GEOLOGICA CARPATHICA, OCTOBER 2016, 67, 5, 495–505 doi: 10.1515/geoca-2016-0031

The Alpine tectonic evolution of the Danube Basin and its northern periphery (southwestern Slovakia)

JOZEF HÓK[1], MICHAL KOVÁČ[1], ONDREJ PELECH[2], IVANA PEŠKOVÁ[2], RASTISLAV VOJTKO[1] and SILVIA KRÁLIKOVÁ[1]

[1]Department of Geology and Paleontology, Faculty of Natural Sciences, Comenius University in Bratislava, Mlynská dolina, Ilkovičova 6, 842 15 Bratislava, Slovak Republic; hok@fns.uniba.sk, kovacm@fns.uniba.sk, kralikova@fns.uniba.sk
[2]State Geological Institute of Dionýz Štúr, Mlynská dolina 1, 817 04 Bratislava, Slovak Republic

(Manuscript received April 19, 2016; accepted in revised form September 22, 2016)

Abstract: The tectonic evolution of the pre-Cenozoic basement, as well as the Cenozoic structures within the Danube Basin (DB) and its northern periphery are presented. The lowermost portion of the pre-Cenozoic basement is formed by the Tatricum Unit which was tectonically affected by the subduction of the Vahicum/Penninicum distal continental crust during the Turonian. Tectonically disintegrated Tatricum overlaid the post-Turonian to Lower Eocene sediments that are considered a part of the Vahicum wedge-top basin. These sediments are overthrust with the Fatricum and Hronicum cover nappes. The Danube Basin Transversal Fault (DBTF) oriented along a NW–SE course divided the pre-Neogene basement of the DB into two parts. The southwestern part of the DB pre-Neogene basement is eroded to the crystalline complexes while the Palaeogene and Mesozoic sediments are overlaid by the Neogene deposits on the northeastern side of the DBTF. The DBTF was activated as a dextral fault during the Late Oligocene–Earliest Miocene. During the Early Miocene (Karpatian–Early Badenian) it was active as a normal fault. In the Middle–Late Miocene the dominant tectonic regime with NW–SE oriented extension led to the disintegration of the elevated pre-Neogene basement under the simple and pure shear mechanisms into several NE–SW oriented horst and graben structures with successive subsidence generally from west to east. The extensional tectonics with the perpendicular NE–SW orientation of the S_{hmin} persists in the Danube Basin from the ?Middle Pleistocene to the present.

Key words: Western Carpathians, Vahicum, wedge-top basin, pre-Cenozoic basement, palaeostress.

Introduction

The Danube Basin (Podunajská nížina) is situated in the southwestern part of Slovakia as the northern continuation of the Pannonian Basin system. The Danube Basin (DB) is geologically divided (Vass et al. 1988) into partial depressions extending between the horst structures of the pre-Cenozoic basement (e.g., the Rišňovce Depression) to the north and the Gabčíkovo Depression to the south. (Fig. 1). Sedimentary infill of the DB consists of Miocene, Pliocene and Quaternary deposits overlying the Hercynian crystalline basement in the south and the Mesozoic and Palaeogene sediments in the northern part.

The aim of the contribution is to give an overview of the tectonic evolution of the DB and its northern margin from the Cretaceous to the Quaternary. The tectonic reconstruction is based on both original and published data, including geological maps (Began et al. 1984; Harčár & Priechodská 1988; Ivanička et al. 1998; Nagy et al. 1998; Pristaš et al. 2000; Maglay et al. 2005; Ivanička et al. 2007; Polák et al. 2011; Fordinál et al. 2012; Potfaj et al. 2014; Teťák et al. 2015; see also the official online map at http://mapserver.geology.sk/gm50js/). The original data represent the set of the geological, structural and lithostratigraphic data collected, analysed and synthesized from the areas or localities where information were not available or insufficient (e.g., Brezovské Karpaty Mts.). Alpine tectonic individualization of the pre-Cenozoic tectonic units, origin and evolution of the Cenozoic sedimentary domains, geochronological and thermochronological (ZFT/AFT) data and the Miocene to Quaternary stress fields are discussed.

The tectonic evolution of the pre-Cenozoic basement

The pre-Alpine (Hercynian) structures are poorly preserved due to the Alpine structural overprinting. The Hercynian orogeny had the opposite vergence as the Alpine orogenesis, namely top generally to SE-S (e.g., Bezák et al. 1997; Ivanička et al. 1998; Polák et al. 2012; Pelech & Hók 2014; Broska & Petrík 2015 and original data).

From the point of view of the Alpine orogeny it is possible to define several basic tectonic units in the pre-Cenozoic basement of the DB. The Tatricum is the lowermost tectonic unit occurring on the surface or directly below the Cenozoic sediments. It includes Palaeozoic crystalline rocks and their sedimentary cover mainly of the Mesozoic age. The Tatricum has been overthrust by the cover nappes of the Fatricum and Hronicum (Plašienka 2003). The Fatricum is mostly composed of the Mesozoic carbonate sediments. In the Tribeč Mts. the Fatricum contains also crystalline rocks as a part of the Veporicum crystalline wedge displaced together with the Mesozoic (and partially Permian) sediments (Fig. 1).

The Vahicum (or Váhicum) Unit (Maheľ 1981; Plašienka et al. 1994; Plašienka 1999) is composed of the Upper Cretaceous sedimentary sequence containing olistholiths of the crystalline basement and the Triassic to Late Cretaceous sediments cropping out in the Považský Inovec Mts. (Rakús in Ivanička & Kohút 2011; Pelech et al. 2016a). New results (Pelech et al. 2016a) document superposition of the Upper Cretaceous sediments above the Tatricum and suggest their evolution in a wedge-top basin covering the external zones of the Internal Western Carpathians (*sensu* Hók et al. 2014). The Hronicum contains a Late Palaeozoic volcano-sedimentary sequence and Mesozoic (mostly Triassic) carbonate sediments. The Hronicum represents the uppermost tectonic unit in the DB area. Besides, the tectonic units already mentioned, the Pieniny Klippen Belt sediments (cf. Began et al. 1984; Mišík 1997) crop out on the NW edge of the investigated area (Fig. 1).

The sense of displacement of tectonic units obtained from the analysis of kinematic indicators is rather uniform with the top to the NW (Hók et al. 1994, 1998, 2013; Lénárt & Hók 2013 and original data). Some fluctuations (to WNW) were registered in the Tatricum and Veporicum tectonic units in the northern portion of the Tribeč Mts. and the Sklené Teplice Horst (Hók et al. 2013). The exceptions represent structures with top to the NE directions of the Hronicum nappe identical in both, the Tribeč Mts. and the Sklené Teplice Horst. Apart from these areas a similar sense of displacement was obtained from the Beckov Castle cliff (Fig. 2). In terms of current knowledge, it is not possible to satisfactorily explain this direction of displacement.

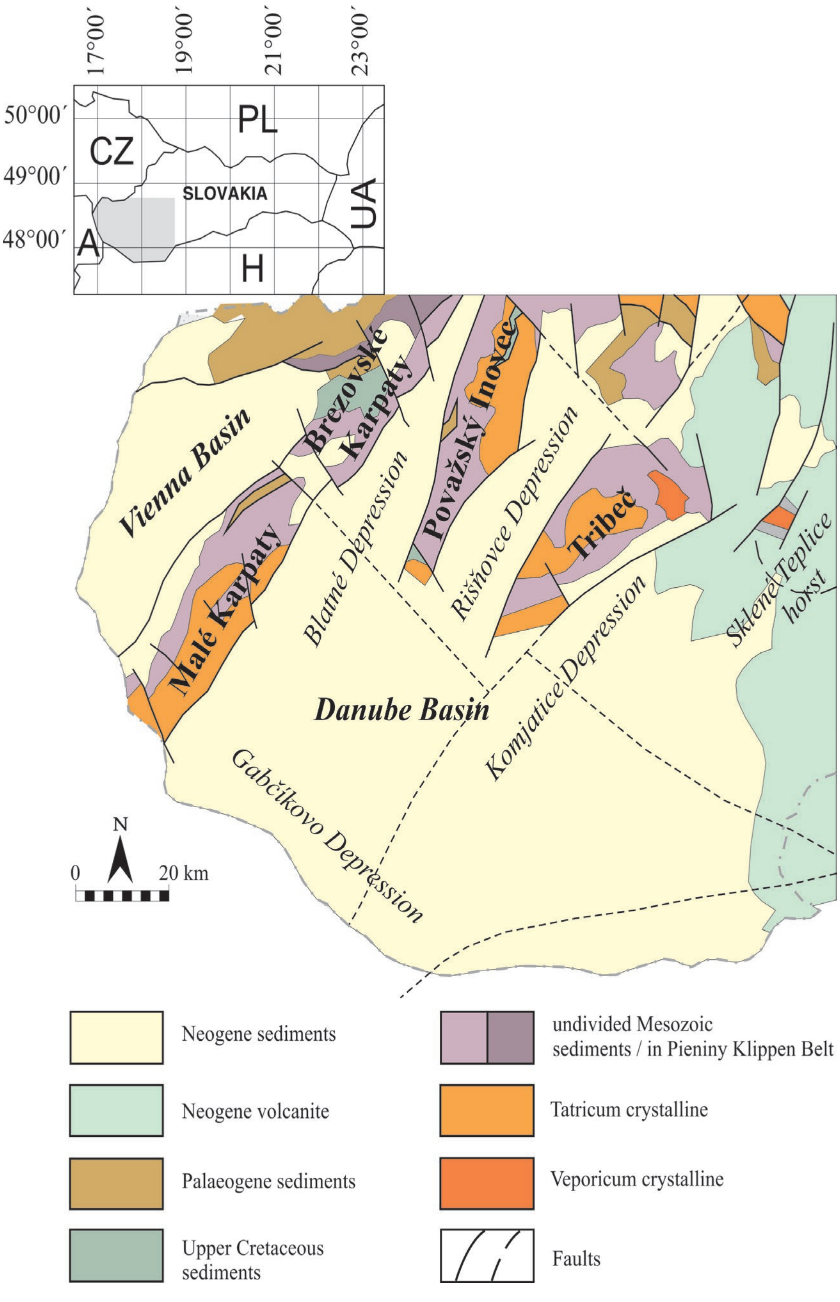

Fig. 1. Simplified geological map of the Danube Basin and surroundings.

The Tatricum tectonic unit

The oldest Alpine tectonic activity is reported from the Tatricum. It is 95 Ma (K/Ar dating, Biely in Kuthan et al. 1963) from the Tatricum cover sequence while the data from the Fatricum tectonically affected crystalline yielded 80 Ma (Ar/Ar dating, Putiš et al. 2009) in the Tribeč Mts. Folding of the Tatricum with generally top to the west-northwest (Fig. 2) before emplacement of the Fatricum crystalline and sedimentary sequences (Fig. 3a,b) was documented by structural data (Ivanička et al. 1998; Lénárt & Hók 2013).

The Albian–Cenomanian sediments of the Tatricum are transgressivelly overlain by the Middle Turonian–Santonian sediments and both sedimentary sequences are covered by the Fatricum nappe in the Považský Inovec Mts. (Pelech et al. 2014; Józsa & Pelech 2014). Geochronological data from the Upper Palaeozoic sediments of the Tatricum cover sequence yielded data between 110–90–60 Ma (U/Pb data from uranium mineralization, Archangeľskij & Daniel 1981; Štimel et al. 1984) respectively 100–80–50 Ma (Ar/Ar data from white micas, Putiš et al. 2009) from shear zones in the crystalline rocks (Fig. 3c,d). During this phase sinistral transpression shear zones occurred in the future Tribeč Mts. granite (Fig. 3c; Kráľ et al. 2002; Lénárt & Hók 2013). These

Fig. 2. The sense and direction of the tectonic displacement for the Tatricum Unit (dark grey arrows), the Fatricum (grey arrows) and the Hronicum (white arrows). The lines indicate the cross-section of the tectonic evolution model in Fig. 3 and Fig. 6.

data mirrored deformation of the Tatricum Unit before the displacement of the Fatricum/Hronicum nappes above the Tatricum. Occurrences of the Upper Cretaceous sediments in a discordant position above the Tatricum crystalline basement in the borehole HPJ-1 (Fig. 4; Pelech et al. 2016b) as well as below the Fatricum and Hronicum (Pelech et al. 2014) prove this conclusion in the Považský Inovec Mts. The ZFT data of 255 Ma from the Tatricum crystalline basement of the northern part of the Považský Inovec Mts. can be considered to be postmetamorphic cooling ages after collapse and exhumation of the Hercynian orogene. It also points to the Tatricum pre-Alpine crystalline basement occupying a rather superficial position during the Cretaceous thrusting (Fig. 4).

Folding and tectonic displacement of the Tatricum cover units with the top to the NW during the Turonian, before emplacement of the Fatricum unit in their tectonic hanging wall has been documented from the Malé Karpaty Mts. (Plašienka et al. 1991, 1993). This situation is also readable on the geological map (cf. Polák et al. 2011).

Based on the above we can conclude that the Tatricum rock sequences were tectonically imbricated and disintegrated prior to the emplacement of the Fatricum and Hronicum tectonic units (Fig. 3a,b) in the DB realm during the Cenomanian–Early Turonian (cca 100–90 Ma).

The Fatricum and Hronicum tectonic units

Displacement/thrusting of the Fatricum and Hronicum were dated within the DB territory from 80 Ma to 70 Ma (Campanian–Maastrichtian; Putiš et al. 2009). This is also confirmed by occurrences of the Upper Cretaceous sediments (Coniacian–?Eocene) in borehole SBM-1 (Mahel' 1985) and the Middle Turonian to Santonian sediments in the central part (Striebornica valley) of the Považský Inovec Mts. (Józsa & Pelech 2014). Both these occurrences of the Upper Cretaceous sediments are situated directly below the Fatricum thrust fault. This situation is slightly different in northern parts of the Internal Western Carpathians. Sedimentation of the Tatricum Mesozoic cover continued in the Veľká Fatra and Tatry Mts. (Cúlová & Andrusov 1964; Boorová & Potfaj 1997) during the Turonian. According to the aforementioned arguments it is possible to conclude that the displacement of the Fatricum and Hronicum nappes was terminated later within the DB region than in areas located further to the east (e.g. Plašienka et al. 1997; Prokešová et al. 2012).

The Vahicum tectonic unit

Occurrence of the ?Uppermost Cretaceous–Lower Palaeogene sediments (Soták et al. 2013) in the borehole KRS-3 (Fig. 3e; Fig. 4) corroborates the existence of a sedimentary basin situated most probably in a piggy-back position atop the Hronicum Unit (Fig. 3b,c). This basin can be considered as a part of the wedge-top basin of the Gosau Group during the Late Cretaceous–Eocene. The Late Cretaceous–Eocene wedge-top basin was connected with the subduction of the Penninic (i.e. Vahic) distal continental crust (Wagreich & Faupl 1994; Wagreich 1995; Frisch & Gawlick 2003; Schmid et al. 2004, 2008) extending from the Eastern Alps to the Western Carpathians (Fig. 3a,b,c). The docking of the Internal Western Carpathians tectonic units close to their present position can be deduced from borehole data and the transgressive position of the Eggenburgian sediments on top of the deformed Oligocene–Lowermost Miocene sediments (Fig. 3d,e). The borehole LU-1 reached below the Palaeogene and Lower Cretaceous sediments of the Internal Western Carpathians the Eocene sediments of the External Carpathians (Flysch Belt) on the northern periphery of the DB (Leško et al. 1982).

The tectonic evolution during the Cenozoic

Continuous changes of the compression direction of the palaeostress field orientations from NW–SE to NE–SW are characteristic for the Late Oligocene to Miocene tectonic evolution of the DB (c.f. Nemčok et al. 1989; Marko et al. 1991, 1995; Fodor 1995).

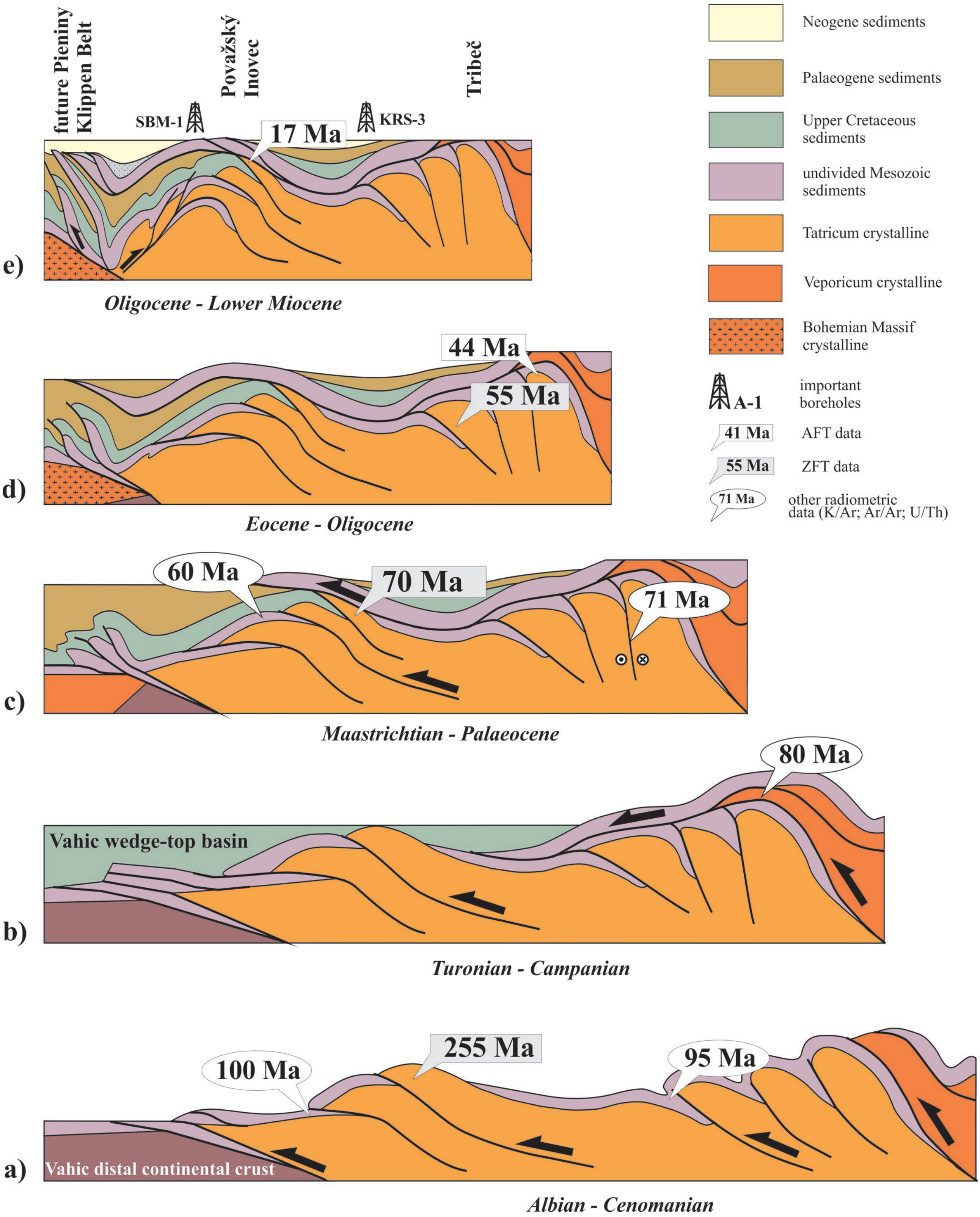

Fig. 3. Simplified evolution of the pre-Cenozoic basement of the northern part of the DB (not to scale; for details see text).

The Late Palaeogene–Early Neogene tectonics

During the Late Cretaceous and Palaeogene the Brezovské Karpaty Mts. area was covered by the sedimentary formations of the Brezová and Myjava Groups (c.f. Salaj et al. 1987; Fordinál, Elečko, Nagy in Polák et al. 2012). In contrast, the Malé Karpaty Mts. were evidently exhumed to the surface and intensively eroded during the Late Cretaceous. (Köhler & Borza 1984; Michalík 1984; Polák et al. 2012). It follows the Brezovské Karpaty Block (BKB) was most probably situated in a palaeogeographic position in relation to the Malé Karpaty Block (MKB) different to its recently position (Köhler et al. 1993).

The new geological and structural data of this study did not confirm the existence and activity of the ENE–SWS oriented Dobrá Voda Fault Zone (*sensu* Marko et al. 1991; Michalík et al. 1992) with back thrusting (generally top to SE) of the Hronicum rock sequence over the Upper Cretaceous sediments within the Brezovské Karpaty Mts. Continuation of the Dobrá Voda Fault Zone to the ENE and SWS is not clear (see fig. 2 in Marko et al. 1991 and Fig. 5), moreover the back thrusting is reported only from the Malé Karpaty Mts. (see fig. 4 and fig. 6 in Marko et al. 1990, 1991; Polák et al. 2012). Observed faults are mostly the normal faults in the Brezovské Karpaty Mts., and the age of the Upper Cretaceous sediments were redefined as the Early Miocene (see Kováč et al. 1991). The faults with backthrust activity were reported, besides the Malé Karpaty Mts. also from the western margin of the Považský Inovec Mts. (Ivanička et al. 2007; Pešková & Hók 2008; Pešková 2011; Pelech & Hók 2014). The activity of the back thrusts lasted until the Late Oligocene–Earliest Miocene. It is proved by angular unconformity between the folded Lower Oligocene sediments and the Lower Karpatian strata on the northern periphery of the Malé Karpaty Mts. (Marko et al. 1990). Furthermore, folded and faulted sediments of the Oligocene–?Karpatian age are tectonically incorporated in the Hronicum nappe on the western margin of the Považský Inovec Mts. (Ivanička et al. 2007; Pelech & Hók 2014; Pelech 2015). Indirect evidence also comes from the angular unconformity between the Upper Eocene and the Karpatian sediments in boreholes (Nižná and Borovce series of boreholes) situated in the Blatné Depression (Biela 1978). It is supposed that the MKB was shifted by dextral movement along the so called the Dobrá Voda Line (*sensu* Fusán et al. 1987; Ludince fault *sensu* Buday 1963; see also Kronome et al. 2014) or the Danube Basin Transversal Fault (DBTF), which is a new name for the above mentioned synonyms to the NW into the area of the future Vienna Basin during the Late Oligocene–Earliest Miocene. The estimated dextral offset of the back thrusts along the DBTF is ca. 15 km (Fig. 5).

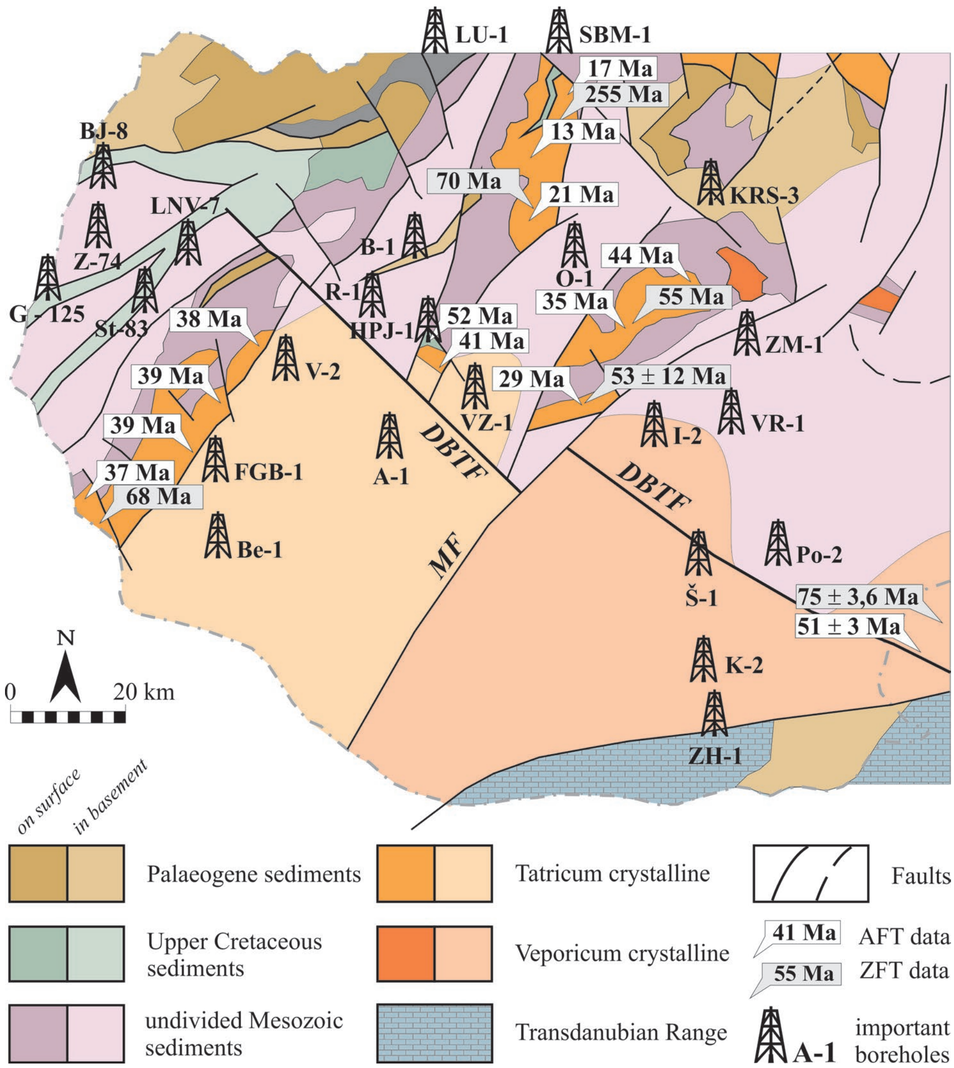

Fig. 4. Simplified map of the pre-Cenozoic basement of the Danube Basin with important boreholes and AFT/ZFT data (Kráľ 1977; Kováč et al. 1994; Koroknai et al. 2001; Danišík et al. 2004; Králiková 2013; Králiková et al. 2016). DBTF — the Danube Basin Transversal Fault was separated by the Mojmírovce Fault (MF) during the Middle Miocene.

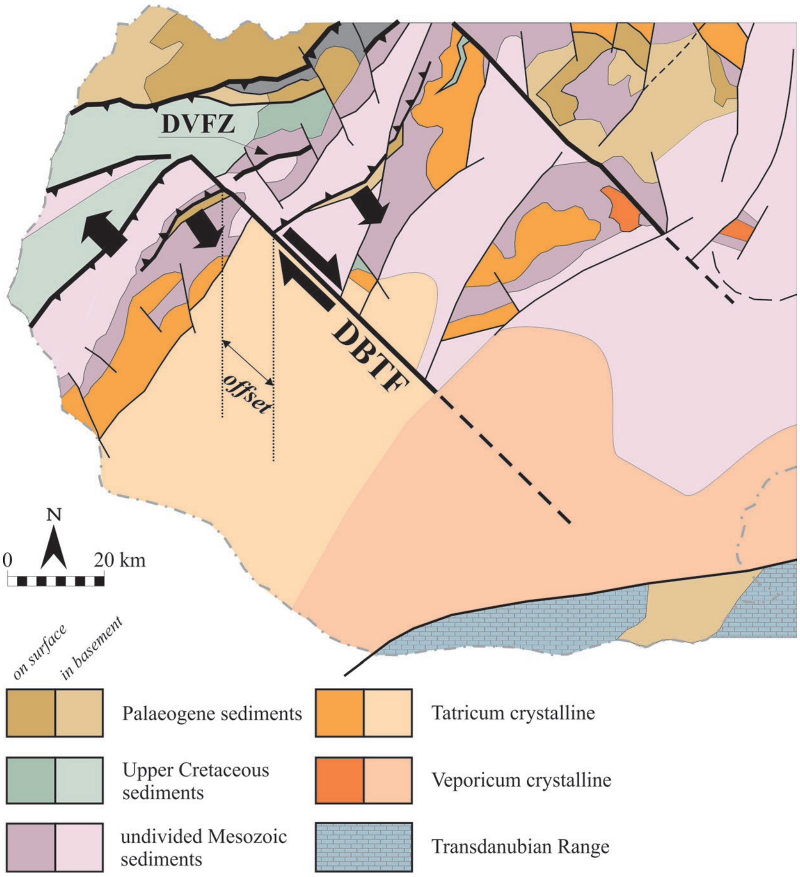

Fig. 5. Supposed and simplified scenario of the Malé Karpaty block shifting along the Danube Basin Transversal Fault (DBTF) during the Late Oligocene. The DBTF was reactivated as a normal fault diping to the NE during the Early Miocene. The DVFZ is the Dobrá Voda Fault Zone — (*sensu* Marko et al. 1991).

The prevailing NW–SE oriented compression in the frontal part of the ancestral Western Carpathians and contemporary extension in the NE–SW direction in the internal zones (Nemčok et al. 1989) reactivated the DBTF as a normal fault during the Eggenburgian–Early Badenian. South from the DBTF course the uplifted pre-Cenozoic basement of the DB was eroded up to the crystalline basement. First sediments were deposited over the crystalline basement south of the DBTF during the Middle Badenian.

The Mesozoic and Palaeogene complexes are preserved only northeast from the DBTF (Fig. 4). The Palaeogene strata together with a significant portion of the Mesozoic sediments were most probably removed by exhumation processes in the central part of the DB during the Oligocene–Earliest Miocene. This is verified by the absence of these sediments in boreholes (Biela 1978; Fusán et al. 1987) as well as by the gradual exhumation of the Tatricum crystalline basement according to published AFT data of ~52 to 20 Ma from the Malé Karpaty, southern portion of the Považský Inovec, and Tribeč Mts. (Kráľ 1977; Kováč et al. 1994; Danišík et al. 2004; Králiková 2013; Králiková et al. 2016). Moreover, the geochronological data are supported by AFT ages of more than ~40 Ma from the easternmost parts of the Eastern Alps indicating a similar age (Dunkl & Frisch 2002). At the same time, it points to the existence of an elevated area between the compressed front of the Internal Western Carpathians (forearc basin) and the retroarc Hungarian Palaeogene Basin above the Transdanubian Range (Tari et al. 1993).

The Neogene tectonics

The area of the present DB began to disintegrate into NE–SW oriented horst and graben structures in the Middle Miocene. This process took place under transtension/extension tectonic regime with the principal palaeostress compression oriented in the N–S to NE–SW direction. (Marko et al. 1991; Fodor 1995; Marko & Kováč 1996; Nemčok et al. 1998; Hók et al. 1999). Obtained data indicate successive opening of the depocentres generally from the west to the east (Fig. 6). During this time, the northern part of the Považský Inovec Mts. was exhumed, indicated by AFT data of ~21 to 13 Ma (Danišík et al. 2004; Králiková et al. 2016). Three main tectonic phases can be recognized in the tectonic evolution of the northern periphery of the DB. The first two phases were connected with simple shearing in the upper crust (*sensu* Wernicke 1985), which led to the opening of half-graben type depressions. A distinct subsidence (Lankreijer et al. 1995) followed by huge accumulation of sediments in the Blatné Depression (up to 2500 m) was accompanied by north-westward tilting of the pre-Neogene basement during the Badenian age (c.f. Rybár et al. 2015). Exhumation of the Tatricum basement and termination of unroofing of the Veporicum unit operated in the Tribeč Mts. (Fig. 6a) at the same time (Hók et al. 1999; Lénárt & Hók 2013).

The second phase is characterized by attenuation of the simple shear tectonic regime. This process is recorded by activity of the Majcichov fault (see Bezák et al. 2004) with significant tilting of the pre-Neogene basement to the northwest, and accumulation of the Sarmatian sediments (up to 1500 m) in the Rišňovce Depression (Fig. 6b). Moreover, the exhumed crystalline basement was sealed by the Sarmatian deposits in the Komjatice Depression (e.g., boreholes Ivánka, Biela 1978). The third tectonic phase can be characterized by pure shear extension (McKenzie 1978) in the Tribeč Mts. and the Komjatice Depression (Fig. 6c) with presence of the angular disconformity between the Sarmatian and Pannonian sediments (Kováč et al. 2008, 2011) and symmetrical character of this depression (Hók et al. 1999).

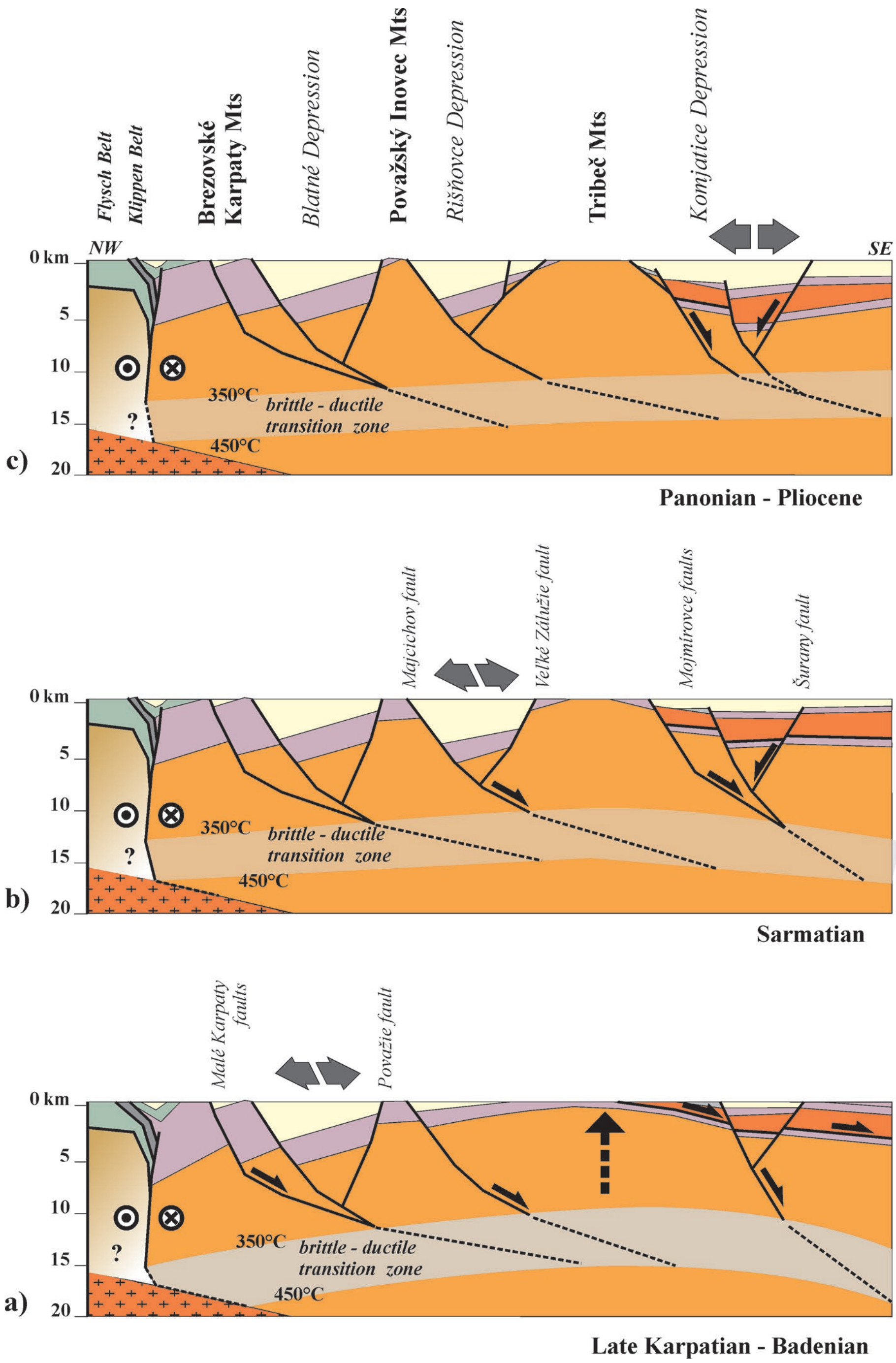

Fig. 6. Successive formation of the Miocene depocentres along the northern periphery of the Danube Basin (compiled according to Gaža & Beinhauerová 1976, 1977; Gaža et al. 1985; Zbořil et al. 1987, 1988; Lankreijer et al. 1995; Hók et al. 1999).

The Pliocene - Quaternary tectonics

The extension with the NW–SE oriented principal minimal palaeostress axis persisted during the Pliocene and Early Pleistocene (Fig. 7a). Orientation of the minimum component of the stress field (Shmin) switched from the NW–SE orientation to NE–SW direction most probably during the Middle Pleistocene (see also Decker et al. 2005). The orientation of the Shmin in a NE–SW direction (Fig. 7b) and so parallel to the Western Carpathians arc (orogen-parallel extension) from the Late Pleistocene to the present time (Littva et al. 2015). The exception is the configuration of the stress field obtained from the earthquake focal mechanism solution in the Blatné Depression and Brezovské Karpaty Mts. (Fojtíková et al. 2010; Jechumtálová & Bulant 2014).

Conclusion

The main results of the contribution can be summarized as follow:

The Tatricum Unit tectonically disintegrated prior to the displacement of the Fatricum and Hronicum tectonic units in its hanging-wall. The general direction sense of tectonic transport of the Tatricum and Fatricum was to the west-northwest. The Hronicum Unit was thrust generally in the same direction except in the Tribeč Mts. and the Sklené Teplice Horst (and Beckov castle cliff) where the sense of movement was to the NE (Fig. 2).

The Upper Cretaceous sediments transgressively overlay the deformed basement of the Tatricum and also the Hronicum units (Fig. 3). These sediments were an integral part of the wedge-top basin system continuing from the Eastern Alps to the Western Carpathians.

During the Late Oligocene the Malé Karpaty block shifted under NW–SE to NNW–SSE oriented compression to transpression, along the Danube Basin Transversal fault (DBTF) to the northwest (Fig. 5). Later, during the Early Miocene the palaeostress regime continually changed from transpression to transtension. The DBTF and parallel NW–SE oriented faults were activated generally as normal faults. The area southwest from the DBTF (in present day coordinates) was subsequently eroded to the crystalline basement (Fig. 4).

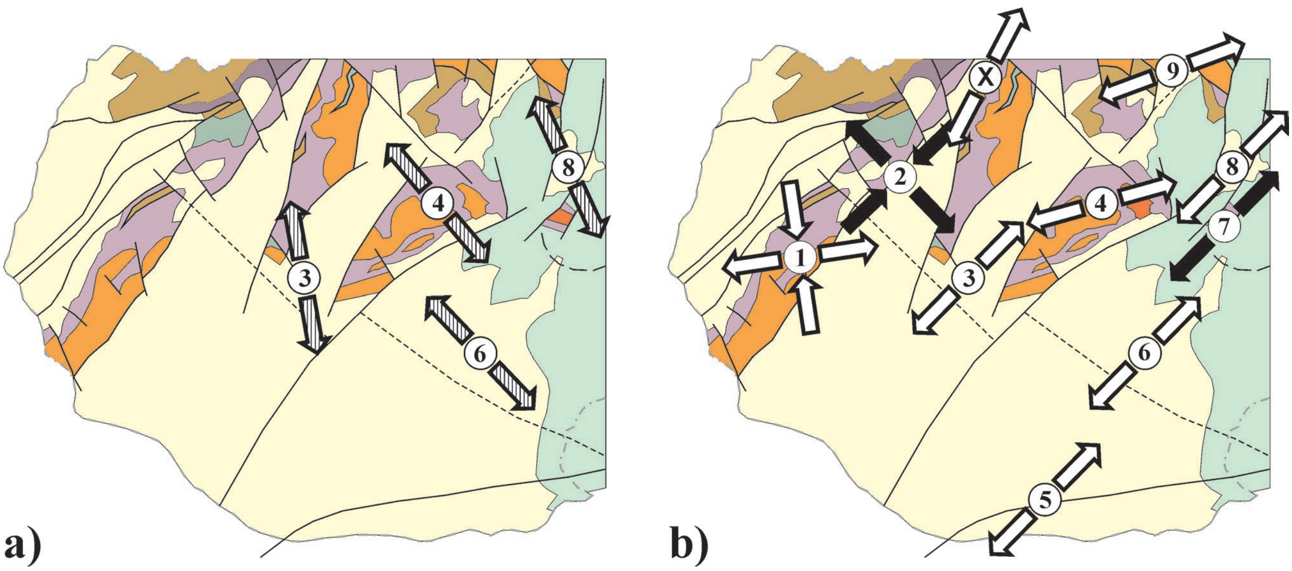

Fig. 7. Simplified geological map of the Danube Basin and surroundings (for explanations see Fig. 1). **a** — orientation of the extension (Shmin) during the Pliocene–?Early Pleistocene; **b** — orientation of the extension (Shmin) during the ?Middle Pleistocene–Holocene. Data were obtained from structural measurements and their interpretations. Black arrows indicate data from interpretation of the focal mechanisms (**2**) and extensometer (**7**). Reference: **1** — Briestenský et al. 2011; **2** — Fojtíková et al. 2010; Jechumtálová & Bulant 2014; **3** — Vojtko et al. 2008; **4** — Hók et al. 2007; **5** — Čepek 1938; **6** — Králiková et al. 2010; **7** — Mentes 2008; **8** — Pulišová & Hók 2015; **9** — Vojtko et al. 2011; **X** — original data.

In the Middle Miocene the extension oriented in a NW–SE direction caused opening of finger-like arranged depressions on the northeast periphery of the DB (Fig. 6a). The subsidence was induced by the simple shear regime in the upper crust in the Blatné Depression during the Badenian. Attenuation of the simple shear regime controlled the deposition in the Rišňovce Depression during the Sarmatian (Fig. 6b) and the pure shear regime operated in the Komjatice Depression during the Pannonian (Fig. 6c).

The extensional tectonic regime with the NW–SE direction of the Shmin persisted in the DB until the Early Pleistocene. From the ?Middle Pleistocene to present time the orogen-parallel extension with the Shmin orientation in a NE–SW direction prevails in the DB area (Fig. 7).

Acknowledgements: The work was financially supported by the Slovak Research and Development Agency under the contracts Nos. APPV-0099-11, APVV-0315-12 and APVV SK HU 2013-0020. We are also thankful to Lászlo Fodor and Miroslav Bielik who improved the quality of the paper with their comments and corrections from their review of the paper.

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