2000; Haas et al., 2001; Haas and Kovács, 2001; Kováč et al., 2002; Filipović et al., 2003; Froitzheim et al., 2008) could represent a Paleocene–Eocene boundary with a similar function like the Periadriatic Fault (Figs. 1 and 2). Moreover, the re-evaluated data reveal that before the Paleogene, the Northern Pannonian domain units were most likely positioned between the Eastern Alpine–Western Carpathian and the Southern Alpine–Dinaride belts (e.g., Csontos et al., 1992; Kováč et al., 1994).

Summarizing the present day knowledge about the nature of the aforementioned crustal boundary (Hurbanovo–Diósjenő Fault), together with an analogous complicated tectonic boundary situated between the Eastern Alpine, Central Western Carpathian and the Northern Pannonian domain complexes represented by the Rába Fault, we could often obtain conflicting explanations. This state of affairs results from the present day situation, because the boundaries of these crustal fragments are mostly covered by a thick Neogene to Quaternary basin fills and their nature is only inferred from several boreholes and seismic lines (e.g., Kílényi and Šefara, 1989; Vass et al., 1993; Balla, 1994; Kováč et al., 2002; Haas et al., 2010, 2014).

According to the present views, the NE–SW oriented Rába Fault (Fig. 1) bordering the Transdanubian Range from the north-west represents a Cretaceous nappe boundary (Horváth, 1993; Fodor and Koroknai, 2000; Haas et al., 2010). However, the north-western margin of the Transdanubian Range Unit was affected and reactivated by a superimposed sinistral oblique-slip movement (Haas et al., 2014). This tectonic character was therefore interpreted as an important structural boundary, which developed during the tectonic escape of the Transdanubian Range crustal fragment from the Alpine compression zone during the Late Paleogene–Early Miocene (Kázmér and Kovács, 1985). This concept interpreted the Rába Fault as a deep-rooted strike-slip zone that might penetrate the entire crust and which separates crustal fragments of significantly different geological structure and palaeogeographic provenance (Balla, 1989).

The Hurbanovo–Diósjenő Fault and its prolongation in the Rapovce–Plešivec Fault (Fig. 1) represent a major structural boundary of W–E to WSW–ENE orientation between the Central Western Carpathians and Transdanubian Range and Bükk units. The fault system is covered by the early Chattian (Kiscellian) sediments deposited above the Northern Pannonian domain and above Central Western Carpathians (Vass, 2002). The elongated shape of the late Chattian to Burdigalian (Egerian to Egggenburian) Pétværására Basin depocentre situated between above eastern prolongation of the fault (Sztanó, 1994) and restriction of the Eocene–earliest Oligocene deposits of the Hungarian Paleogene Basin (Tari et al., 1993), together with the structural data documenting a NW–SE orientation principal maximal paleostress axis (e.g. Vass et al., 1993; Mártón and Fodor, 2003) led us to assume that Hurbanovo–Diósjenő Line represented a Late Oligocene – Early Miocene dextral wrench fault zone. The north-eastern prolongation of the Hurbanovo–Diósjenő and Rapovce–Plešivec faults is formed by the Rozňava Fault zone (Vass et al., 1993; Plašienka et al., 1997a,b). Further east, this boundary is obliquely cut by the Darnó Fault that might have significantly displaced it to the NE.

The Darnó Fault of NE–SW orientation is located between the Bük Mountains and the Hungarian Paleogene Basin to the west (Fig. 1). The Darnó Fault (Telegdi-Roth, 1937; Schréter, 1942; Báldi, 1983) in an even broader sense is called also as Darnó Zone (Haas et al., 2014). The kinematics of this zone justified by the field measurements (Fodor et al., 2005) and seismic profile interpretations (Sztanó & Tari, 1993) can be considered as a compressional deformation belt. The basement rooted reverse faulting characterized by a large amplitude and southern vergency (thick-skinned back thrust) occurred along the southern margin of the fault zone. The Paleozoic rocks are thrust over the Mesozoic and Oligocene rocks located in the foreland of the Uppony Hills in the east (Schréter, 1952; Pantó, 1954), so the thrust time along the Darnó Zone is dated from the latest Rupelian to Early Miocene. Nevertheless, several authors identified the strike-slip kinematics of the fault and postulated a 20–30 km sinistral displacement (e.g. Jaskó, 1946; Zelenka et al., 1983; Grill et al., 1984; Less et al., 1988; Szemptérey, 1997).

Schmid et al. (2008) thought that the Darnó Fault could be one of the most important structures separating the mega-units. He speculated that the line is a continuation of the Palaeogene–Early Miocene Periadriatic Fault functioning as a right lateral strike-slip fault. On contrary, according to Haas et al. (2014) occurrence of different nappes of the same nappe series on each sides of the fault was caused by variable pre-Cenozoic denudation and deformation. Therefore this boundary holds no primary importance and does not represent a boundary between two tectonic mega-units. If the Darnó Fault does not represent tectonic contact between the Transdanubian and Bükk mega-units (Haas et al., 2014) the situation would be similar to the circumstances at the present contact of the Southern Alpine and Dinaridic units in Slovenia and northern Croatia. This fact also supports our view not only on the original position of the Transdanubian Range, but also on the tectonic character of its boundaries.
The next important point of our model and compilation of the palinspastic maps is the origin and function of the Rába Fault ancestor. On the first view, the position of the Rába Fault is similar to the Giudicaria Fault, which divides the Western and Eastern Alpine segments. Similarly, the Rába Fault divides the Eastern Alps from the Western Carpathian-Northern Pannonian segment of the ALCAPA microplate. Moreover, both faults represent Oligocene bend zones that were later transformed to strike-slip zones deforming the boundary between the northern and southern realms of the Alpine orogenic system (Periadriatic and Hurbanovo–Diošjénő faults; Figs. 6 and 7). In the west, the Giudicaria bend zone was formed during the Oligocene (Pomella et al., 2011). Similarly along the Eastern Alpine – Western Carpathian and Transdanubian Range Unit boundary, the Rába bend developed (Ballá, 1994). Origin of this bends was forced by the push of Adriatic plate, which led to shortening of the colliding orogenic system and its overriding the irregular margin of the Northern European platform with two rigid protrusions (spurs) toward the south. Later on, due to an increase of the compressional stresses, these bends acquired a character of sinistral strike-slip faults.

The final stage of the collision is well documented by termination of thrusting along the Alpine–Carpathian front, vanishing from the west to east: in the Western Alps during the Priabonian–Early Oligocene, in the Central and Eastern Alps during the Oligocene–earliest Miocene, and in the Western Carpathians from the Early Miocene onward (e.g., Jiříček, 1979; Kováč et al., 1998; Ustaszewski et al., 2010). The final Miocene thrusting of the Outer Carpathian nappes over the foredeep continued along the orogenic front up to its south-eastern extremity (Vrancea Zone), where it occurred in the Pliocene (e.g., Meulenkamp et al., 1996).

The progradation of collision from the west to east is confirmed not only by the last thrust events and development of foredeep depocentres along the orogenic front, but also by the evolution of depocentres in the orogen hinterland (e.g., Kázmér et al., 2003). Starting from the Priabonian, depocentres of the Hungarian Paleogene Basin migrated eastwards from the Transdanubian Central Range toward the Bükk Unit (Szántó, 1995; Tari et al., 1993; Rasser et al., 2008). Furthermore, the compression in the axial zone of orogenic system is well documented by the Oligocene–Lower Miocene uplift of the Alps (e.g., Dunkl & Demény, 1997; Hejl, 1997; Neubauer et al., 1997, 1999; Fügenschuh, 2000; Dunkl & Frisch, 2002; Dunkl et al., 2003; Kuhlemann, 2007; Bertrand et al., 2015) together with the western margin of the Central Western Carpathians (basement of the Danube Basin) including the Transdanubian Range Unit (time of origin and formation of the Rába bend – later Rába Fault).

In contrast to that, the eastern part of the Central Western Carpathians collapsed and subsidence of the Central Western Paleogene Basin occurred at that time. This extension was likely triggered by the Magura subduction roll-back in front of this part of the orogen. Collisional regime and uplift of the northern margin of the Central Western Carpathians commenced as late as in the Middle Miocene when thrusting of the orogenic system over the platform culminated (Danišk et al., 2010, 2012; Králiková, 2013; Králiková et al., 2014a,b).

5. Conclusions

Re-evaluation of the existing and new geological, sedimentological, biostratigraphical, and structural data from the Outer and Central Western Carpathians and North Pannonian Domain were summarized in a new interpretation of the Paleogene palaeogeography and geodynamics. The presented ideas are supplemented by a series of palinspastic and digital terrain model maps.

- Regarding the position with respect to the structural axis of the orogen, the synorogenic Paleogene basins were included in two basic groups – the fore-axis and back-axis basin systems (Fig. 2).
- The forward system comprises oceanic zones consumed in front of the prograding orogenic wedge with off-scraped sediments accreted to its tip, as well as marginal wedge-top depressions and the large-scale fore-arc basin developed on the upper plate. The retrowedge-related backward system embraces short-living wrench zone furrows and the large retro-arc basin.
- The development of the Western Carpathian accretionary wedge was in a close relationship to the outward propagation of subduction. The stacking events at the leading edge of the orogenic system were often related to temporary collisions with the intra-oceanic continental fragments – ridges. (i) The Southern Penninic–Vahic subduction terminated in the Danian and was followed by the Paleocene–Eocene underthrusting of the Oravic Czorsztyn Ridge. Subduction of the remnant Iľačove–Kričevo Basin in the east came to end during the Bartonian–Priabonian times. A part of the Paleocene–Middle Eocene subduction complexes (Iľačove Unit) was buried below the orogenic front and underwent the low-grade metamorphism during the Late Eocene–Oligocene, and then it was partly exhumed in the Early Miocene. (ii) Subduction of the Northern Penninic–Magura Ocean floor migrated from west to east; it began during the Lutetian in the west and during the Bartonian–Priabonian in the east. The vanishing Magura subduction was accompanied by a continuous growth of the fold-and-thrust system with maximum shortening during the Oligocene. Subduction of the Silesian–Krosno basement and development of the fold-and-thrust system commenced during the Late Oligocene, with the most significant shortening during the Miocene.
- The Paleogene evolution of the Central Western Carpathians is characterized by the Late Cretaceous–Paleocene exhumation and erosion of the Tatric, Veporic, and Gemenic units followed by formation of wedge-top and fore-arc basins. (i) The Paleocene–Middle Eocene evolution was associated with opening of the wedge-top basin depocentres of the Myjava–Hričov Zone, located along frontal margin of the advancing Eastern Alpine – Western Carpathian orogenic system. Lateral translations of individual segments generated crustal thinning. It resulted in opening of a lower-middle Lutetian basin in the western part of Central Western Carpathians, which probably connected the Magura oceanic realm with the Ligurian remnant basin and later also with the Dinaric foredeep. (ii) In the Late Eocene, margins of the Central Western Carpathians were stretched by accelerated Magura subduction pull and the Central Carpathian Paleogene Basin opened. The fast subsidence of this fore-arc basin reached its maximum in the Oligocene. The basin was filled not only with material derived from uplifted parts of the Central Western Carpathians, but mostly from the raised Outer Carpathian accretionary wedge complexes. The provenance analysis of turbidite systems, which laterally prograded from opposite sides of the basin, documents localization of their sources in the north-west (Rhenodanubian and Magura units) and from imbricated parts of the Iľačove–Kričevo and Szolnok zones in the south-east.
- In the uniform Northern Hungarian–Slovenian Paleogene Basin, the sedimentation began by the Paleocene–Early Eocene transgression from the west, and was followed by a distinct basin subsidence during the Late Eocene. (i) The Oligocene retro-arc compression brought about additional partial exhumation and surface uplift of the Central Western Carpathian basement complexes in the west (basement of the Neogene Danube Basin) and was associated with erosion of the Eocene sediments in the Northern Hungarian Basin lying above the Transdanubian Unit. The basin depocentres migrated toward the east (Bükk Unit), where the Pétervására Basin opened in the Late Oligocene. (ii) During the latest Oligocene–Early Miocene, individualization of the ALCAPA microplate took place, followed by its tectonic escape from the squeezed zone between the Eastern Alpine–Western Carpathian and Southern Alpine–Dinaric domains. The Northern Hungarian part of the Paleogene basin was transferred
north-eastward along the Mid Hungarian tectonic zone for more than 200 km from its previous position.

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