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Miocene basin opening in relation to the north-eastward tectonic extrusion of the ALCAPA Mega-Unit

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Abstract: The opening and evolution of the Western Carpathians Miocene basins was closely related to the north-eastward tectonic extrusion of the ALCAPA Mega-Unit lithosphere caused by the final stage of collision of the Eastern Alpine–Western Carpathian orogenic system with the European Platform and Alpine convergence with the Adria plate. The roll back effect of the oceanic or thinned continental crust of the Magura–Krosno realms, subduction below the front of the Carpathians in the north-east, east and relative plate velocities led to gradual stretching of the overriding micro-plates (defined as the ALCAPA and Tisza Dacia Mega-Unit). Diverse movement trajectories of the ALCAPA crustal wedge individual segments (Eastern Alps, Western Carpathians, and Northern Pannonian domain) were accompanied by several counter-clockwise rotational phases. Beside the interpreted Early Miocene "en-block" counter-clockwise rotation, most of the rotations in the Central Western Carpathians were caused by "domino-effect tectonics" inside strike-slip zones and took part in the basin opening, which was in most cases followed by rapid subsidence.

Key words: Neogene, ALCAPA Mega-Unit, structural evolution, basin development, "en block and domino-effect" counter-clockwise rotations.

Introduction and regional setting

The Miocene structural evolution of the Pannonian back arc basin, surrounded by the Alpine–Carpathian and Dinaride orogenic systems, was dominated by an extensive drift of unamalgamated microplates — Mega-Units: ALCAPA and Tisza–Dacia (Balla 1984; Ratschbacher et al. 1991a, b; Csontos et al. 1992; Kováč et al. 1994, 2017a; Csontos 1995; Konečný et al. 2002; Ustaszewski et al. 2008; Balázs et al. 2016; van Gelder et al. 2017; etc.). The Early Miocene palaeogeography and geodynamic history of the area points to a different layout of sedimentary basins and elevated parts of mountains serving as a source of sediments. Moreover, in front of the moving segments of the continental lithosphere toward the European Platform the folded and thrust deposits of remnant flysch troughs and foredeep depocentres accreted gradually to the Carpathian orogenic system front (e.g., Kováč et al. 1998, 2017a and references therein). Similarly, the basins in the orogene hinterland were in many cases located at least 200 km toward the southwest in respect to their recent position (e.g., Fodor et al. 1998; Tari et al. 1992; Schmid et al. 2008; Kováč et al. 2016, 2017a).

During the Middle–Late Miocene the tension in the subducting plate, involving now lithosphere formerly underlying the Outer Carpathian nappes (Royden et al. 1993a, b) caused widespread stretching of the overriding, partially amalgamated ALCAPA and Tisza–Dacia Mega-Units (e.g., Csontos 1995; Konečný et al. 2002; Balazs et al. 2017) expressed in the synrift stage of the back arc basin system (e.g., Horváth 1993; Magyar et al. 1999; Kováč 2000; Konečný et al. 2002; Balázs et al. 2016, 2017). Coupling to the subducting plate retreat north-eastward in front of ALCAPA and eastward in front of the Tisza–Dacia caused a continuous intense tension in both mega-units (Royden et al. 1993a, b; Csontos 1995; Kováč et al. 1998, 2017a; Balázs et al 2016). During the opening of sub-basins the movement trajectory of the ALCAPA Mega-Unit documents several counter-clockwise rotational phases (Fig. 1). The southern, Tisza–Dacia Mega-Unit rotated clockwise (e.g., Panaiotu 1998; Dupont-Nivet et al. 2005; Balázs et al. 2016). Moreover, counter-clockwise (CCW) rotations were also measured in the Outer Western Carpathian accretionary wedge, which documents a common movement trajectory of the whole, extruding system north-eastward (Márton et al. 2016).

The structural evolution of ALCAPA is handled in terms of a coupled system of: (1) Alpine orogene belt development owing to convergence of the Adria plate (2) lateral extrusion of the ALCAPA Mega-Unit lithosphere assisted by transform faults, (3) Carpathian gravity driven subduction of the oceanic or sub-oceanic lithosphere underlying former flysch basins and (4) back arc extension associated with the diapiric uprise of asthenospheric mantle followed by its cooling (e.g., Konečný et al. 2002; Balázs et al. 2016, 2017; van Gelder et al. 2017 and references therein).

The edge of the ALCAPA Mega-Unit, which originated in connection with the Miocene lateral extrusion of the Eastern Alps, Central Western Carpathians, and Northern Pannonian domain segments north-eastward, is rimmed by the Pieniny

Klippen Belt, which forms the innermost part of the Outer Western Carpathian accretionary wedge. The movement trajectory of ALCAPA was strongly influenced by the collision of the Eastern Alps and the Central Western Carpathians with the uneven edge of the European Platform.

During the Early Miocene, the collision operated along the frontal portion of the Eastern Alps, thrusted over the European Platform (Grad et al. 2009), while the Western Carpathians still propagated toward the embayment in the platform margin. Therefore, CCW rotation of the extruding crustal wedge was more moderate in the west and faster in the east (e.g., Márton et al. 1999, 2000b, 2004, 2007, 2009a, b, 2013, 2016; Márton & Fodor 2003). In the Eastern Alps an Early Miocene (~20–17 Ma) ~30° CCW rotation was determined, while in the whole Western Carpathians and Northern Pannonian domain the CCW rotation reached values up to ~50°.

The Middle Miocene rotation of crustal blocks (Fig. 1) in the Western Carpathians and North Pannonian Domain (Transdanubian Range and Bükk units) depended on the influence of several geodynamic factors. In the west, the oblique collision terminated, while in the east the front of the moving crustal wedge proceeded north-eastward into the vanishing gulf of the flysch troughs realm of the future Outer Western Carpathians. The influence of the rigid continental crust of the platform namely the Bohemian Massif, reaching far south below the Eastern Alpine over-thrust, and the accelerated pull of subduction in the east led not only to a curvature of the ALCAPA movement trajectory, but also to its stretching from the west to the east (e.g., Csontos 1995; Schmid et al. 2013; Scharf et al. 2013; Kováč et al. 2017a). In contrast to the Eastern Alps, an additional ~20° CCW rotation was documented in the western part of the Central Western Carpathians and the Northern Pannonian domain in the Early Miocene, followed by ~30° (~16–14 Ma) CCW rotation in the Middle Miocene. The last Middle/Late Miocene (~12–10 Ma) ~30° CCW rotation was measured at the eastern margin of the Central Western Carpathians in the area of the Transcarpathian Basin (Márton et al. 2007).

The general trends of the ALCAPA rotational movement trajectory and the apparent change of the orientation of stress field are consistent. In the Eastern Alps the main compressional stress axis was prevailingly oriented in a N–S direction during the whole Miocene, whereas in the western part of the Central Western Carpathians and Northern Pannonian domain a gradual apparent clockwise rotation of the main compressional stress axis is recorded (e.g., Csontos et al. 1992; Decker et al. 1993, 1994; Kováč & Hók 1993; Vass et al. 1993; Kováč et al. 1995, 2017a; Marko et al. 1995; Decker &

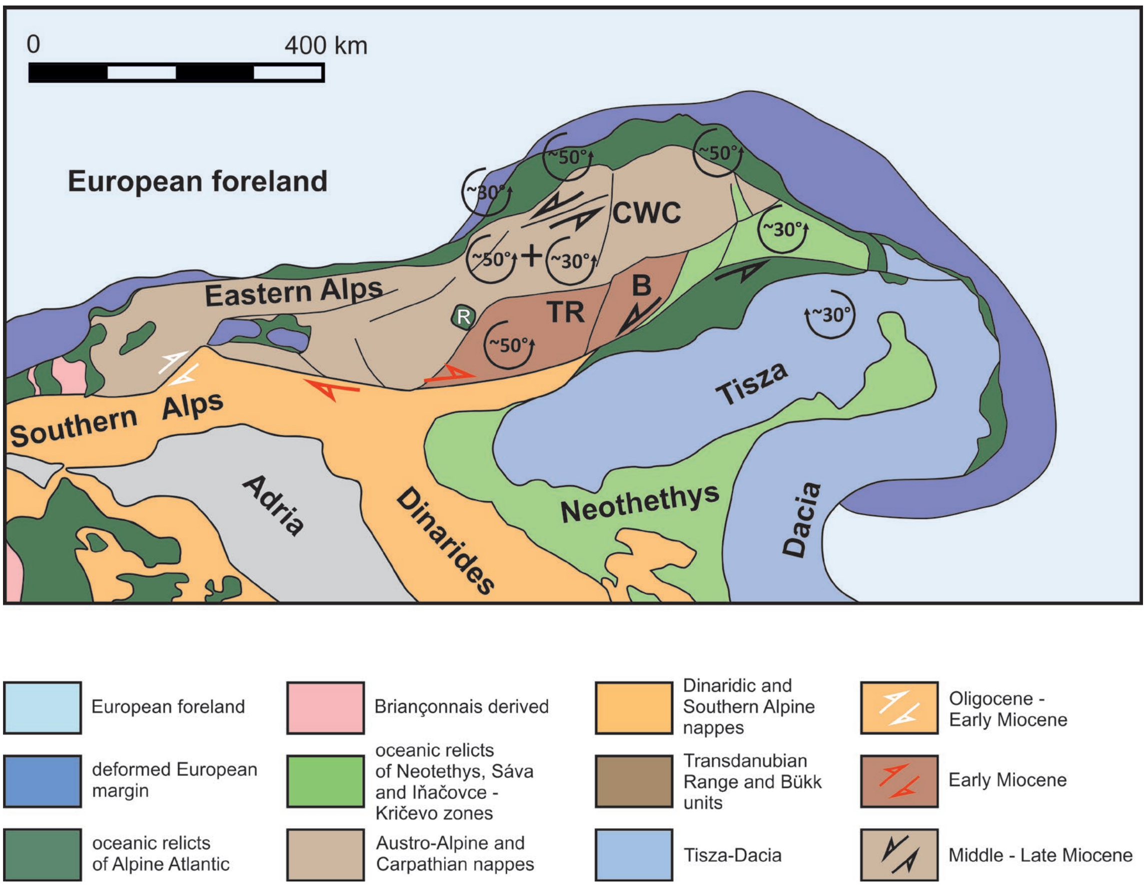

Fig. 1. Tectonic scheme of the Alpine–Carpathian–Pannonian system with marked ALCAPA and Tisza–Dacia Mega-units and rotation of their individual segments (CWC — Central Western Carpathians; TR — Transdanubian Range; B — Bükk Mountains).

Peresson 1996; Fodor et al. 1999; Linzer et al. 2002; Márton & Fodor 2003; Pešková et al. 2009; Bučová et al. 2010; Vojtko et al. 2010; Beidinger et al. 2011; Šimonová & Plašienka 2011; Sůkalová et al. 2012; Pulišová & Hók 2015).

Taking into consideration the previous results, we can document the existence of a latest Oligocene to earliest Miocene compressional tectonic regime with the WNW–ESE oriented main compressional axis (σ_1) in the western portion of the Central Western Carpathians and Northern Pannonian domain, followed by transpressional tectonics with the N–S oriented σ_1 roughly at the boundary of the Early/Middle Miocene. The Middle and early Late Miocene evolution was controlled by a transtensional tectonic regime with the NW–SE oriented minimal stress axis (σ_3) and perpendicular compression, respectively (e.g., Fodor 1995; Marko et al. 1995; Fodor et al. 1999; Pešková et al. 2009; Bučová et al. 2010; Vojtko et al. 2010).

In the eastern portion of the Central Western Carpathians the palaeostress field measurements include the Early Miocene compression with the NNE–SSW to NE–SW directed σ_1, which changed its position to the N–S direction at the end of the Early Miocene (Vass et al. 1988, 1993; Csontos & Nagymarosy 1998; Plašienka et al. 1998; Márton & Fodor 2003; Petrik et al. 2016; Kováč et al. 2017a). The Middle Miocene (Badenian) evolution of the Novohrad–Nógrád Basin in southern Slovakia and northern Hungary located above the Central Western Carpathians and Northern Pannonian domain as well as the Eastern Slovak Basin was controlled by an extensional tectonic regime with the NE–SW oriented σ_3. The change from an extensional to transtensional tectonic regime is indicated by the rotation of the main compressional stress axis σ_1 from a subvertical to a NNW–SSE-oriented subhorizontal position. At the boundary of the Middle/Late Miocene (Late Sarmatian–Early Pannonian), subsidence of the Eastern Slovak Basin was controlled by the NNW–SSE to N–S oriented σ_3 (Kováč et al. 1995) similar to the Late Miocene extension with the NW–SE oriented σ_3 in the area of the Northern Pannonian domain (Kováč & Hók 1993; Vass et al. 1993; Petrik et al. 2016).

Faulting has played a tremendous role during the last period of the Western Carpathians tectonic evolution, and the pattern of faults is one of the most important features of the area. Brittle dislocations, mainly strike-slip fault zones have allowed the propagation of individual detached crustal segments of the orogenic system, as well as their individual parts — blocks. The structural evolution can therefore be modelled by several methods such as inversion, P–T axes or right dihedra methods (cf. Turner 1953; Compton 1966; Arthaud 1969; Angelier & Mechler 1977; Angelier 1994; Aleksandrowski 1985). All the aforementioned methods try to find the spatial position of the principal maximum (compressional) stress axis (σ_1), the intermediate stress (rotational) axis (σ_2), the principal minimal (tensional) stress axis (σ_3), as well as the ratio (Φ) between them. The temporal variability of extension and subsidence can be compared with the results of recent numerical modelling (e.g., Balázs et al. 2017).

The main goal of the study was to propose a model in which the Neogene structural evolution of the orogenic system conforms to the measured palaeostress fields, changing in time and space. In addition, the measured CCW rotations in individual parts of the extruding segment of the Western Carpathians are causally related to the main basin depocentres opening and their accelerated subsidence.

The Miocene structural pattern evolution model

The analysis of the aforementioned structural data pointed to the behaviour of compressional and extensional tectonic regimes with respect to the development stages of the Western Carpathian orogenic system axial part (Fig. 2).

(i) The Early Miocene (~22–17 Ma) compression perpendicular to the trend of movement of the Central Western Carpathian segment resulted from collision of the Outer Western Carpathians accretionary wedge front with the oceanic or thinned crust in the embayment of the European Platform (Fig. 2A). In the west, this transpressional tectonic regime is represented by the measured palaeostress field with the prevailingly NW–SE oriented σ_1, which controlled the evolution of the wedge-top basin represented by the Early Miocene deposits of the Vienna Basin and Váh river valley at present (Kováč et al. 2017a). In the east, along the edge of the Central Western Carpathians the measured main compression with NNE–SSW oriented σ_1 was responsible for inversion and disintegration of the Central Carpathian Palaeogene fore-arc basin (Kováč et al. 2016). Both measurements are in a good agreement with the curved track of the Western Carpathians' movement as a whole, and confirm the results of Márton et al. (2013, 2016) who assume that the present shape of the Pieniny Klippen Belt is partly due to an oroclinal bending before the Oligocene.

(ii) At the end of the Early and beginning of the Middle Miocene (~17–16 Ma), the accelerated oblique collision of the ALCAPA Mega-Unit with the Bohemian Massif occurred. The prevailing orientation of the measured σ_1 axis is approximately in the N–S direction in the Central Western Carpathians. During the Karpatian (~17 Ma) the rifting in the Eastern Slovak Basin started along the NW–SE dextral strike-slips in a transtensional tectonic regime (Kováč et al. 1995) and was followed by the Early Badenian (~16 Ma) opening of the Vienna Basin pull-apart depocentres by the NE–SW left lateral strike-slips (Nemčok et al. 1989; Fodor 1995; Lankreijer et al. 1995; Marko et al. 1995). This statement is in line with the end of the first ~50° CCW rotation of the Central Western Carpathians and Northern Pannonian domain, as well as with oblique movement/collision of the Western Carpathians with the European Platform (Fig. 2B). Moreover, the measured 30° CCW rotation of the Ždánice Unit probably occurred at the same time (Márton et al. 2009b) and can be assigned not only to the last thrust of the Outer Western Carpathian nappes over the foredeep, but also to oblique north-eastward movement of ALCAPA (Kováč et al. 2017a).

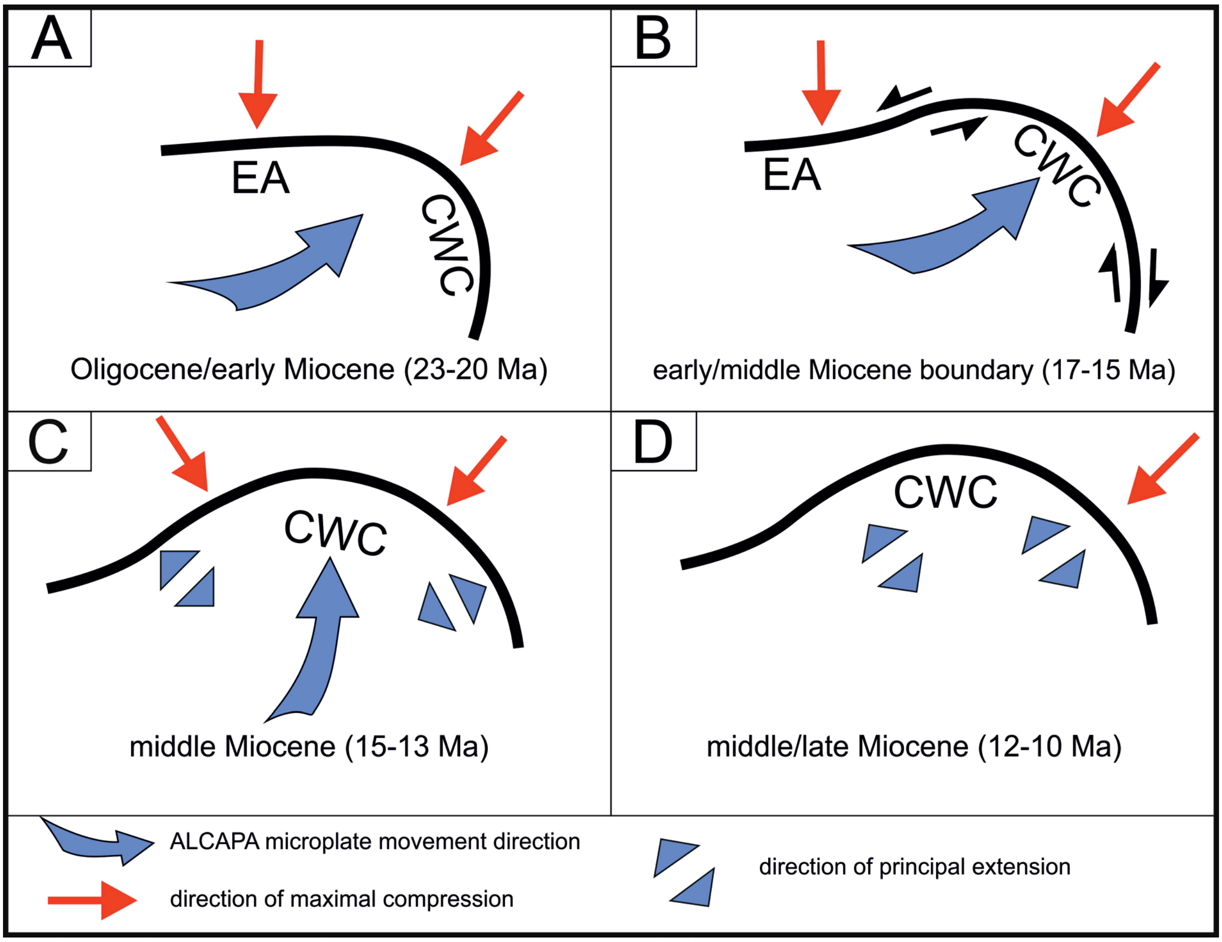

Fig. 2. Movements of the ALCAPA microplate with direction of compression and extension (EA — Eastern Alps; CWC — Central Western Carpathians).

(iii) The Middle Miocene palaeostress field had the main compressional axis still oriented perpendicular to the Outer Western Carpathian accretionary wedge, while the extension was parallel to the orogenic arc until the Late Badenian (~16–13.5 Ma). In the west, the extensional tectonic regime with the NW–SE oriented σ_3 axis opened the Danube Basin along the NNE–SSW to NE–SW normal listric faults in the hinterland of the Central Western Carpathians (Kováč et al. 2011a; Sztanó et al. 2016). In the east, the transtensional tectonic regime with NE–SW (NNE–SSW) oriented σ_1 prevailed during the synrift evolutionary stage of the Eastern Slovak Basin (Fig. 2C).

(iv) The measured late Middle/Late Miocene (Sarmatian/early Pannonian; ~12.6–10 Ma) palaeostress field controlled subsidence in the hinterland basin system depocentres, which were opened by an extensional tectonic regime with the NW–SE oriented σ_3 (e.g., Danube Basin and Eastern Slovak Basin). This regime (Fig. 2D) controlled the infill of basins and was probably induced by the still active subduction pull beneath the front of the Eastern Carpathians (e.g., Konečný et al. 2002; Kováč et al. 2017a).

Model of basin opening and subsidence

The Miocene north-eastward extrusion of the ALCAPA Mega-Unit led to significant stretching of this crustal wedge, estimated as more than 100 km in the Central Western Carpathian segment (e.g., Konečný et al. 2002; Kováč et al. 1997, 1998, 2017a). Comparison of the basin opening (e.g., Kováč et al. 1995, 2011a; Lankreijer et al. 1995) with dating of measured CCW rotations brings evidence that the development of extensional basins was at least partly compensated by the rotation measured in individual crustal blocks of the stretched ALCAPA Mega-Unit (Figs. 1 and 3A–C). Based on previous research, two types of spin rotation could be distinguished: *(i)* "domino-effect" rotation of each block in strike-slip zones and *(ii)* "en block" rotation both confirmed by interpretation of palaeomagnetic measurements after 20 Ma (e.g., Márton et al. 2000a, 2016). The presented structural model of the extruding crustal wedge takes into account CCW rotations and movement trajectories of its individual segments as follows in subsections.

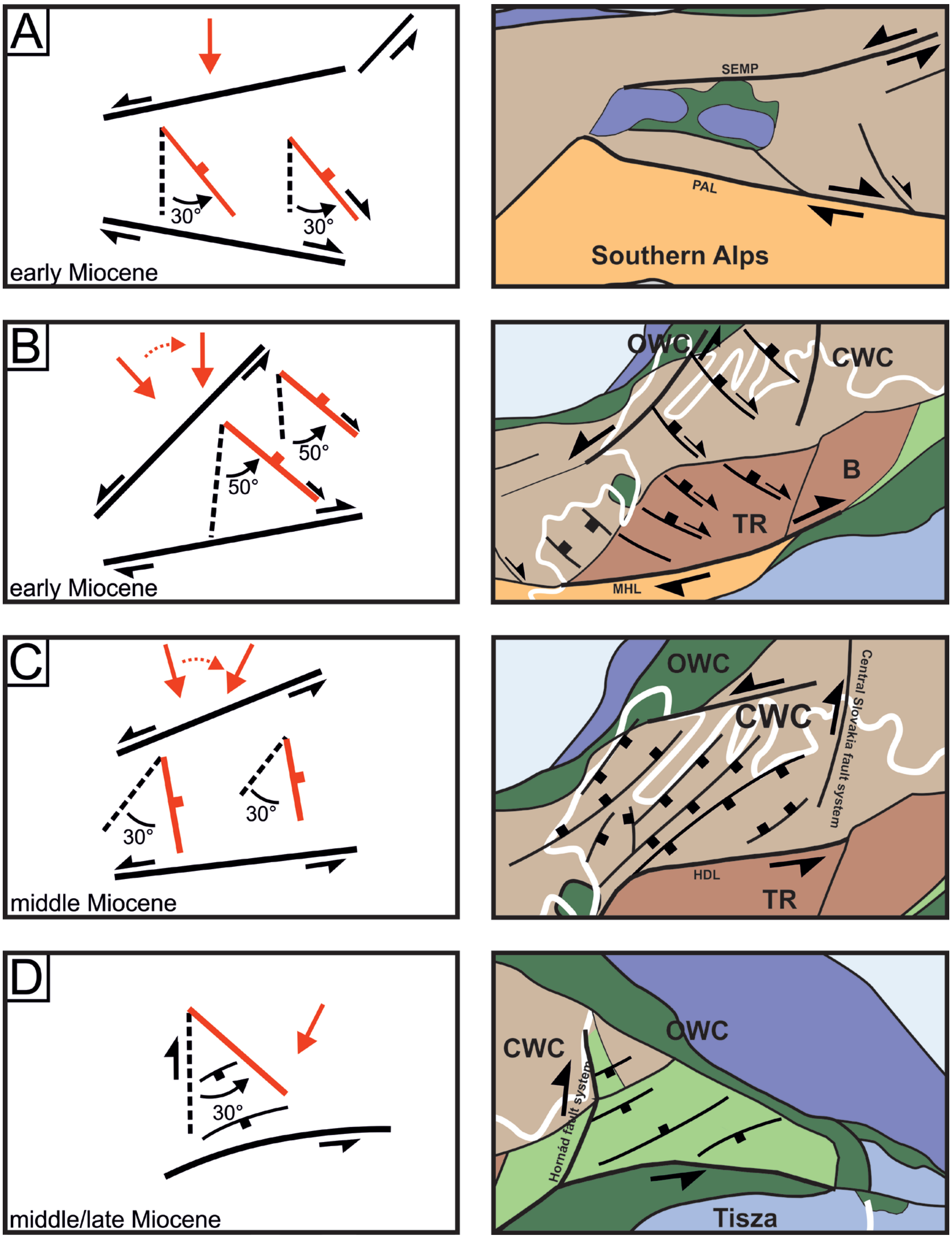

Fig. 3. Schemes/models of the early Miocene Eastern Alpine tectonic extrusion (**A**) and the Alpine–Carpathian junction disintegration (**B**), the middle Miocene and the middle/late Miocene rifting of the Western Carpathians back-arc basin system (**C** & **D**); model of rotations in different parts of the ALCAPA region (PAL — Peri-Adriatic Fault; SEMP — Salzach–Ennstal–Mariazell–Puchberg Fault; OWC — Outer Western Carpathians; CWC — Central Western Carpathians; MHL — Middle Hungarian Line; HDL — Hurbanovo–Diosjeno Fault; TR — Transdanubian Range; for legend see Fig. 1).

Early Miocene

In the Eastern Alps (Fig. 3A), the measured Early Miocene ~30 CCW rotation was explained as a result of "domino-effect" block rotations in a wrench zone (Márton et al. 2000a). The present shape of the Eastern Alps suggests this brittle deformation between the WSW–ENE oriented left lateral Salzach–Ennstal–Mariazell–Puchberg strike slip fault and the right-lateral Periadriatic shear zone striking WNW–ESE (Periadriatic, Mölltal, Hochstuhl, and Pöls-Lavantal faults) which operated during the extrusion of the ALCAPA Mega-Unit toward the east (e.g., Ratschbacher 1991a,b; Kováč et al. 1994, 2017a; Linzer et al. 2002; Scharf et al. 2013; Schmid et al. 2013; van Gelder et al. 2017). Later, in the Late Miocene to present, the fault activity was concentrated in the NNW–SSE striking normal faults (e.g., Scharf et al. 2013).

The Central Western Carpathians, Northern Pannonian domain, Pieniny Klippen Belt, and Outer Western Carpathians underwent rotation ~50° CCW to be considered as "en block" rotation (Márton & Fodor 2003; Márton et al. 2013, 2016; Kováč et al. 2017a). In comparison to the Eastern Alps, the Early Miocene movement trajectory of the Central Western Carpathian and Northern Pannonian domain segments was directed more to the north-east, and the measured CCW rotation exceeded the documented rotation in the Eastern Alps. The difference in length of the movement trajectory and size of rotation resulted in collapse of the area around the Eastern Alps, Central Western Carpathians and Northern Pannonian domain.

Van Gelder et al. (2017) characterized the Oligocene–Early Miocene initial phase of convergence of the Adria plate and Eastern Alps as oblique, accompanied by lateral extrusion of the ALCAPA Mega-Unit lithosphere. The deformation and strain propagation in the upper plate during the Adria subduction is similar to classical indentation models. In both cases the upper plate displays a transition from compressional structures near the confined boundary, to strike-slip and extensional structures towards the weak lateral boundary represented by the western portion of the Central Western Carpathians together with the Transdanubian Range (the elevated pre-Neogene basement of the Danube Basin). This area (Fig. 3A,B) started to collapse along at present NW–SE to WNW–ESE normal faults, later with a dextral shear component during the Early Miocene (Kováč 2000; Márton & Fodor 2003; Hók et al. 2016). The stepwise collapse took place between the edge of the Eastern Alps in the northwest (Mur–Mürz Fault) and the newly forming zone of the Mid-Hungarian Fault with a dextral strike-slip movement in the southeast (Fodor et al. 1998). Disintegration of the uplifted junction of the Alps, Central Western Carpathians, and Northern Pannonian domain (before the opening of the Middle/Late Miocene Danube Basin; cf. Tari et al. 1992; Tari & Horváth, 1995) documents the exhumation history of crystalline complexes in this area (Kráľ 1977; Kováč et al. 1994, 2017b; Danišík et al. 2004; Králiková et al. 2016; Marko et al. 2017). Moreover, our hypothesis is also supported by the pre-Middle Miocene erosional level. From the south to the north the following units occur stacked one on the other. The lowermost Penninic Unit is located in the Rechnitz area, and toward the north-east the pre-Miocene basement of the Danube Basin central part is built up by the Tatric crystalline complexes. However, along the northern margin of the Danube Basin the crystalline complexes are covered by the Mesozoic sedimentary sequences and nappe units, and finally the crystalline complexes with the Mesozoic sedimentary cover, nappe units and preserved Palaeogene basin fill are present in the northernmost portion of the basin, as well as in the axial zone of the Central Western Carpathians (e.g., Biela 1978; Fusán et al. 1987; Hók et al. 2016; Klučiar et al. 2016). This evidence can be explained only by stretching towards the north-east. This was probably associated with tiny "domino-effect" block rotations similar to the rotations identified in the Eastern Alps (Fig. 3B).

The stretching induced by rotational movement of the extruding crustal wedge also contributed to the opening of basins in the orogen hinterland, along the ALCAPA Mega-Unit's southern margin (e.g., Csontos et al. 1992; Kováč et al. 1994; Fodor et al. 1998). In the west, the Styrian Basin subsided (e.g., Sachsenhofer et al. 1997; Linzer et al. 2012), more to the east the Novohrad–Nógrád Basin was formed above the Central Western Carpathian and Northern Pannonian domain basement (e.g., Vass et al. 1993; Kováč et al. 2017a). Along the eastern edge of the ALCAPA Mega-Unit the movement first led to disintegration and uplift of the Central Carpathian Palaeogene Basin in a fore-arc position. After the Ottnangian hiatus, the Early Miocene CCW rotation was compensated by the opening and subsidence of pull-apart depocentres of the Eastern Slovak Basin at the end of this period (Kováč et al. 1995, 2017a).

Middle–Late Miocene

From the Middle Miocene onwards the Eastern Alpine convergence gained an orthogonal character attributed to the frequently documented Miocene switch in the Adria plate motion (e.g., van Gelder et al. 2017). The different parts of the ALCAPA Tisza–Dacia Mega-units were extended by variable amounts and the already segmented area of the Pannonian Basin System broke up into relatively small blocks, most probably partly detached at a crustal level (Balázs et al. 2016). Stretching of the lithosphere segments was caused by the continuing roll back effect of the gradually ceasing subduction below the front of the Carpathians (e.g., Kováč et al. 1994; Konečný et al. 2002; Balázs et al. 2017).

The Central Western Carpathian basins development was closely linked to the continuing stretching of the crust in the north-eastern direction. Two measured CCW rotations ~30° were determined during this time (e.g., Márton & Fodor 2003; Márton et al. 2007). The first ~30° CCW rotation was documented in the western part of the Central Western Carpathians and was dated to the Early Badenian (Márton & Fodor 2003). The second documented ~30° anticlockwise rotation, dated to the late Sarmatian–early Pannonian is known from the Eastern Slovak Basin (Márton et al. 2007).

Both mentioned CCW rotations occurred during the final stage of collision of the Western Carpathians with the platform and it is assumed that they were associated with a wrenching event gradually proceeding across the Central Western Carpathian segment from west to east. It started in the western part of the Central Western Carpathians and took place between an ENE–WSW left-lateral strike-slip zone which is expressive in the map view, northerly from the Danube Basin (Marko 2012; Marko et al. 2017) and the Hurbanovo–Diósjenő Fault in the basin's south-eastern part, striking along the northern margin of the Transdanubian Unit of the Northern Pannonian domain (Klučiar et al. 2016).

Interpretation of seismic data from the western part of the Western Carpathians (e.g., Kováč et al. 2011a; Magyar et al. 2013; Hók et al. 2016) corroborated with results of structural geology (Vojtko et al. 2008, in press) as well as data from wells and outcrops (Biela 1978; Joniak 2016; Rybár et al. 2016; Šujan et al. 2016a, b; Sztanó et al. 2016; Kováč et al. 2017a, b) has proved diachronous extension of the Danube Basin and migration of basin depocentres in time from west to east across the basin. These facts correlated with similarly focused studies from the Pannonian Basin System confirm the same results from the Tisza–Dacia Mega-Unit area in the Middle and Late Miocene (e.g., Balázs et al. 2016).

The Middle Miocene opening of the Danube Basin depocentres (Fig. 3C), was controlled by extension which activated pre-existing structures of the Cretaceous nappe stack as detachments or low-angle normal faults working in a simple shear mechanism (e.g., Tari et al. 1992; Horváth 1993; Lankreijer et al. 1995). The westerly located Blatné depression opened in the Badenian and the Rišňovce depression during the Sarmatian, in both cases the opening was followed by a maximum of sedimentation (Kováč et al. 2011a, 2017b; Sztanó et al. 2016). In the eastward located Komjatice depression the sedimentation reached its maximum in the Pannonian (Šujan et al. 2016b; Sztanó et al. 2016), after the next rotation ~30 CCW rotation of the ALCAPA Mega-Unit, documented in the Transcarpathian depression at the Middle/Late Miocene boundary (Fig. 3D). In the Late Miocene a dominant normal fault activity of pure shear mechanism is documented on the Danube Basin margins (Majcin et al. 2015; Hók et al. 2016), resulting in significant footwall exhumation during the Late Miocene and Pliocene (Šujan et al. 2017). At the end of the Middle Miocene several extensional basins were also formed in the more or less rigid body of the axial portion of the Central Western Carpathians along the Central Slovak Fault System (e.g., Nemčok & Lexa 1990; Kováč & Hók 1993; Kováč et al. 2017a) with an accelerated subsidence in the Late Miocene (Kováč et al. 2011b).

The synrift subsidence in the Eastern Slovak Basin lasted from Late Badenian–Sarmatian to early Pannonian times (e.g., Rudinec 1989; Kováč et al. 1995). This fact yields an indirect confirmation of our hypothesis, that the rotation was compensated by stretching of the eastern edge of the ALCAPA Mega-Unit during the late Middle/early Late Miocene. Moreover, the thickness of the Sarmatian strata is much greater in the east than in the west (e.g., Kováč et al. 1995, 1996; Lankreijer et al. 1995). Taking into consideration the aforementioned facts, we can relate the last measured ~30° CCW rotation to the final north-eastward movement of the eastern edge of Mega-Unit before its docking in an embayment of the European Platform margin. The extension controlling the basin subsidence was induced by the last stage of subduction in front of the Western/Eastern Carpathians (Kováč 2000; Konečný et al. 2002; Kováč et al. 2017a) together with the ~30° CW rotation of the Tisza–Dacia Mega-Unit in the south, which began from the Late Badenian (Dupont-Nivet et al. 2005). The CCW rotation measured at the eastern edge of the ALCAPA Mega-unit coincides with similar rotations measured in the outermost nappes of the Eastern Carpathians (Borislav–Pokuttya and Sambir–Rozniatow units; Márton et al. 2000b, 2007) divided from the Outer Western Carpathians by an approximately N–S running dextral strike slip zone crossing the units of the Outer Western Carpathians (Dukla and Skole units) to the south (Hnylko et al. 2015).

Conclusions

The scheme of the main stages of structural development in the Eastern Alpine–Central Western Carpathian orogenic system during the Neogene can be expressed as follows (Fig. 2):

(i) in the Late Oligocene/Early Miocene (~24–20 Ma) an orogen perpendicular compression led to individualization of the ALCAPA Mega-Unit lithosphere and together with subduction pull (roll back effect) caused its extrusion eastward; which resulted in collapse of the crustal wedge at the Alpine–Western Carpathian–Transdanubian Range junction (20–17 Ma);

(ii) around the Early/Middle Miocene boundary (~17–15 Ma) the orogen perpendicular compression, acting during the oblique collision of the Western Carpathians with the Bohemian Massif, led to opening of pull-apart depocentres in the Vienna and Eastern Slovak basins;

(iii) during the early Middle Miocene, the orogen parallel extension in the Central Western Carpathians resulted in hinterland (back arc) basin system formation (~15–13 Ma);

(iv) and finally, in the late Middle/early Late Miocene (~12–10 Ma) the NW–SE oriented extension led to the last synrift subsidence in the northern portion of the Pannonian Basin System.

The opening of basins in the Central Western Carpathians and Northern Pannonian domain started during the Early Miocene and lasted until the Late Miocene. However, the overall extensional direction remained roughly constant through time (NNE–SSW to NE–SW), the present map view of basin depocentres is caused by a significant amount of CCW rotations of the ALCAPA Mega-Unit segments modifying the original location and geometry of basins and their depocentres. The periods of the maximal subsidence of basins in relation to the CCW rotations of individual segments of the ALCAPA Mega-Unit and their movement trajectories can be characterized as follows (Fig. 3):

(i) in the west, the Early Miocene collision of the Eastern Alps (Fig. 3A). associated with a wrenching stage accompanied by a ~30° CCW "domino-effect" rotation of crustal blocks extruding eastward (Márton et al. 2000a). For the rest of the crustal wedge, built up from the Northern Pannonian domain, Central Western Carpathians, Pieniny Klippen Belt, and Outer Western Carpathians an ~50° anticlockwise "en block" rotation was proposed (Márton et al. 2013). In the western part of the Central Western Carpathians, a collapse of the junction area of the Eastern Alps, Central Western Carpathians, and Northern Pannonian domain was documented before

the opening of the Middle/Late Miocene Danube Basin. The disintegration of this elevated zone associated with normal faulting, with an assumed "domino-effect" rotation between the edge of the Eastern Alps (Mur-Mürz Fault) and the juvenile Mid-Hungarian dextral fault zone in the south; as a continuation of the Eastern Alpine structural evolution (Fig. 3B).

(ii) The Middle Miocene final stage of the Western Carpathian oblique collision with the European Platform led to the next ~30° CCW "domino-effect" rotations in the crustal segments of the Central Western Carpathians and Northern Pannonian domain (Fig. 3C,D). The wrenching started in the west during the early Middle Miocene (northern Danube Basin) and proceeded to the east until the Middle/Late Miocene boundary (Eastern Slovak Basin). The rotation of blocks was partly induced by the clockwise rotation of the Tisza–Dacia Mega-unit associated with collision of the Eastern Carpathians and the European Platform.

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References

Aleksandrowski P. 1985: Graphical determination of principal stress directions for slickenside lineation populations: An attempt to modify Arthaud's method. *J. Struct. Geol.* 7, 73–82.

Angelier J. 1994: Fault slip analysis and paleostress reconstruction. In: Hancock P.L. (Ed.): Continental deformation. *Pergamon Press*, *University of Bristol (U.K.)*, London, 53–100.

Angelier J. & Mechler M. 1977: Sur une méthode graphique de recherche des contraintes principales également utilisable en tectonique et en seismologie: la méthode des diédres droits. *Bull. Soc. Géol. Fr.* 7, 1309–1318.

Arthaud F. 1969: Méthode de détermination graphique des directions de raccourcissement, d'allongement et intermédiare d'une population de failles. *Bulletin Société Géologique de France*, 11, 729–737.

Balázs A., Matenco L., Magyar I., Horváth F., & Cloetingh S. 2016: The link between tectonics and sedimentation in back-arc basins: New genetic constraints from the analysis of the Pannonian Basin. *Tectonics*, 35, doi:10.1002/2015TC004109.

Balázs A., Magyar I., Matenco L., Sztanó O., Tőkés L. & Horváth F., 2017: Morphology of a large paleo-lake: Analysis of compaction in the Miocene–Quaternary Pannonian Basin. *Global Planet. Change*, in press, doi: 10.1016/j.gloplacha.2017.10.012

Balla Z. 1984: The Carpathian loop and the Pannonian basin: a kinematic analysis. *Geophys. Trans.*, 30, 4, 313–353.

Beidinger A., Decker K. & Roch K.H. 2011: The Lassee segment of the Vienna Basin fault system as a potential source of the earthquake of Carnuntum in the fourth century a.d. *Int. J. Earth Sci.* 100, 1315–1329.

Biela A. 1978: Deep wells in Western Carpathians: Vienna basin, Danube basin. Regionálna geológia Západných Karpát 10, 1–224 (in Slovak).

Bučová J., Plašienka D. & Mikuš V. 2010: Geology and Tectonics of the Vršatec Klippen area (Pieniny Klippen Belt, Western Slovakia). *Proc. 19th Congress of the Carpath.-Balkan Geol. Assoc. Thessaloniki, Aristotle University*, Greece, 197–207.

Compton R.R., 1966: Analysis of Pliocene-Pleistocene deformation and stresses in northern Santa Lucia Range, California. *Geol. Soc. Ame. Bull.* 77, 1361–1380.

Csontos L. 1995: Cenozoic tectonic evolution of the Intra-Carpathian area: a review. *Acta Vulcanol.* 7, 1–13.

Csontos L. & Nagymarosy A. 1998: The Mid-Hungarian line: a zone of repeated tectonic inversions. *Tectonophysics* 297, 1–4, 51–71.

Csontos L., Nagymarosy A., Horváth F. & Kováč M. 1992: Tertiary tectonic evolution of the Intra-Carpathian area: A model. *Tectonophysics* 208, 1–3, 221–241.

Danišík M., Dunkl I., Putiš M., Frisch W. & Kráľ J. 2004: Tertiary burial and exhumation history of basement highs along the NW margin of the Pannonian Basin – an apatite fission track study. *Austrian J. Earth Sci.* 95 (96), 60–70.

Decker K. & Peresson H. 1996: Tertiary kinematics in the Alpine–Carpathian–Pannonian system: links between thrusting, transform faulting and crustal extension. In: Wessely G. & Liebl W. (Eds.): Oil and Gas in Alpine Thrust belts and Basins of central and eastern Europe. *EAGE Spec. publ.* 5, 69–77.

Decker K., Meschede M. & Ring U. 1993: Fault slip analysis along the northern margin of the Eastern Alps (Molasse, Helvetic nappes, North and South Penninic flysch, and the Northern Calcareous Alps). *Tectonophysics* 223, 3–4, 291–312.

Decker K., Peresson H. & Faupl P. 1994: Die miozäne Tectonik der östlichen Kalkalpen: Kinematik, Paläospannungen und Deformationsaufteilung während der "lateral Extrusion" des Zentralalpen. *Jahrb. Geol. Bundesanst.* 137, 5–18.

Dupont-Nivet G., Vasiliev I., Langereis Cor G., Krijgsman W. & Panaiotu C. 2005: Neogene tectonic evolution of the southern and eastern Carpathians constrained by paleomagnetism. *Earth Planet. Sci. Lett.* 236, 374–387.

Fodor L. 1995: From transpression to transtension: Oligocene–Miocene structural evolution of the Vienna Basin and the East Alpine–Western Carpathian junction. *Tectonophysics* 242, 151–182.

Fodor L., Jelen B., Márton E., Skaberne D., Čar J. & Vrabec M. 1998: Miocene-Pliocene tectonic evolution of the Slovenian Periadriatic Fault: Implications for Alpine-Carpathian extrusion models. *Tectonics* 17, 690–709.

Fodor L., Csontos L., Bada G., Györfi I. & Benkovics L., 1999: Tertiary tectonic evolution of the Pannonian basin system and neighbouring orogens: a new synthesis of paleostress data. In: Durand B., Jolivet L., Horváth F. & Séranne M. (Eds.): The Mediterranean Basins: Tertiary extension within the Alpine Orogene. *Geol. Soc. London*, 165, 295–334.

Fusán O., Biely A., Ibrmajer J., Plančár J. & Rozložnik L. 1987: Basement of the Tertiary of the Inner West Carpathians. *GÚDŠ*, Bratislava, 1–103.

Grad M., Brückl E., Majdánski M., Behm M., Guterch A. & CELEBRATION 2000 & ALP 2002 Working Groups, 2009: Crustal structure of the Eastern Alps and their foreland: seismic model beneath the CEL10/Alp04 profile and tectonic implications. *Geophys. J. Internat.* 177, 279–295.

Joniak P. 2016: The Upper Miocene rodents from the Pezinok in the Danube Basin, Slovakia. *Acta Geologica Slovaca* 8, 1, 1–14.

Hnylko O.M., Hnylko S.R. & Generalova L.V. 2015: Formation of the structure of the Klippen zones and the interklippen flysch of inner Ukrainian Carpathians — results of convergence and collision of microcontinental terranes. *Vestnik of Saint Petersburg University*, *series 7, Geology* 2, 4–24 (in Russian with English summary).

Hók J., Kováč M., Pelech O., Pešková I., Vojtko R. & Králiková S. 2016: The Alpine tectonic evolution of the Danube Basin and its northern periphery (southwestern Slovakia). *Geol. Carpath.* 67, 5, 495–505.

Horváth F. 1993: Towards a mechanical model for the formation of the Pannonian basin. *Tectonophysics* 226, 333–357

Klučiar T., Kováč M., Vojtko R., Rybár S., Šujan M. & Králiková S. 2016. The Hurbanovo–Diósjenő Fault: A crustal-scale weakness zone at the boundary between the Central Western Carpathians and Northern Pannonian Domain. *Acta Geologica Slovaca* 8, 1, 59–70.

Konečný V., Kováč M., Lexa J. & Šefara J. 2002. Neogene evolution of the Carpatho–Pannonian region: an interplay of subduction and back-arc diapiric uprise in the mantle. *EGS Stephan Mueller Spec. Publ.* Ser. 1, 105–123.

Kováč M. 2000: Geodynamic, palaeogeographic, and strctural evolution of the Carpathian–Pannonian region in Miocene: a new insight to the Neogene Basin of Slovakia [Geodynamický, paleogeografický a štruktúrny vývoj Karpatsko-panónskeho regiónu v miocéne: nový pohľad na neogénne panvy Slovenska]. *VEDA*, Bratislava, 1–202.

Kováč P. & Hók J. 1993: The Central Slovak fault system: The field evidence of a strike slip. *Geol. Carpath.* 44, 3, 155–159.

Kováč M., Kráľ J., Márton E., Plašienka D. & Uher P. 1994: Alpine uplift history of the Central Western Carpathians: Geochronological, paleomagnetic, sedimentary and structural data. *Geol. Carpath.* 45, 2, 83–96.

Kováč M., Kováč P., Marko F., Karoli S. & Janočko J. 1995: The East Slovakian Basin — A complex back arc basin. *Tectonophysics* 252, 1–4, 453–466.

Kováč M., Hudáčková N., Rudinec R. & Lankreijer A. 1996: Basin evolution in the foreland and hinterland of the Carpathian accretionary prism during the Neogene: evidence from the Western to Eastern Carpathians Junction. *Annales Tectonicae* X, 1–2, 3–19.

Kováč M., Bielik M., Lexa J., Pereszlényi M., Šefara J., Túnyi I. & Vass D. 1997: The Western Carpathian intramountane basins. In: Grecula P. et al. (Eds.): Geological evolution of the Western Carpathians. *Mineralia Slovaca*, Monograph., Bratislava, 43–65.

Kováč M., Nagymarosy A., Oszczypko N., Slaczka A., Csontos L., Marunteanu M., Matenco L. & Márton M. 1998: Palinspastic reconstruction of the Carpathian–Pannonian region during the Miocene. In: Rakús M. (Ed.): Geodynamic development of the Western Carpathians. *GSSR*, Bratislava, 189–217.

Kováč M., Synak R., Fordinál K., Joniak P., Tóth Cs., Vojtko R., Nagy A., Baráth I., Maglay J. & Minár J. 2011a: Late Miocene and Pliocene history of the Danube Basin: inferred from development of depositional systems and timing of sedimentary facies changes. *Geol. Carpath.* 62, 6, 519–534.

Kováč M., Hók J., Minár J., Vojtko R., Bielik M., Pipík R., Rakús M., Kráľ J., Šujan M. & Králiková S. 2011b: Neogene and Quaternary development of the Turiec Basin and landscape in its catchment: a tentative mass balance model. *Geol. Carpath.* 62, 4, 361–379.

Kováč M., Plašienka D., Soták J., Vojtko R., Oszczypko N., Less Gy., Ćosović V., Fügenschuh B. & Králiková S., 2016: Paleogene palaeogeography and basin evolution of the Western Carpathians, Northern Pannonian domain and adjoining areas. *Global Planet. Change* 140, 9–27.

Kováč M., Márton E., Oszczypko N., Vojtko R., Hók J., Králiková S., Plašienka D., Klučiar T., Hudáčková N. & Oszczypko-Clowes M. 2017a: Neogene palaeogeography and basin evolution of the Western Carpathians, Northern Pannonian domain and adjoining areas. *Global Planet. Change* 155, 133–154.

Kováč M., Rybár S., Halásová E., Hudáčková N., Šarinová K., Šujan M., Baranyi V., Kováčová M., Ruman A., Klučiar T. & Zlinská A., 2017b: Changes in Cenozoic depositional environment and sediment provenance in the Danube Basin. *Basin Res.* 30, 1, 97–131.

Kráľ J. 1977: Fission track ages of apatites from some granitoid rocks in West Carpathians. *Geol. Zbor. Geol. Carpath.* 28, 269–276.

Králiková S., Vojtko R., Hók J., Fügenschuh B. & Kováč M. 2016: Low-temperature constraints on the Alpine thermal evolution of the Western Carpathian basement rock complexes. *J. Struct. Geol.* 91, 144–160.

Lankreijer A., Kováč M., Cloetingh S., Pitoňák P., Hlôška M. & Biermann C. 1995: Quantitative subsidence analysis and forward modelling of the Vienna and Danube basins: thin-skinned versus thick-skinned extension. *Tectonophysics* 252, 1–4, 433–451.

Linzer H.-G. & Tari G. 2012: Structural correlation between the Northern Calcareous Alps (Austria) and the Transdanubian Central Range (Hungary). In: Gao D. (Ed.): Tectonics and sedimentation: Implications for petroleum systems. *AAPG Memoir* 100, 249–266.

Linzer H.-G., Decker K., Peresson H., Dell'Mour R. & Frisch W. 2002: Balancing lateral orogenic float of the Eastern Alps. *Tectonophysics* 354, 3–4, 211–237.

Magyar I., Geary D.H. & Müller P. 1999: Paleogeograhic evolution of the Late Miocene Lake Pannon in Central Europe. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 147, 151–167.

Magyar I., Radivojević D., Sztanó O., Synak R., Ujszászi K. & Pócsik M. 2013: Progradation of the paleo-Danube shelf margin across the Pannonian Basin during the Late Miocene and Early Pliocene. *Global Planet. Change* 103, 168–173.

Majcin D., Bilčík D. & Klučiar T. 2015: Thermal state of the lithosphere in the Danube Basin and its relation to tectonics. *Contributions to Geophysics and Geodesy* 45, 193–218.

Marko F. 2012: Cenozoic stress field and faulting at the northern margin of the Danube Basin (Western Carpathians, Slovakia). *Mineralia Slovaca* 44, 3, 213–230.

Marko F., Plašienka D. & Fodor L. 1995: Meso-Cenozoic tectonic stress fields within the Alpine-Carpathian transition zone: a review. *Geol. Carpath.* 46, 1, 19–27.

Marko F., Andriessen P.A.M., Tomek Č., Bezák V., Fojtíková, L., Bošanský M., Piovarči M. & Reichwalder P. 2017: Carpathian Shear Corridor — A strike-slip boundary of an extruded crustal segment. *Tectonophysics* 703–704, 119–134.

Márton E. & Fodor L. 2003: Tertiary paleomagnetic results and structural analysis from the Transdanubian Range (Hungary): rotational disintegration of the Alcapa unit. *Tectonophysics* 363, 3–4, 201–224.

Márton E., Mastella L. & Tokarski A.K. 1999: Large counterclockwise rotation of the Inner West Carpathian Paleogene Flysch — Evidence from paleomagnetic investigation of the Podhale Flysch (Poland). *Phys. Chem. Earth. Part A* 24, 645–649.

Márton E., Kuhlemann J., Frisch W. & Dunkl I. 2000a: Miocene rotations in the Eastern Alps — palaeomagnetic results from intramontane basin sediments. *Tectonophysics* 323, 3–4, 163–182.

Márton E., Vass D. & Túnyi I. 2000b: Counterclockwise rotations of the Neogene rocks in the East Slovak Basin. *Geol. Carpath.* 51, 3, 159–168.

Márton E., Tokarski A.K. & Halász D. 2004: Late Miocene counterclockwise rotation of the Pieniny andesites at the contact of the Inner and Outer West Carpathians. *Geol. Carpath.* 55, 5, 411–419.

Márton E., Tischler M., Csontos L., Fügenschuh B. & Schmid S.M. 2007: The contact zone between the ALCAPA and Tisza–Dacia mega-tectonic units of Northern Romania in the light of new paleomagnetic data. *Swiss J. Geosci.* 100, 1, 109–124.

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

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

Márton E., Grabowski J., Plašienka D., Túnyi I., Krobicki M., Haas J. & Pethe M. 2013: New paleomagnetic results from the Upper Cretaceous red marls of the Pieniny Klippen Belt, Western Carpathians: evidence for general CCW rotation and implications for the origin of the structural arc formation. *Tectonophysics* 592, 1–13.

Márton E., Grabowski J., Tokarski A.K. & Túnyi I. 2016: Palaeomagnetic results from the fold and thrust belt of the Western Carpathians: an overview. *In:* Pueyo E.L., Cifelli F., Sussman A.J. & Oliva-Urcia B. (Eds.): Palaeomagnetism in Fold and Thrust Belts: New Perspectives. *Geol. Soc., London, Spec. Publ.* 425, 7–36.

Nemčok M. & Lexa J. 1990: Evolution of the basin and range structure around the Žiar mountain range. *Geol. Carpath.* 41, 3, 229–258.

Nemčok M., Marko F., Kováč M. & Fodor L. 1989: Neogene tectonics and paleostress changes in the Czechoslovakian part of the Vienna Basin. *Jahrb. Geol. Bundesanst.* 132, 443–458.

Panaiotu C. 1998: Paleomagnetic constraints on the geodynamic history of Romania. *Reports on Geodesy 7 (37), Monograph of Southern Carpathians, Warshaw Institute of Technology*, 49–71.

Pešková I., Vojtko R., Starek D. & Sliva Ľ. 2009: Late Eocene to Quaternary deformation and stress field evolution of the Orava region (Western Carpathians). *Acta Geol. Pol.* 59, 1, 73–91.

Petrik A., Beke B., Fodor L. & Lukácz R. 2016: Cenozoic structural evolution of the southwestern Bükk Mts. and the southern part of the Darnó Deformation Belt (NE Hungary). *Geol. Carpath.* 67, 1, 83–104.

Plašienka D., Soták J. & Prokešová R. 1998: Structural profiles across the Šambron–Kamenica Periklippen Zone of the Central Carpathian Paleogene Basin in NE Slovakia. *Mineralia Slovaca*, 30, 3, 173–184.

Pulišová Z. & Hók J. 2015: The palaeostress analysis of the fault rupture of the Žiarska kotlina Basin. *Acta Geol. Slov.* 7, 103–111.

Ratschbacher L., Merle O., Davy P. & Cobbold P. 1991a: Lateral extrusion in the Eastern Alps; part 1: Boundary conditions and experiments scaled for gravity. *Tectonics* 10, 2, 245–256.

Ratschbacher L., Frisch W., Linzer H.G. & Merle O. 1991b: Lateral extrusion in the Eastern. Alps; part 2: Structural analysis. *Tectonics* 10, 2, 257–271.

Royden L.H. 1993a: Evolution of retreating subduction boundaries formed during continental collision. *Tectonics* 12, 3, 629–638.

Royden L.H. 1993b: The tectonic expression slab pull at continental convergent boundaries. *Tectonics* 12, 2, 303–325.

Rudinec R. 1989: New view onto the development of the Transcarpathian depression during the Neogene. *Mineralia Slovaca*, 21, 1, 27–42.

Rybár S., Kováč M., Šarinová K., Halásová E., Hudáčková N., Šujan M., Kováčová M., Ruman A. & Klučiar T. 2016: Neogene changes in paleogeography, paleoenvironment and the provenance of sediment in the norther Danube Basin. *Bull. Geosci.* 91, 2, 367–398.

Sachsenhofer R.F., Lankreijer A., Cloetingh S. & Ebner F., 1997: Subsidence analysis and quantitative basin modelling in the Styrian Basin (Pannonian Basin System, Austria). *Tectonophysics*, 272, 2–4, 175–196.

Scharf A., Handy M.R., Favaro S., Schmid S.M. & Bertrand A. 2013: Modes of orogen-parallel stretching and extensional exhumation in response to microplate indentation and roll-back subduction (Tauern Window, Eastern Alps). *Int. J. Earth Sci.* 102, 1627–1654.

Schmid S., Bernoulli D., Fügenschuh B., Matenco L., Schefer S., Schuster R., Tischler M. & Ustaszewski K. 2008: The Alpine–Carpathian–Dinaridic orogenic system: correlation and evolution of tectonic units. *Swiss J. Geosci.* 101, 139–183.

Schmid S.M., Scharf A., Handy M.R. & Rosenberg C.L. 2013: The Tauern Window (Eastern Alps, Austria): a new tectonic map, with cross-sections and a tectonometamorphic synthesis. *Swiss J. Geosci.* 106, 1–32.

Šimonová V. & Plašienka D. 2011: Fault kinematics and paleostress analysis in the Butkov quarry (Manín Unit, Western Carpathians). *Acta Geologica Slovaca* 3, 1, 21–31 (in Slovak with English summary).

Šujan M., Slávik I., Galliková Z., Dovičin P. & Šujan M. 2016a: Pre-Quaternary basement of Bratislava (part 1): genetic vs. geotechnical characteristics of the Neogene foundation soils. *Acta Geologica Slovaca* 8, 1, 71–86.

Šujan M., Braucher R., Kováč M., Bourlès D., Rybár S., Guillou V. & Hudáčková N. 2016b: Application of the authigenic $^{10}Be/^{9}Be$ dating method to Late Miocene–Pliocene sequences in the northern Danube Basin (Pannonian Basin System): Confirmation of heterochronous evolution of sedimentary environments. *Global Planet. Change* 137, 35–53.

Šujan M., Kováč M., Hók J., Šujan M., Braucher R., Rybár S. & de Leeuw A. 2017: Late Miocene fluvial distributary system in the northern Danube Basin (Pannonian Basin System) depositional processes, stratigraphic architecture and controlling factors of the Piešťany Member (Volkovce Formation). *Geol. Quarterly* 61, 3, 521–548.

Sůkalová Ľ., Vojtko R. & Pešková I. 2012: Cenozoic deformation and stress field evolution of the Kozie chrbty Mountains and the western part of Hornád Depression (Central Western Carpathians). *Acta Geologica Slovaca* 4, 1, 53–64.

Sztanó O., Kováč M., Magyar I., Šujan M., Fodor L., Uhrin A., Rybár S., Csillag G. & Tőkés L. 2016: Late Miocene sedimentary record of the Danube/Kisalföld Basin: interregional correlation of depositional systems stratigraphy, and structural evolution. *Geol. Carpath.* 67, 6, 525–542.

Tari G. & Horváth F. 1995: Overview of the Alpine evolution of the Pannonian Basin. In: Horváth F., Tari G. & Bokor Cs. (Eds.): Extensional collapse of the Alpine orogene and hydrocarbon prospects in the basement and basement fill of the western Pannonian Basin. *AAPG International Conference and Exhibition, Nice, France, Guidebook to Fieldtrip* 6, 7–19.

Tari G., Horváth F. & Rumpler J. 1992: Styles of extension in the Pannonian Basin. *Tectonophysics* 208, 1–3, 203–219.

Turner F.J. 1953: Nature and dynamic interpretation of deformation lamellae in calcite of three marbles. *Am. J. Sci.* 251, 276–298.

Ustaszewski K., Schmid S.M., Fügenschuh B., Tischler M., Kissling E. & Spakman W. 2008. A map-view restoration of the Alpine–Carpathian-Dinaridic system for the Early Miocene. *Swiss J. Geosci.* 101, Supplement 1, 273–294.

van Gelder I.E., Willingshofer E., Sokoutis D. & Cloetingh S.A.P.L. 2017: The interplay between subduction and lateral extrusion: A case study for the European Eastern Alps based on analogue models. *Earth Planet Sci Lett* 472, 82–94.

Vass D., Hók J., Kováč P. & Elečko M. 1993: The Paleogene and Neogene tectonic events of the Southern Slovakia depressions in the light of the stress-field analyses. *Mineralia Slovaca* 25, 2, 79–92.

Vass D., Kováč M., Konečný V. & Lexa J. 1988: Molasse basins and volcanic activity in West Carpathian Neogene — its evolution and geodynamic character. *Geol. Zbor. Geol. Carpath.* 39, 5, 539–561.

Vojtko R., Hók J., Kováč M., Sliva Ľ., Joniak P. & Šujan M. 2008: Pliocene to Quaternary stress field change in the Western Carpathians (Slovakia). *Geol. Quarterly* 52, 1, 19–30.

Vojtko R., Tokárová E., Sliva Ľ. & Pešková I. 2010: Reconstruction of Cenozoic paleostress fields and revised tectonic history in the northern part of the Central Western Carpathians (the Spišská Magura and Východné Tatry Mountains). *Geol. Carpath.* 61, 3, 211–225.

Vojtko R., Klučiar T., Králiková S., Hók J. & Pelech O. 2018: Late Badenian to Quaternary tectonic evolution of the Danube Basin (Slovakia) based on palaeostress reconstruction. *Acta Geologica Slovaca*, in press.