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Tectonic map of the pre-Cenozoic basement of the northern Danube Basin

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Abstract: The Danube Basin is located in the southwest of Slovakia in the northwestern part of the Pannonian Basin System. It consists of Cenozoic deposits, with Miocene sediments comprising the dominant portion in volume. The following paper presents a tectonic map of the pre-Cenozoic basement of the Danube Basin (DB) based on the integration of relevant data from geology, geophysics, biostratigraphy, and tectonics from the past to recently published and archival works. Analysis of boreholes and geophysical data has shown that the western and eastern parts of the DB pre-Cenozoic basement is dominated by Paleozoic crystalline rocks of the Tatric and Veporic nappes, while Mesozoic sediments belonging to the Tatric sedimentary cover, Fatric and Hronic cover nappes are found on the northern margin. The southeastern part of the DB is formed by the rock complexes of the Transdanubian Range Unit. The origin of these Carpathian and Austroalpine tectonic units is the result of Eo-Alpine (Late Cretaceous) tectonic processes. The recent arrangement of the pre-Cenozoic basement was shaped by Neo-Alpine (Miocene) tectonic processes in the extensional/transtension tectonic regime. Tectonic units of Carpathian origin together with the Transdanubian Range Unit can be correlated with the Austroalpine units.

Keywords: Slovakia, Western Carpathians, Neo-Alpine faults, lithotectonic units

Introduction

The Danube Basin represents the northern extension of the Miocene Pannonian back-arc basin system (Royden & Horváth 1988). The sedimentary infill of the Danube Basin comprises Paleogene, Neogene, and Quaternary deposits (Biela 1978a; Fusán et al. 1987; Šujan et al. 2021), which overlie a Variscan crystalline basement and upper Paleozoic to Mesozoic sediments of the Transdanubian Range Unit in the south. Mesozoic sediments are mainly found in the northern part (Biela 1978a; Fusán et al. 1987). The region of the Danube Basin was subdivided (Vass et al. 1988) into several partial depressions (Blatné, Rišňovce and Komjatice depressions), which are bounded by horst structures of the pre-Cenozoic basement (Malé Karpaty, Považský Inovec and Tribeč Mountains) to the north and the Gabčíkovo–Želiezovce depressions to the south (Figs. 1, 2). In the past, the pre-Cenozoic basement of the Danube Basin had been the subject of several partial research works (Buday et al. 1965; Buday & Špička 1967a, b; Gaža & Beinhauerová 1976, 1977; Zbořil et al. 1987), which eventually resulted in a complex publication (Fusán et al. 1987). Following this period, the issue has since been elaborated in several papers (Balla 1994; Hók et al. 1999, 2016, 2021; Kronome et al. 2014; Bezák et al. 2023).

This contribution includes an overview of the geological, geophysical, and structural data of the Danube Basin. An integrated methodological approach was employed to interpret the position of the principal fault structures and the arrangement of tectonic units in the pre-Cenozoic basement of the Danube Basin. The initial phase involved expert selection, comparison, and review of existing lithostratigraphic, biostratigraphic, and lithotectonic data for both pre-Cenozoic and Cenozoic rock complexes, as well as the location and evaluation of boreholes (e.g., Gaža 1963, 1968, 1974, 1978; Lunga 1963; Vass & Gabčo 1966; Gaža & Beinhauerová 1976, 1977; Biela 1978a, b; Remšík et al. 1979; Remšík & Franko 1979; Pěničková et al. 1984; Gaža et al. 1985; Fendek et al. 1986; Körössy 1987; Klago 1988; Klago & Matejčeková 1988;

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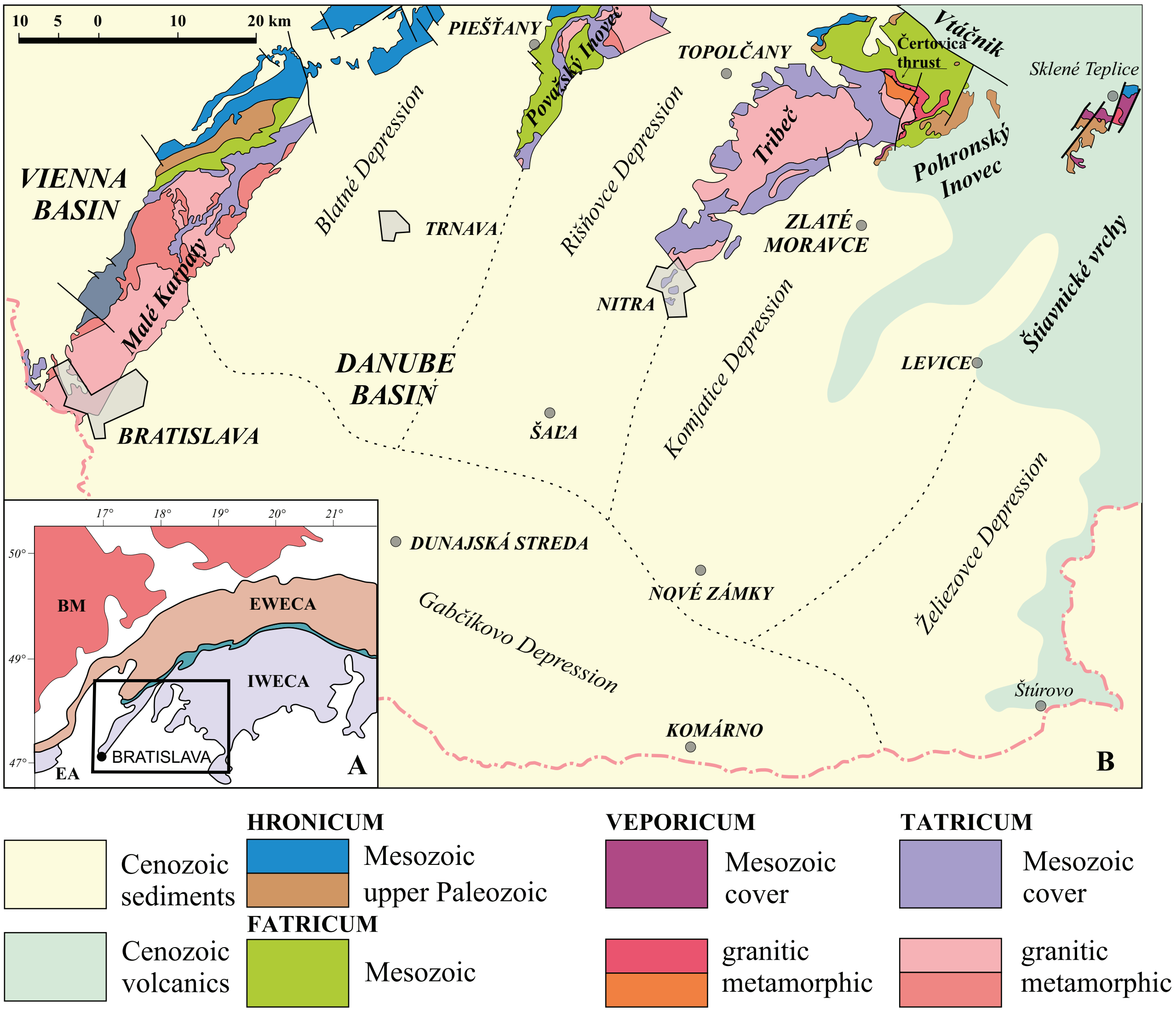

Fig. 1. A — The position of the investigated area (rectangle). MB – Bohemian Massif; EA – Eastern Alps; EWECA – External Western Carpathians; IWECA – Internal Western Carpathians. **B** — Simplified geological map of the Danube Basin and sub-basins (modified from Vass et al. 1988).

Klago & Tyleček 1988; Koroknai et al. 2001; Fordinál et al. 2002; Král et al. 2013).

Relevant geophysical data from gravimetry (e.g., Zbořil et al. 1984, 1987; Bielik et al. 2002; Pašteka et al. 2017), seismic (e.g., Vozár et al. 1998; Šályová & Mojžiš 2009a, b, c), and complex geophysical studies (e.g. Šefara et al. 1987, 1998; Kilényi & Šefara 1989), along with reinterpretations of geophysical data and borehole correlations, integrate new stratigraphic insights (e.g., Rybár et al. 2016, 2024; Sztanó et al. 2016; Šarinová et al. 2018, 2021; Šujan et al. 2021; Rybár & Kotulová 2023). Subsequently, the collected data were visualised and a structure map was compiled, highlighting the principal faults and the distribution of the tectonic units (Fig. 3). The methodology also involves a review of the geodynamic evolution of the area, including paleostress orientations and the current tectonic regime (Nemčok et al. 1998; Hók et al. 2016). The outcome is a tectonic map of the pre-Cenozoic basement of the Danube Basin, based on the most recent progress and present-day accepted concepts. The presented map can serve as a basis for correlating the pre-Cenozoic rock complexes with surface occurrences, drilling, and geophysical data, which will allow reconstructing the geological structure prior to the deposition of Cenozoic sediments and volcanics. Knowledge of the rheological properties of the rocks of the pre-Cenozoic basement and the kinematics of their interfaces is an essential basis for the assessment of seismic source zones in Slovakia. Tectonically-stabilised areas are favourable for the safe disposal of the whole spectrum of waste types, including high-level waste from nuclear energy. The rock complexes, which underlie the Cenozoic sediments, have significant potential in terms of normal and mineral waters, as well as geothermal resources.

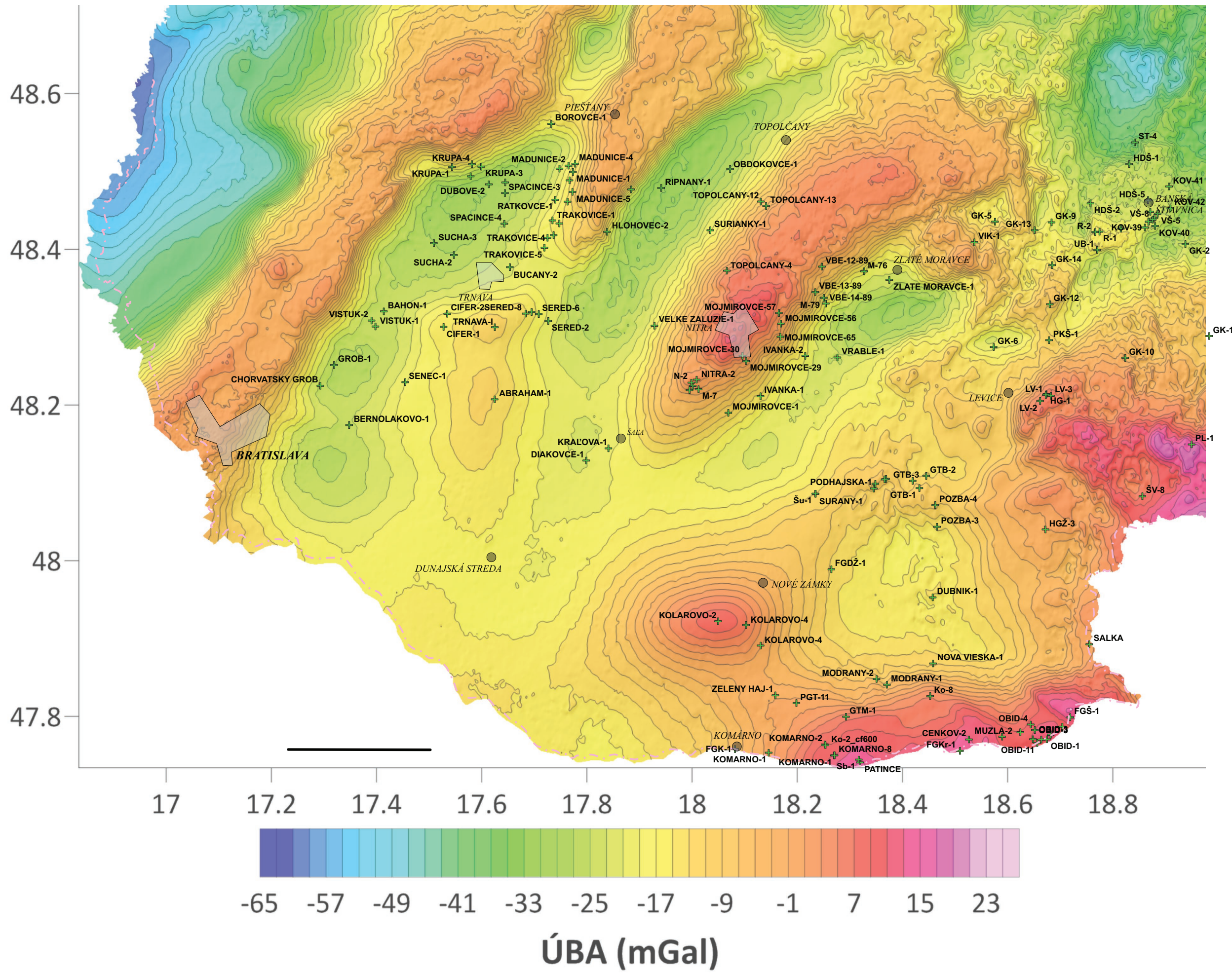

Fig. 2. Map of the Bouguer anomaly (Pašteka et al. 2017; Zahorec et al. 2021) and borehole locations.

Tectonic units forming the pre-Cenozoic basement

The Pre-Cenozoic basement, which contains the Eo-Alpine tectonic units (Late Cretaceous), is exposed in horst structures and limits the extension of Miocene sediments. The Tatricum is the lowermost and most autochthonous unit and is composed of Paleozoic crystalline with a cover of Mesozoic carbonates; it also contains a negligible portion of late Paleozoic siliciclastic sediments. The Tatric crystalline basement in the northwestern part of the Malé Karpaty Mountains is overthrust above the Borinka Unit, which is interpreted as part of the Austroalpine (Plašienka 2018; Hók et al. 2022). The Veporicum, as well as the Tatricum, contains a Paleozoic crystalline and sedimentary cover (late Paleozoic to Mesozoic). Along the so-called Čertovica thrust, the Veporicum was displaced above the Tatricum. In addition to the crustal tectonic units, Fatricum and Hronicum thin-skinned nappes are also present, which predominantly contain Mesozoic carbonate sediments with late Paleozoic volcano-sedimentary succesion in the Hronicum (Fig. 1).

The western and central parts of the Danube Basin are composed of crystalline rocks belonging to the Tatricum, whereas the eastern part is characterised by the Veporic crystalline basement (Dlabač & Adam 1959; Adam & Dlabač 1961; Gaža & Beinhauerová 1977; Fusán et al. 1987; Hók et al. 2021). The Tatric crystalline basement rocks include late Paleozoic granitoids (Carboniferous) and Paleozoic metamorphic rocks (Devonian). These granitoids intruded the metamorphic rocks (phyllites to gneisses) in the Malé Karpaty Mountains, where this relationship can be observed on surface outcrops (Polák et al. 2012; Digital Geological Map of the Slovak Republic 2023). Similar rock types were drilled in the Raj-1 borehole near the village of Rajka, as well as in the Msz-1 and Msz-2 boreholes in Mosonszolnok (Fig. 3) in northwestern Hungary (Körössy 1987; Kronome et al. 2014). Metamorphic rocks and granitoids identical to those found in the Malé Karpaty Mountains are also exposed near the willages of Hainburg and Jois in northeastern Austria. These pre-Cenozoic basement sequences in Austria and Hungary are undoubtedly part of the Tatricum and can be atributed to Carpathian tectonic provenance (Hók et al. 2022; Reiser et al. 2024).

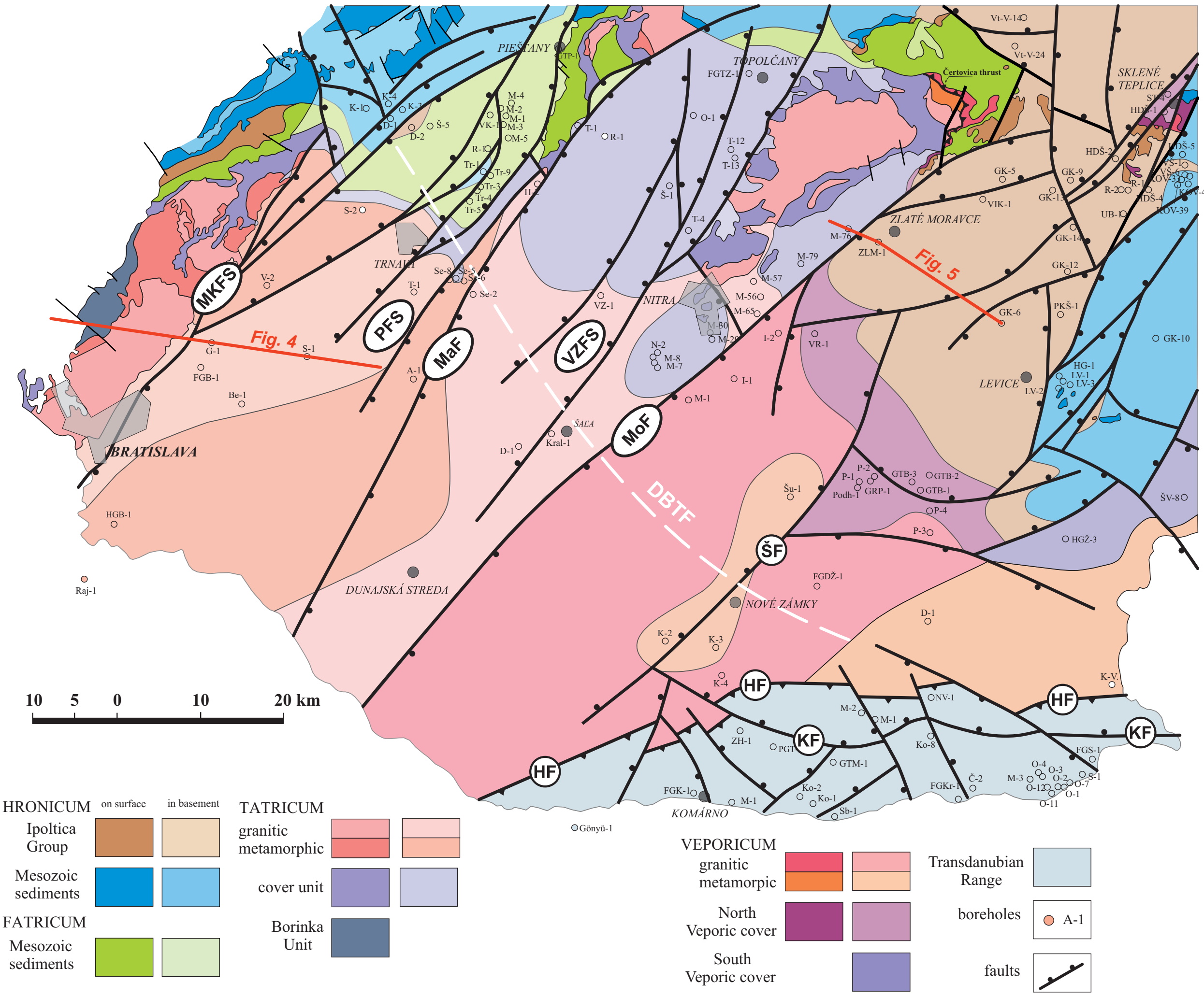

Fig. 3. Tectonic map of the pre-Cenozoic basement of the Danube Basin showing major fault systems and structures. Abbreviations: DBTF – supposed position of the Danube Basin Transverzal Fault, MKFS – Malé Karpaty fault system, PFS – Považie fault system, MaF – Majcichov fault, VZFS – Veľké Zálužie fault system, MoF – Mojmírovce fault, ŠF – Šurany fault, HF – Hurbanovo fault, KF – Kamenica fault.

The Eo-Alpine tectonic contact between the Tatricum and Veporicum (Čertovica thrust) is visible in the northeastern part of the Tribeč Mountains (Hók et al. 1998; Ivanička et al. 2007; Digital Geological Map of the Slovak Republic 2023). However, this boundary becomes indistinct to the southwest, where it is conventionally aligned with the presumed continuation of either the Šurany Fault (Fusán et al. 1987) or the Mojmírovce Fault (Hók et al. 2016, 2021; Rybár et al. 2024). The Veporic crystalline complex includes Paleozoic granitoids and metamorphic rocks, with granitoids frequently overlying metamorphic rocks (*see* Klinec 1966). Boreholes Kolárovo-2 (K-2), Šurany-1 (Š-1), and Dubník-1 (D-1) confirm the presence of Veporicum beneath the Miocene sediments found in the southeastern area (Biela 1978a). The presence of the Veporicum in the northeastern part of the Danube Basin basement is indirectly indicated by the occurrence of Hronicum in the areas of Sklené Teplice and Levice. In these locations, the Hronicum is observed solely in a tectonic superposition above the Veporicum and/or Fatricum (*cf.* Hók et al. 2013, 2021; Digital Geological Map of the Slovak Republic 2023).

Broska et al. (2024) presented an overly simplistic interpretation of the Eo-Alpine thrust contact between the Tatricum and Veporicum in the southwestern portion of the Tribeč Mts. Their interpretation relies primarily on contrasting geochemical properties of the granitoids. However, borehole RAO-3 revealed an intrusive contact between these granitoid bodies (Madarás et al. 2004), and no Mesozoic sediments were found between the granitoid sheets, providing no clear evidence of Eo-Alpine displacement (*cf.* fig. 14 in Broska et al. 2024).

Mesozoic and sporadic late Paleozoic sediments are predominantly concentrated in the northern part of the Danube Basin (Buday & Špička 1967a; Gaža & Beinhauerová 1976;

Biela 1978b; Fusán et al. 1987). The Mesozoic sediments are represented by various carbonate facies associated with the Tatricum, Fatricum, and Hronicum (Hók et al. 2019). Specifically, the Hronicum is characterised by a thick volcano-sedimentary sequence of late Paleozoic age, known as the Ipoltica Group (*sensu* Vozárová & Vozár 1981) and predominantly widespread within the pre-Cenozoic basement of the northeastern part of the Danube Basin (Fig. 3).

The southeastern margin of the Danube Basin basement is dominated by the rock complexes of the Transdanubian Range Unit (Buday & Špička 1967a; Fusán et al. 1987), which form the uppermost/southernmost part of the Austroalpine nappe system (Haas & Budai 2014; Dunkl et al. 2019). The Transdanubian Range is separated from the Tatric and Veporic crystalline complexes by the Rába–Hurbanovo–Diósjenő fault system (Gaža & Beinhauerová 1977; Fusán et al. 1987; Balla 1994; Szafián et al. 1999; Koroknai et al. 2001; Haas & Budai 2014).

NE–SW oriented faults divide the northern part of the Danube Basin into typical basin-and-range topography, with Blatné, Rišňovce, and Komjatice depressions or sub-basins (Figs. 1, 2). The faults were formed under a transtensional/extensional tectonic regime, with the paleostress compression oriented in a N–S to NE–SW direction during the Miocene (Fodor 1995; Nemčok et al. 1998; Šujan et al. 2021). Significant subsidence and accumulation of Badenian sediments in the Blatné Depression (up to 2500 m), Sarmatian sediments in the Rišňovce Depression (up to 1500 m), and Pannonian sediments in the Komjatice Depression (up to 1000 m) indicate a successive opening of the depocenters, generally progressing from west to east (Fusán et al. 1987; Lankreijer et al. 1995; Hók et al. 2016; Šujan et al. 2021).

The Pre-Cenozoic basement of the ***Blatné sub-basin*** is made up of the Hronicum and Fatricum in its northeastern part. The Hronic sediments are tectonically imbricated into several nappes, as observed in borehole Dubové-2 (D-2; Biela 1978a). Crystalline basement complexes of the Tatricum dominate the southwestern part of the depression and extend into adjacent areas in Austria and Hungary (Fig. 3). The oldest Miocene sediments in the Danube Basin (Lower Badenian) have been identified in the Blatné Depression. The sediments overlying the Mesozoic limestones contain pebbles derived from the crystalline basement, as well as from late Palaeozoic volcanosedimentary rocks of the Ipolitica Group (Rybár et al. 2015, 2016; Šarinová et al. 2021).

The pre-Cenozoic basement of the ***Rišňovce sub-basin*** consists exclusively of rock sequences belonging to the Tatricum (Fig. 3). The identification of the Tatric Mesozoic sediments and granites significantly revises previous interpretations, which had suggested the presence of the Fatricum in the pre-Cenozoic basement (Fusán et al. 1987). The occurrence of Paleogene (Eocene) sediments overlying Tatric Triassic carbonates in the Topolčany (FGTZ-1) borehole (Fendek et al. 1986) indicates substantial erosion of the pre-Cenozoic basement before the Eocene. A similar stratigraphic relationship is observed on the eastern slopes of the Považský Inovec Mountains, where Paleogene sediments uncomfortably overlie the Tatric granites (Digital Geological Map of the Slovak Republic 2023). This assumption is supported by the dating of pseudotachylites (49.7±1.3 Ma) in granites from the RAO-1 well in Tribeč (Kohút & Sherlock 2016), indicating seismic/tectonic activity. Gradual exhumation of the granitoid core is also indicated by ZFT and AFT ages (69–53 Ma and 40–28 Ma) from the Tribeč granites (Králiková et al 2016). The oldest Miocene sediments and volcanic rocks above the crystalline basement found in the Kral-1 (Kráľová-1) borehole were dated to the early Badenian (14.1 million years) in the southern part of the Rišňovce sub-basin (Rybár et al. 2024).

The Komjatice sub-basin pre-Cenozoic basement is composed of the Hronic upper Paleozoic volcano-sedimentary complex of the Ipoltica Group, which is underlain by the Veporic Mesozoic cover and crystalline rocks. Geophysical data suggest that the Ipoltica Group forms a specific nappe structure in the northeastern corner of the Komjatice Depression (Figs. 2, 3). Similar structure configurations are observed at the surface of the Tribeč Mountains (Ivanička et al. 1998), as well as in the Podhradie-86 (Po-86) borehole beneath the Neogene volcanic rocks in the Vtáčnik Mountains (Biela 1978a; Biely 1979). The oldest Cenozoic/Miocene sediments were found in the ZLM-1 (Zlaté Moravce-1) borehole in the northeastern part of the Komjatice sub-basin. The basal Cenozoic strata (Zlaté Moravce Fm., upper Badenian–Sarmatian) comprise poorly-rounded, altered granitoids, meta-greywacke, meta-arkose, quartz arenite, carbonates, and occasional melaphyre (Šarinová et al. 2018).

The Želiezovce sub-basin is in the easternmost part of the Danube Basin (Fig. 1). It is the only depression within the Danube Basin that contains Paleogene (Oligocene) sediments, commonly referred to as the Buda Paleogene, Štúrovo Paleogene, or Hungarian Paleogene Basin (e.g., Fordinál et al. 2002; Vass 2002; Kováč et al. 2016). The pre-Cenozoic basement of the Želiezovce sub-basin consists of rock complexes of the Western Carpathians (IWECA) and the Transdanubian Range Unit, which are separated by the Hurbanovo Fault. IWECA rocks belong to both the South and North Veporic units (*see* Hók et al. 2019). The crystalline basement of the southern and northern Veporicum cannot be distinctly separated due to the similarity of the rock complexes. However, in boreholes Dolné Semerovce-8 (ŠV-8) and Želiezovce-3 (HGŽ-3), Mesozoic sediments of the Southern Veporicum were identified based on lithostratigraphy along the northeastern margin (Fig. 3) of the Želiezovce sub-basin (Biela 1978a; Vozár in Matura et al. 2000). In the Želiezovce sub-basin, Oligocene sediments have been identified in the Salka (K-V) and Želiezovce (HGŽ-3) boreholes (Vass & Gabčo 1966; Fordinál et al. 2002), as well as in several boreholes in Hungary (Korec-Laky & Nagy-Gellai 1985), which are near the Salka or Želiezovce boreholes.

The Gabčíkovo sub-basin represents the deepest part of the Danube Basin (Kilényi & Šefara 1989) with the composition of the pre-Cenozoic basement in its central area remaining largely unknown (*see* Haas & Budai 2014). However, borehole data from the surrounding region suggest the presence of a Tatric and Veporic crystalline basement in this portion of the basin (Fusán et al. 1987). Based on similar lithostratigraphy, geological evolution, and structural features, the Tatric and Veporic crystalline basement units can be correlated with the Troiseck-Floning Nappe, which is part of the Silvretta-Seckau Nappe System in the Eastern Alps. However, the tectonic position within the Alpine nappe stack is not exactly the same (Reiser et al. 2024). Devonian black biogenic siliceous deposits and grey-brown nodular limestone were documented in the ZH-1 borehole (Zelený Háj 1; Biely & Kullmanová 1979) on the eastern margin of the Gabčíkovo sub-basin. These sediments can be correlated with Paleozoic sequences of the Transdanubian Range Unit (Haas & Budai 2014) or with Austroalpine/Southern Alpine sequences (Haas et al. 2000; Schmid et al. 2008; Dunkl et al. 2019; Reiser et al. 2024). Thus, the pre-Cenozoic basement of the Gabčíkovo sub-basin is composed of the Tatricum, Veporicum, and Transdanubian Range Unit, which show strong correlation with the Austroalpine units of the southeastern margin of the Eastern Alps.

The Pre-Cenozoic basement underlying the Neogene volcanic rocks on the northeastern margin of the Danube Basin is exposed near Sklené Teplice (Konečný et al. 1998; Hók et al. 2013). The basement rocks belong to the tectonic units of the northern Veporicum and Hronicum (Fig. 1) and have been primarily characterized through borehole data obtained from the covered region between Sklené Teplice and Levice. The area is predominantly composed of Mesozoic carbonate sediments and volcano-sedimentary rocks of the Hronicum. The varying facies of Mesozoic carbonates and the distinct lithologies of the volcano-sedimentary rocks have enabled the identification of several nappes within the Hronicum tectonic unit (Hók et al. 2020; Hók & Olšavský 2023).

Principal faults

The main faults in the Danube Basin represent structures that resulted from the collision of the Western Carpathians with the European Platform during the latest Oligocene and Miocene (e.g., Nemčok et al. 1998; Kováč 2000). Within the Danube Basin, prerift processes leading to deformation of the lithosphere and crust have been defined, followed by extensional processes in the back arc associated with polyphase rifting (Šujan et al. 2021), as well as the formation of normal faults. The location and activity of the principal faults within the Danube Basin area were determined through the integration of geological, borehole, and geophysical data. Faults with a verified offset of the pre-Cenozoic basement greater than 500 meters are depicted in the accompanying map (Fig. 3).

The Hurbanovo Fault (HF) is a significant E–W oriented, first-order structural discontinuity in the Danube Basin, which separates the major tectonic units of the Internal Western Carpathians (IWECA), specifically the Veporicum, from the Transdanubian Range Unit (Buday et al. 1965; Gaža 1974; Fusán et al. 1987; Balla 1994; Nemesi et al. 1997; Šefara et al. 1998; Haas & Budai 2014; Klučiar et al. 2016). The tectonic and kinematic nature of this discontinuity has been subject to varying interpretations (e.g., Tarri et al., 1993; Vass et al. 1993; Balla 1994; Nemesi et al. 1997; Kováč et al. 2002; Haas et al. 2010; Haas & Budai 2014). The HF connects with the NE–SW trending Rába Line to the southwest and with the Diósjenő Line to the E–NE (Nemesi et al. 1997; Haas & Budai 2014; Klučiar et al. 2016). The Rába Line and HF are a projection of the Eo-Alpine thrust plane of the Austroalpine nappe system, which generally dips to the south–southeast and which was later (Neo-Alpine) modified and reactivated by low-angle extensional deformation (Horváth 1993; Tari & Horváth 2010; Tari et al. 2021). The northern/northeastern continuation of the Transdanubian Range Unit into the territory of Slovakia is proved by data from boreholes NV-1 (Nová Vieska-1), Mo-2 (Modrany-2), ZH-1 (Zelený Háj-1), and partly from FGK-1 (Komárno) and Gönyü-1 as well, while the northern termination is interpolated between the above-mentioned boreholes and the boreholes that had certainly penetrated the Veporicum (Kolárovo well series, Dvory nad Žitavou-1 (FGDŽ-1) and Dubník-1 (D-1)). The northern termination of the Transdanubian Range Unit should be identical to the HF course. Notwithstanding the above, the normal fault located south of this contact was considered to be the HF (e.g., Gaža & Beihauerová 1977; Remšík & Franko 1979; Fusán et al. 1987; Kováč et al. 2018; Šujan et al. 2021; Bezák et al. 2023). We propose the name “Kamenica fault” for this north-dipping Neo-Alpine normal fault, located south of the HF (Fig. 3). Both the Hurbanovo and the Kamenica faults are segmented by normal faults oriented in the NW–SE direction (Remšík & Franko 1979; Klago 1988). Surface investigations of NW–SE oriented faults reveal evidence of Quaternary activity (Čepek 1938; Hók et al. 2016).

The Danube Basin Transversal Fault (DBTF) is an indistinct boundary in the pre-Cenozoic basement oriented in the NW–SE direction, which separates the crystalline basement in the southwestern part from the northern part, containing Mesozoic sediments (Fig. 3). This interface has been referred to by various names, including the Őlvéd Line (*sensu* Telegdi Roth 1929), the Ludince Zone (*sensu* Buday et al. 1965), the Ludince Line (*sensu* Gaža & Beinhauerová 1977), the Dobrá Voda Line (*sensu* Fusán et al. 1987), as well as being known as the Danube Basin Transversal Fault (DBTF; *sensu* Hók et al. 2016). However, the precise continuation of the DBTF from the Malé Karpaty Mountains towards the Danube Basin is significantly disturbed by younger NE–SW oriented faults that had formed during the Middle Miocene, making it difficult to trace its course.

The southern (central) part of the Danube Basin pre-Cenozoic basement has been eroded down to the Tatric and Veporic crystalline basement levels. Apatite fission track analysis indicates that the exhumation of the Veporic crystalline basement occurred between 65 and 55 Ma, while the Tatric crystalline basement was exhumed between 51–33 Ma (Koroknai et al. 2001; Králiková et al. 2016; Vojtko et al. 2016; Tari et al. 2021). The exhumation of these crystalline complexes was initiated by Eo-Alpine crustal nappe stacking, which led to crust thickening and was later followed by isostatic equilibration and subsequent unroofing during the Paleocene to Oligocene in the Internal Western Carpathians, including the Danube basement (Lillie et al. 1994; Jeřábek et al. 2012; Majcin et al. 2015).

From this perspective, the Danube Basin Transversal Fault can be interpreted as the terminal segment of a large core complex (Danubius Antiform *sensu* Tari et al. 2021) dominated by low-angle mylonitic shear zones (Fig. 4).

NE–SW trending faults played a crucial role in shaping the Danube Basin during the Miocene. The development of the Blatné Depression during the Badenian was predominantly controlled by the **Malé Karpaty Fault System** with SE-dipping normal faults and by the **Považie Fault System**, which comprises NW-dipping antithetic faults (Fig. 3). The Malé Karpaty Fault System (MKSZ) consists of several faults that were previously described in the past, such as the Bratislava fault, Budmerice fault, Vištuk fault, Boleráz fault, Smolenice fault, Kátlovce fault, and Čaníkovce/Šenkvice fault (*sensu* Buday et al. 1962), even the Malé Karpaty fault and Čachtice fault (*sensu* Bezák et al. 2004) along with the entire Malé Karpaty fault system (*sensu* Maglay et al. 2011). According to previous studies, the Považie Fault System (PFS) includes several separate faults, such as the Váh fault, Trnava faults, and the Cífer fault (*sensu* Buday et al. 1962), as well as the Považie fault (*sensu* Bezák et al. 2004) or the Považie fault system (*sensu* Bielik et al. 2002; Maglay et al. 2011).

The Majcichov Fault (Buday et al. 1962; Fusán et al. 1987; Pristaš et al. 2000; Bezák et al. 2004), which is also referred to as the Rišňovce Fault (Bielik et al. 2002; Šujan et al. 2021) or the Ripňany-Galanta Fault (Rybár & Kotulová 2023; Rybár et al. 2024), separates the Považský Inovec horst structure from the Neogene sedimentary infill of the Rišňovce Depression. The original and priority designation, "Majcichov Fault" (MaF), as defined by Buday et al. (1962), is therefore used as the standard terminology in this study. The MaF exhibits the largest normal displacement among the faults in the Danube Basin, with more than 3500 meters of offset, as evidenced by the Neogene sediments thickness in the Ripňany-1 borehole (R-1; Biela 1978a), which did not reach the pre-Cenozoic basement. The primary tectonic and syn-sedimentary activity along the MaF occurred from the late Badenian to the Sarmatian (Lankreijer et al. 1995), possibly extending into the Pannonian. The significance of the MaF is further highlighted by the pronounced halfgraben asymmetry of the Rišňovce Depression, where the deepest part is located along its northwestern margin (Kilényi & Šefara 1989). The southeastern slope of the depression, which is adjacent to the Tribeč Mountains, is moderate and disturbed by the **Veľké Zálužie Fault System** (VZFS; Pristaš et al. 2000). It is also known as the Veľké Zálužie Faults (*sensu* Buday et al. 1962). Geophysical data suggest that the MaF extends southwestward into the central part of the Danube Basin (Sztanó et al. 2016). Its continuation in the Hungarian section of the basin may correspond to a fault that separates the Mihályi High from the Kenyeri depression.

The northwestern boundary of the Komjatice Depression is delineated by the **Mojmírovce Fault** (MoF), which separates the depression from the Tribeč Mountain (Dlabač & Adam 1959). Although the Mojmírovce Fault and the Čertovica Fault are often interpreted as a single fault structure (Hrušecký 1999; Tari et al. 2021; Rybár & Kotulová 2023; Rybár et al. 2024), they differ significantly in origin and tectonic history. The Mojmírovce Fault is a Neo-Alpine (Neogene) normal

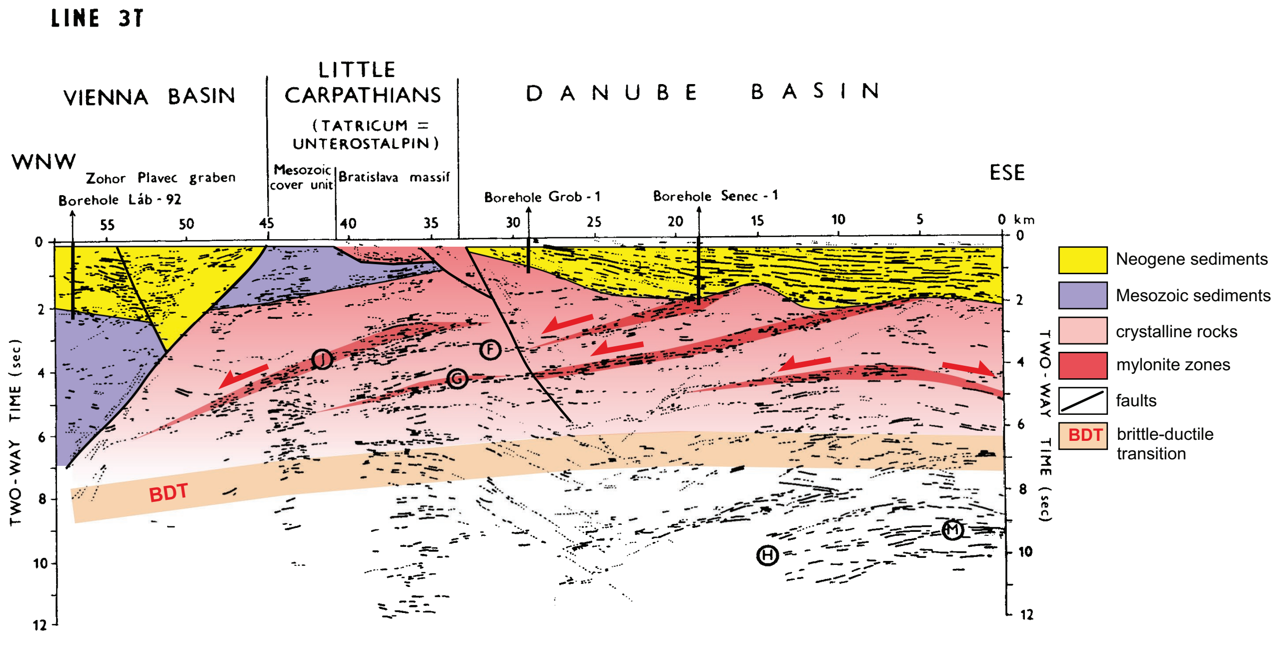

Fig. 4. Interpretation of the seismic time cross-section 3T (Tomek & Thon 1988; Šefara et al. 1998, modified), illustrating extensive unroofing of the crystalline basement in the central part of the Danube Basin.

fault, while the Čertovica Fault is an Eo-Alpine (Cretaceous) thrust fault (Gaža & Beinhauerová 1976; Hók et al. 1999, 2019; Putiš et al. 2009). The juxtaposition of the Tatricum and Veporicum tectonic units along the Mojmírovce Fault results from the substantial vertical displacement along this fault (Fig. 5).

The Šurany Fault (ŠF; Adam & Dlabač 1961; Buday et al. 1962; Gaža & Beinhauerová 1976, 1977) defines the south-eastern boundary of the deepest part of the Komjatice sub-basin. Although Šutora et al. (1988) suggested that the Šurany Fault may represent a potential sinistral strike-slip fault, no conclusive evidence has been provided to support this interpretation.

Conclusions

The pre-Cenozoic basement of the Danube Basin is part of the fold-and-thrust structure, which had formed during the Late Cretaceous (Eo-Alpine) tectonic processes. The Tatricum and Veporicum are crustal (thick-skinned) tectonic units containing Variscan crystalline rocks and Mesozoic sedimentary cover with a negligible presence of Carboniferous and Permian Palaeozoic sediments. The Veporicum was thrust above the Tatricum along the so-called Čertovica thrust, which is visible on the surface in the Tribeč Mountains. The Transdanubian Range Unit of Austroalpine provenance is displaced over the Veporicum along the Rába–Hurbanovo thrust and completely covered by Miocene sediments on the present-day territory of Slovakia. The Fatricum and Hronicum are thin-skinned nappes that contain Mesozoic sediments, while the Hronicum also contains Carboniferous and Permian volcano-sedimentary rocks (Ipoltica Group). Mesozoic sediments of the Fatric and Hronic nappes are concentrated along the northern margin of the Danube Basin, while the southern part contains only crystalline basement rocks of the Tatric and Veporic units. The crystalline basement rocks had been exhumed (Danubius Antiform) beginning from the end of the Eocene until the beginning of the Oligocene and were later (Neo-Alpine) overlain by Miocene sediments due to the Pannonian Basin System back-arc extension. The extensional tectonic regime triggered the formation of normal faults that dissected the Eo-Alpine structure. Along the northern margin of the Danube Basin, typical topography of basins and ranges has developed with the gradual opening of depocentres, which generally progress from west to east.

The Neo-Alpine tectonic activity primarily shaped the Danube Basin structural framework, resulting in a complex network of normal and transtensional faults that had been active from the Badenian to the Pannonian, with some faults showing evidence of reactivation during the Quaternary.

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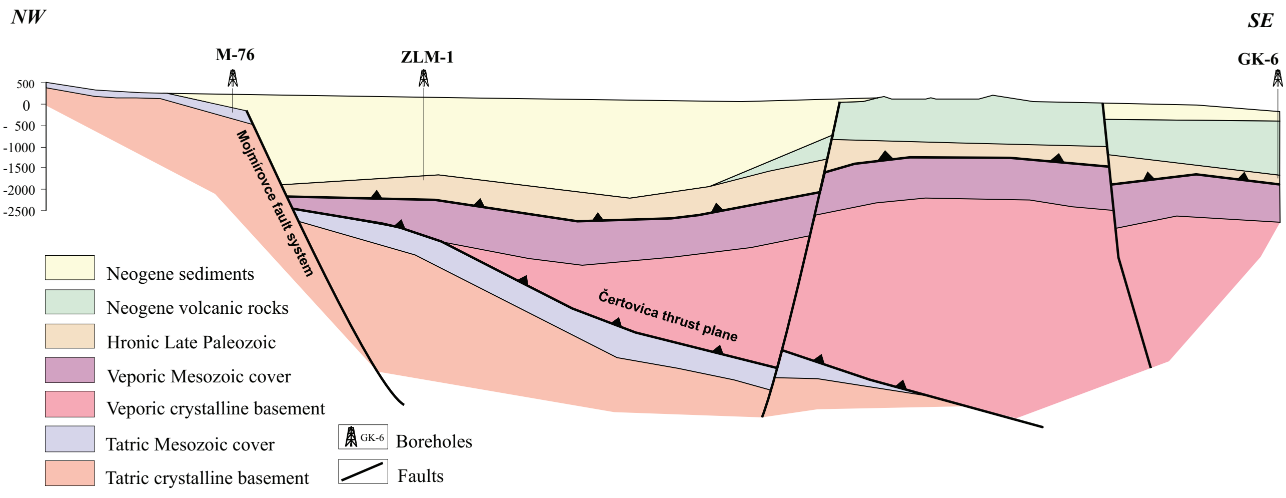

Fig. 5. Interpretation of the Eo-Alpine Čertovica thrust fault and the Neo-Alpine Mojmírovce normal fault (modified from Hók et al. 1999).

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