The Hurbanovo–Diösjenő Fault: A crustal-scale weakness zone at the boundary between the Central Western Carpathians and Northern Pannonian Domain

Tomáš Klučiar, Michal Kováč, Rastislav Vojtko, Samuel Rybár, Michal Šujan & Silvia Králiková
Department of Geology and Palaeontology, Faculty of Natural Sciences, Comenius University in Bratislava, Mlynská dolina, Ilkovičova 6, SK-842 15 Bratislava, Slovakia

AGEOS

Hurbanovo-Diösjenő zlom: kôrová oslabená zóna na hranici medzi Centrálnymi Západnými Karpatmi a Severopanónskou oblasťou

Abstract: The boundary between the Central Western Carpathians and the Northern Pannonian Domain – two crustal fragments with a different geodynamic provenance is represented by the Hurbanovo–Diösjenő Fault. The fault itself is located in the northern edge of the Transdanubian Unit and is covered by the relatively thick Neogene to Quaternary fill of the Danube Basin. The nature of this tectonic boundary is explained very contradictory because it is known only from several boreholes drilled in the 1950–70s. Moreover, interpretation of the seismic profiles is missing. The description of aforementioned boreholes often displays an old-fashioned biostratigraphy and outdated tectonic explanation of the Hurbanovo–Diösjenő Fault activity. Re-evaluation of the deep borehole cores penetrating the fill of several different Neogene and Palaeogene basins located above or near the Hurbanovo–Diösjenő Fault supported by structural analysis allowed a new interpretation of the Cenozoic activity along this fault zone: (1) during the Oligocene collision of the Eastern Alpine–Western Carpathian orogenic system with the European Platform, latter replaced by the Early Miocene formation of the ALCAPA microplate and its successive tectonic escape eastward required a dextral strike-slip movement along the fault; (2) a sinistral strike-slip movement along the fault is documented during the Middle Miocene evolution of the Danube and the Novohrad–Nógrad basins; and (3) a tectonic extinction of this crustal weakness zone was confirmed for the Late Miocene, when the Lake Pannon was formed. The renewed activity of this tectonic boundary as a normal fault is expected as a result of the Central Western Carpathian tectonic inversion phase in the Early Pliocene.

Key words: Danube Basin, Hurbanovo–Diösjenő Fault, Palaeogene, Neogene, crustal-scale weakness zone

1. INTRODUCTION

The study area is located among the Eastern Alps, Central Western Carpathians, and Transdanubian Range (Fig. 1). The boundaries of these tectonic megaunits, forming pre-Neogene basement of the Danube Basin, are represented by two main tectonic structures: the Rába and Hurbanovo–Diösjenő faults (e.g., Haas et al., 2014). The NE–SW striking Rába Fault separates the Austroalpine from Transdanubian Unit along the eastern margin of the Danube Basin (Fig. 1). Moreover, in the central part of the basin the approximately W–E Hurbanovo–Diösjenő Fault forms boundary between the Central Western Carpathian and Transdanubian units. The fault is considered to be a complicated contact zone which separates complexes comparable to the Eastern Alps – Western Carpathians from units which bear a strong resemblance to the Southern Alpine (Transdanubian) and Dinarides (Bükk) tectonic units. Both aforementioned tectonic boundaries are sealed by a thick Neogene to Quaternary sedimentary deposits of the Danube Basin and are mostly known only from several boreholes. The Rába Fault is also discovered from geophysical interpretation of several seismic profiles, as well (e.g., Tari et al., 1992; Horváth, 1993; Horváth & Cloetingh, 1996).

The nature of these crustal discontinuities has often been explained very contradictory (e.g., Kilényi & Šefara, 1989; Vass et al., 1993; Balla, 1994; Konečný et al., 2002; Kováč et al., 2002; Haas et al., 2010, 2014). In the contemporary point of view of the Cenozoic evolution of the Western Carpathians, the previous results obtained from deep boreholes were not properly interpreted. Moreover, the local names of basin depressions and their classification often differ in the Slovak and Hungarian sides. These differences between Slovak and Hungarian parts also contributed to the lack of clarity in the past.

The oldest, Palaeogene, deposits of the basin are restricted to the Northern Pannonian domain (Želiezovce Depression of the Danube Basin) and in the literature are usually referred to the Buda Basin or the Slovenian-Hungarian Palaeogene Basin (e.g., Tari et al., 1993; Fodor et al., 1998; Haas et al., 2001; Fordinál et al., 2002; Kováč et al., 2016). The Late Oligocene–Early Miocene sedimentary sequence, which has been deposited above the Northern Pannonian Domain and the Central Western Carpathians with a main depocentre located more to the east, is regarded as the Pétervására Basin

Manuscript received 2016-02-05
Revised version accepted 2016-05-03

(Sztanó, 1994). The older Palaeogene to Lower Miocene strata is sealed by the Middle Miocene sediments of the Danube Basin in the west and the Novohrad–Nógrád Basin in the east and are located on both the Central Western Carpathian and Northern Pannonian Eo-Alpine nappe pile (Vass et al., 1993). Finally, the Late Miocene–Pliocene basin fill belongs to the northern margin of the Pannonian Basin System (e.g., Horváth, 1993; Horváth & Cloetingh, 1996; Magyar et al., 1999[a], 1999[b]; Kováč et al., 2011). However, the local name of the basin (Danube Basin) is the same as in the case of the Middle Miocene strata.

The main aim of the presented study is to refine knowledge on the possible geotectonic role of the Hurbanovo–Diösjenő Fault, which formed a principal tectonic boundary between the Central Western Carpathian and Transdanubian tectonic units during the Miocene. Moreover, we try to establish a uniform model, the role of the faulting on this boundary, especially the Hurbanovo–Diösjenő Fault and its relationship to the geodynamic evolution of the Western Carpathians. New data obtained by a detailed sedimentary analysis of the several boreholes, interpretation of the structural measurements, and re-evaluation of the existing palaeostress field data (e.g., Tari et al., 1993; Vass et al., 1993; Marko et al., 1995; Fodor et al., 1998; Kováč, 2000; Márton & Fodor, 2003; Haas et al., 2014) were used in order to fulfil main goals.

2. METHODS

For the purposes of basin analysis, well core samples were collected, cut in half perpendicularly to the bedding plane, washed, and treated with dispersive glue. The samples were

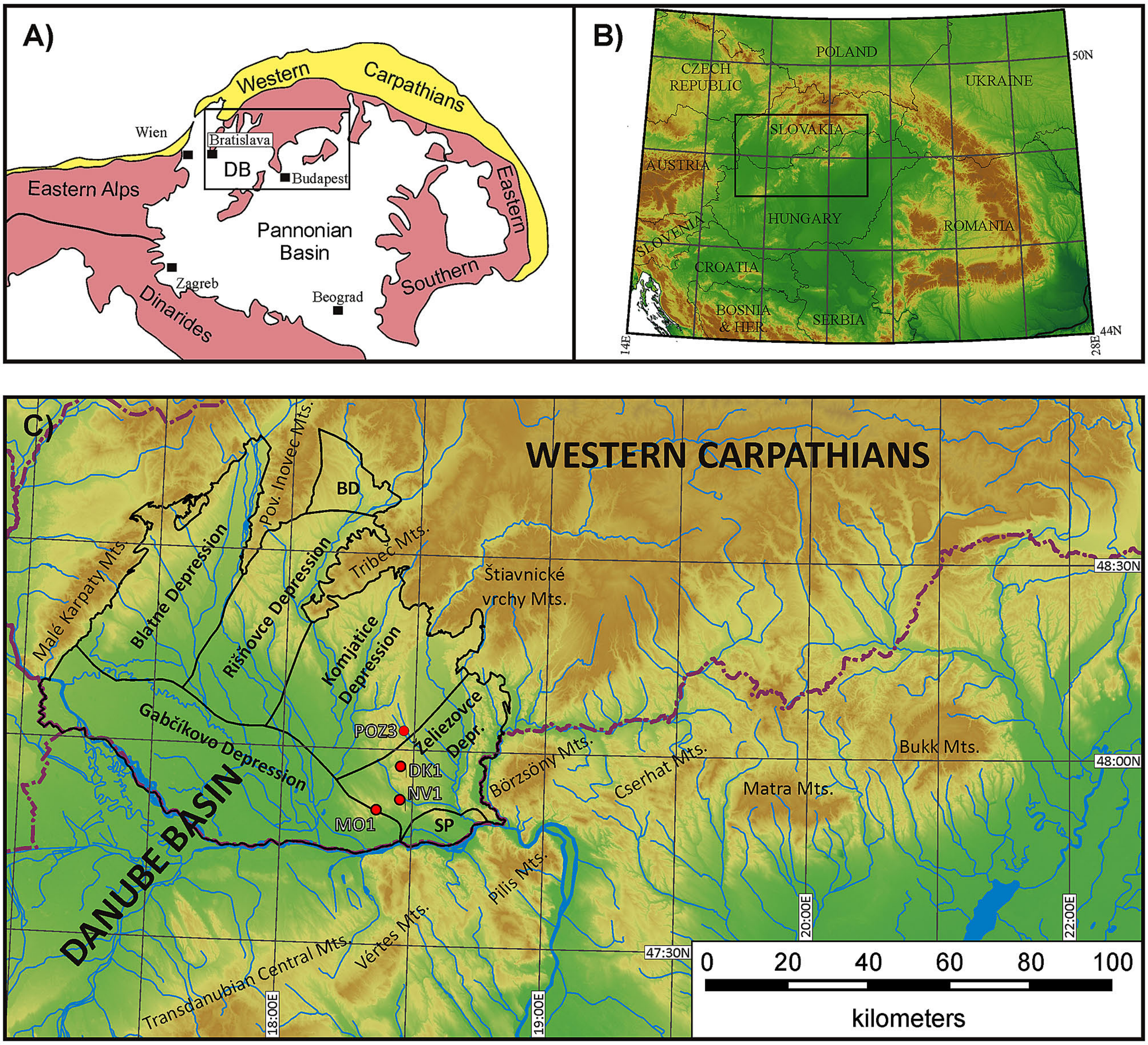

Fig. 1: A) Localization of the study area in the Alpine-Carpathian-Pannonian system; B) Hybsometric model with location of the study area; C) The study area with the principal geographic unit, Miocene depressions in the Danube Basin and location of the interpreted boreholes. Note: SP - Štúrovo Palaeogene sequence.

later scanned and digitalized. Further lithological evaluation was based on reinterpretation of spontaneous potential (SP) and resistivity (RT) well logs, according to Rider (1996), Emery & Myers (1996), and Catuneanu (2006). Spontaneous potential is passive electrical geophysical method based upon the measurement of spontaneous or natural electrical potential developed in the earth and measured in MV (milivolts) unit. Resistivity represents resistance of a rock to the passage of an electric current (Rider, 1996). Electrofacies were grouped in units with similar response and correlated between studied well profiles, taking into account all available geochronologic data.

Chronology of the Palaeogene and Middle Miocene sequences was based on biostratigraphy of calcareous nannoplankton, benthic and planktonic foraminifera. Late Miocene chronology was supported by biozones of molluscs *sensu* Magyar et al. (2007) and by dinoflagellates, as well as by radiometric dating using authigenic ^{10}Be/^{9}Be method (Šujan et al., 2016).

Data concerning the Late Miocene sequence were supported by study of counter-flush boreholes, which were drilled during 60's in a dense grid to depths 300–600 m. Spatial distribution and lithology of the Volkovce Formation representing the uppermost part of studied lithological column was inferred also by field study of outcrops.

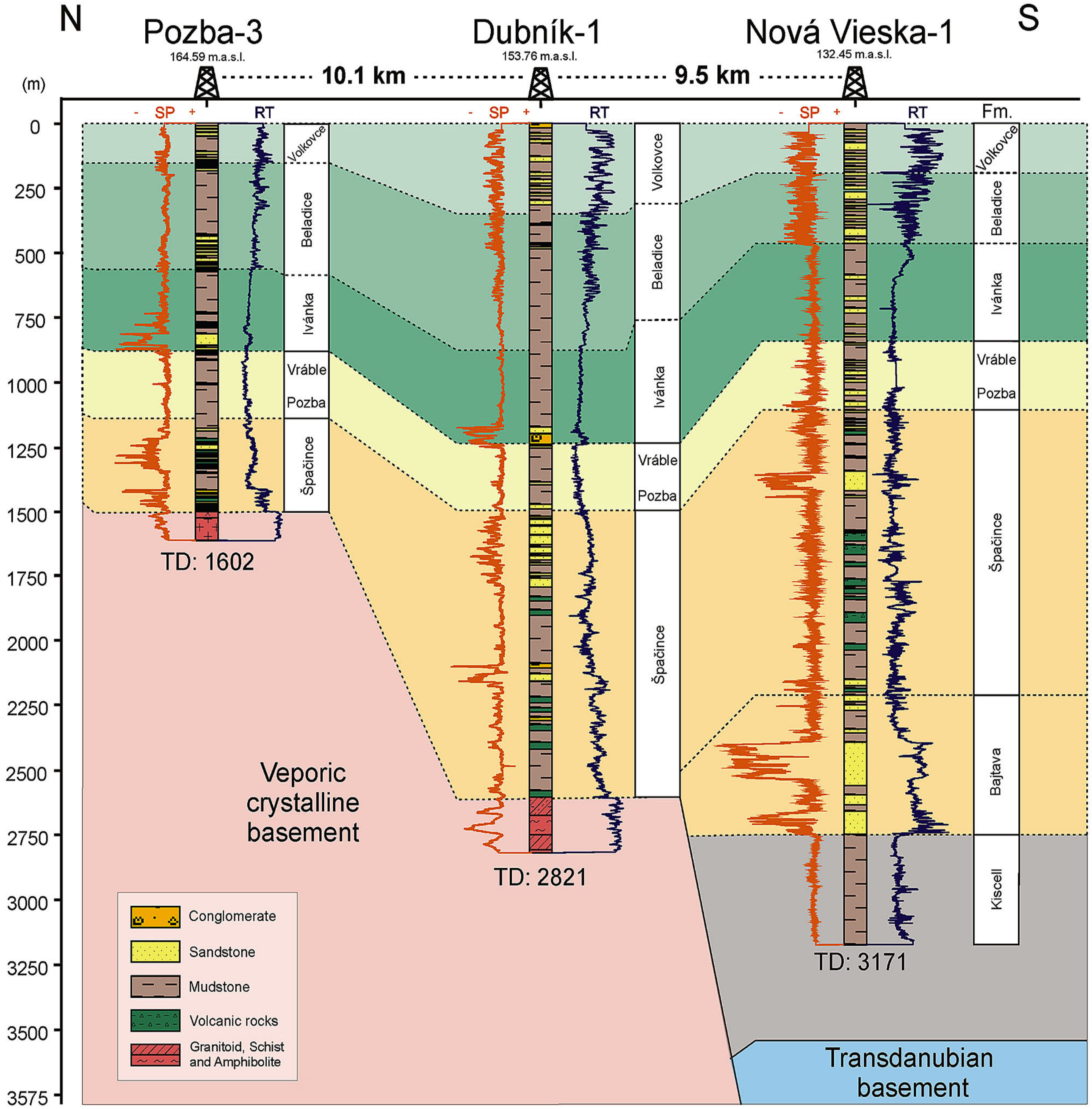

Fig. 2: Correlation profile across the Pozba-3 (POZ-3), Dubník-1 (DK-1), and Nová Vieska-1 (NV-1) boreholes. Note: dotted lines represent correlative horizons based on lithostratigraphy; orange curve represents spontaneous potential (SP), and blue curve represents resistivity (RT).

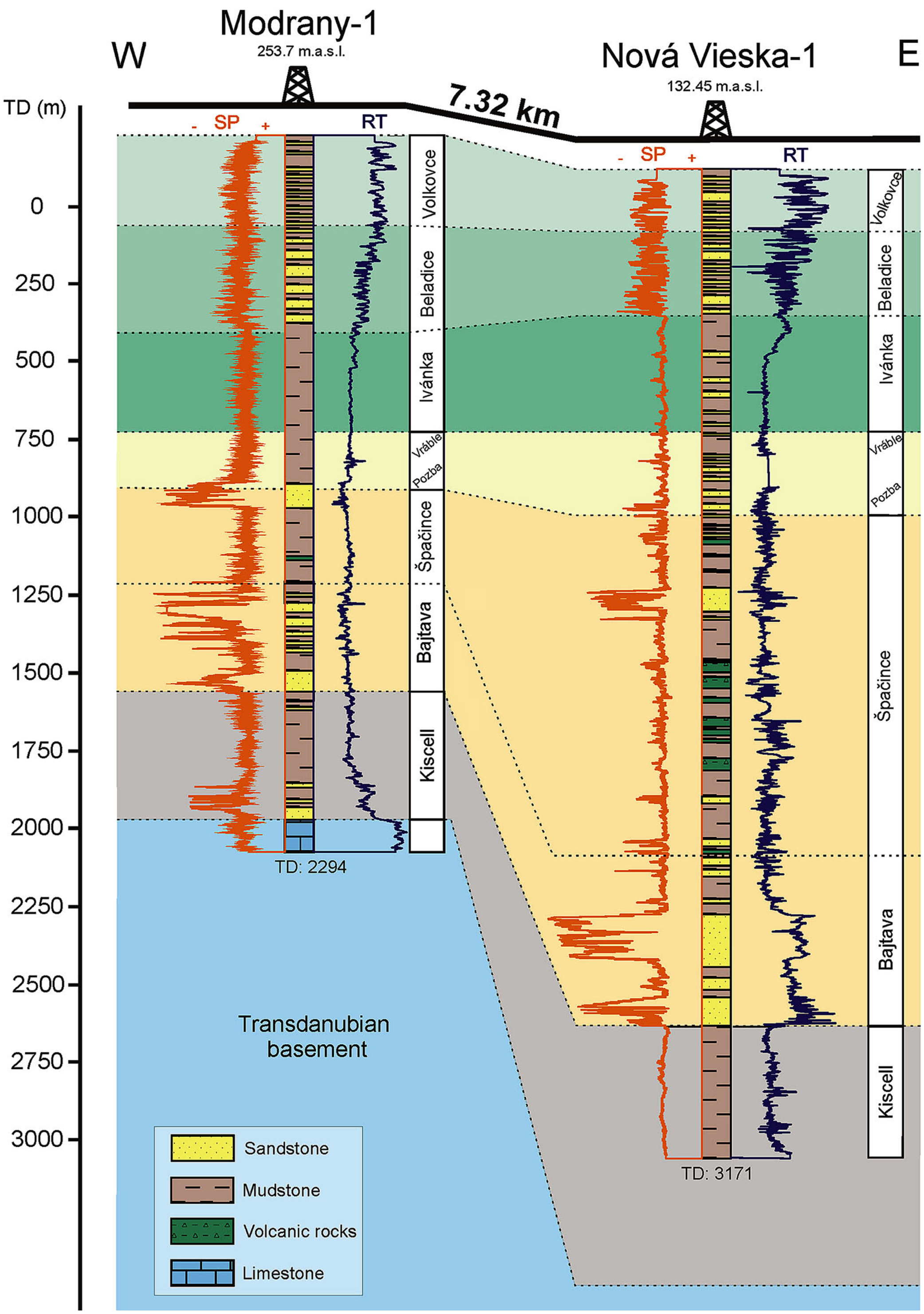

Fig. 3: Correlation profile across the Modrany-1 (MO-1) and Nová Vieska-1 (NV-1) boreholes. Note: dotted lines represent correlative horizons based on lithostratigraphy; orange curve represents spontaneous potential (SP) and blue curve represents resistivity (RT).

3. RESULTS OF BASIN ANALYSIS

3.1. Palaeogene sedimentary record

The Palaeogene sedimentary sequence is more than 400 m thick in the NV-1 borehole (Nová Vieska) which is situated in the Želiezovce Depression of Danube Basin (Figs. 1, 2, and 3). The "Kiscell" Formation is composed of the grey to dark grey bioturbated mudstone with intercalation of rare fine-grained sandstone beds. The sedimentary analysis of the MO-1 (Modrany) borehole core samples revealed littoral to onshore environment and a deeper sublitoral environment with occasional distal gravity currents or tempestites in the NV-1. Moreover, the amount of redeposited Late Eocene fossils, together with lithoclasts from the Tatric/Veporic crystalline basement at the base document not only partial disintegration of the retro-arc basin above the Transdanubian Unit (e.g., Tari et al., 1993) but also denudation of the exhumed Tatric and/or Veporic basement beneath the Danube Basin.

3.2. Neogene sedimentary record

The Middle Miocene sedimentary sequence starts with the Bajtava, Špačince, and Pozba formations (Langhian; Lower Badenian), whose thickness varies across the study area from 500 m in the north (POZ-3 borehole – Pozba) through 700 m (DK-1 borehole – Dubník) to 1700 m (NV-1 borehole) in the south (Figs. 2 and 3). The lowermost portion of the sedimentary record is represented by the Bajtava Formation. At the NV-1 and MO-1 boreholes it does not contain volcanic debris. This part of the sequence is missing in the boreholes located above the Veporic crystalline basement (Fig. 2). The Bajtava Formation (NV-1 and MO-1 boreholes) was deposited after a strong tectonic phase at the Early/Middle Miocene boundary which was associated with oblique collision of the Western Carpathians with the European Platform in the west. Shortening of the Central Western Carpathian orogenic wedge in a compressive tectonic regime resulted in southward back-thrusting of the Central Western Carpathians (e.g., Kováč et al., 1989; Marko et al., 1995; Pešková et al., 2009). Similar tectonic phenomena was also observed along the southern margin of the Transdanubian Unit, where thrusting on the neighbouring Tisza microplate was documented (Csontos & Nagymarosy, 1998). It is assumed that flexure in the inner portion of the Transdanubian Unit with respect to the arc was formed and resulted in subsidence of this area evidenced by deposition of basal conglomerates from the front of the Veporic Unit. Such type of depositional environment was documented in the north-western part (Blatné Depression) of Danube Basin before the beginning of rifting accompanied by volcanism, as well (Rybár et al., 2015). Therefore, coarse-grained deposits of the MO-1 and NV-1 wells without volcanic material and with detritus of the Western Carpathian provenance could represent a short existing basin depocentre in the study area, which was deposited on the northern edge of the Transdanubian Unit (Figs. 2 and 3).

The Langhian opening of the Danube Basin associated with evolution of volcanic centres, which have been buried beneath the basin fill up to the present (Hrušecký, 1999). The subsiding depressions were also supplied by a large amount of volcaniclastic sediments from the Central Slovak–Northern Hungarian volcanic field (e.g., Kováč et al., 1998[a]; Konečný et al., 2002; Pécskay et al., 2006). The juvenile Želiezovce Depression was subsiding along the Hurbanovo–Diösjenő Fault and the parallel Rapovce Fault in the Novohrad-Nógrád Basin (southern Slovakia–northern Hungary). Rifting of the basin depocentre evidently started along the W–E oriented Hurbanovo–Diösjenő Fault. The following Langhian (Lower Badenian) subsidence associated with enhanced tectonic movement along the NE–SW to NNE–SSW normal faults in the Želiezovce Depression (Tari et al., 1992; Kováč et al., 2011).

The Langhian Želiezovce Depression (~15.0–12.7 Ma) was bordered by the subaquatic Pozba elevation in the north and Transdanubian swell in the south (Fig. 2). The shallow sublitoral environment is evidenced by the presence of algal reefs. Material derived from the reefs was transported by gravitational currents into the deeper parts of depression (DK-1 well). Sediments of the Špačince Formation (Vass, 2002) were deposited in sublitoral environment and were sourced by material from the Central Western Carpathian crystalline basement and the Central Slovak–Northern Hungarian volcanic fields. During the deposition of the Špačince Formation a migration of depocentres from the south (Transdanubian basement) to the north occurred (Veporic crystalline basement), this is suggested by a variation in sediment thickness (Figs. 2 and 3).

The Pozba and Vráble formations (Serravallian; Upper Badenian and Sarmatian) sediments (Vass, 2002) were deposited in sublittoral environment with a shallowing upward trend and do not reach a thickness higher than 300 m. However, the Pozba Formation was considered to be Middle to Upper Badenian in age (cf. Hók et al., 1999), previously. The sequence is composed of grey, calcareous mudstone rich in organic components, and volcaniclastic material. The following fill-up of this depocentre suggests gradual cessation of the faulting.

During the Late Miocene (~11.5–5.6 Ma) the Želiezovce Depression represented a relatively shallow "sublitoral zone" of Lake Pannon (Magyar et al., 1999a; Cziczer et al., 2009). The flooding proceeded and culminated at approximately 11.0–10.5 Ma, which led to deepening of the depression. In the south-eastern portion of depression, water covered the Eo-Alpine Transdanubian Unit which represented a submerged swell (similar to the Pozba elevation in the north; Fig. 3). After 9.3 Ma, the lacustrine sediments of the Ivanka–Szák Formation was gradually covered by deltaic to alluvial plain deposits (Beladice and Volkovce formations; Kováč et al., 2010, 2011; Šujan et al., 2016; Figs. 2 and 3). Alluvial deposition in low dynamic conditions lasted up to ca. 6.0 Ma (Šujan & Rybár, 2014; Šujan et al., 2016).

4. OVERVIEW OF KNOWLEDGE ON FAULT ZONES IN JUNCTION AREA

Investigated area represents the boundary between the Austroalpine- Central Western Carpathian orogenic belt on one side and the Northern Pannonian Domain on the other side (e.g., Fusán et al., 1987; Schmid et al., 2008; Hass et al., 2014; Kováč et al., 2016). The Austroalpine–Central Western Carpathian belt is composed of superimposed nappe stack: the Lower Nappe Group (Peninic, Vahic, and Tatric units), the Middle Nappe Group (Veporic, Hronic, and Fatric units), and the Upper Nappe Group (Gemeric, Meliatic, Turnaic, and Silicic units; Hók et al., 2014). The Transdanubian Unit is considered to be the Upper Austroalpine Unit due to its tectonic position (Tari, 1994, Fodor et al., 2003; Tari & Horváth, 2010; Fodor et al., 2013). However, the Transdanubian lithostratigraphical facies show a Southern Alpine affinity (Haas et al., 1995). The Bükk, Szendró, and Upony units represent a paraautochtonous, low grade metamorphic Palaeozoic to Mezozoic succession which shows lithostratigraphic analogue with the Southern Alpine-Dinaridic units, as well (e.g., Csontos, 1988, 2000; Haas & Kovács, 2001; Filipovic

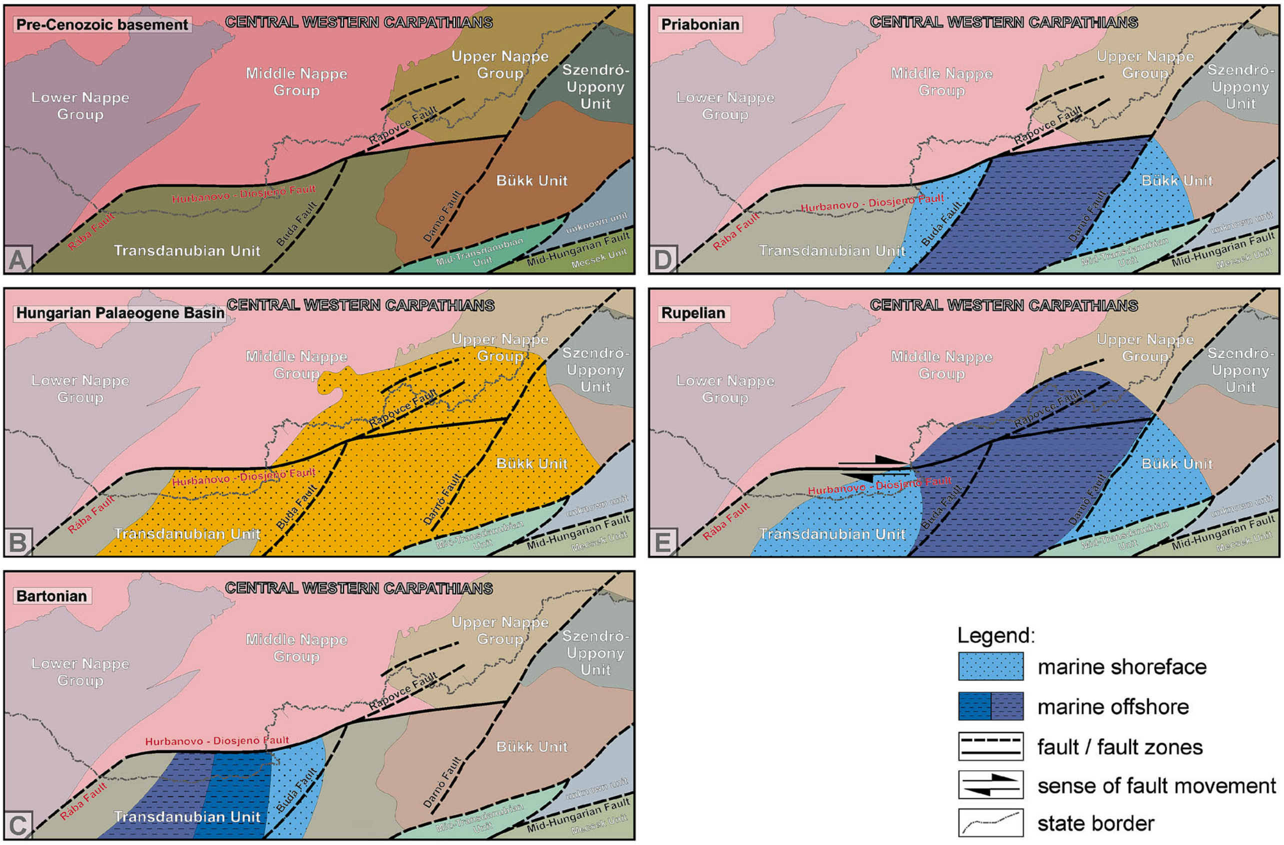

Fig. 4: Model of the Palaeogene basin evolution (based on Tari et al., 1993): (A) Pre-Cenozoic basement of the Danube Basin; (B) Known extent of the Hungarian Palaeogene Basin deposits drawn by orange with dots; (C) Bartonian retro-arc basin marine flooding; (D) Priabonian retro-arc basin marine flooding; (E) Rupelian retro-arc basin marine flooding.

et al., 2003). The discontinuity between aforementioned two crustal fragments with different provenance is represented by the NE–SW striking of Rába Fault which passes to the W–E directed Hurbanovo–Diösjenő Fault in the north (Figs. 4 and 5).

According to some authors, the Rába Fault represents a Cretaceous nappe thrust (Horváth, 1993; Fodor & Koroknai, 2000; Haas et al., 2010). However, during the mid-Miocene opening of the Danube Basin, the former Cretaceous thrust was significantly modified and the fault was reactivated as a sinistral oblique-slip fault. The north-western margin of the Transdanubian Unit was affected by deformation and the structural pattern is attributed to this deformation (Haas et al., 2014). This tectonic structure was earlier interpreted as a primary structural boundary (Kázmér & Kovács, 1985) which was developed during the tectonic escape of the Transdanubian Range crustal fragment from the Alpine collision zone during the Late Palaeogene–Early Miocene. In this concept, the Rába Fault was interpreted as a deep-rooted sinistral strike-slip zone which separates crustal fragments with significantly different geological origin (Balla, 1989).

In the central part of Danube Basin, the W–E striking Hurbanovo–Diösjenő Fault most probably forms eastern continuation of the Rába Fault (Šefara et al. 1998; Konečný et al. 2002). The Hurbanovo–Diösjenő Fault represents a major crustal discontinuity between the Central Western Carpathians and Northern Hungarian Domain. The eastern termination of the fault is still not well known. It is interrupted by the Darnó Fault that might significantly displace it to the north-east (Figs. 4 and 5). The primary structural pattern of the Hurbanovo–Diösjenő Fault is quite uncertain; a dextral strike-slip faulting is assumed in the Palaeogene (Balla, 1989; Bada et al., 1996). This is in good agreement with the measured palaeostress field (Márton & Fodor, 2003) and with the restriction of the Eocene retro-arc basin deposits (Tari et al., 1993). A thick-skinned south-vergent back-thrusting occurred along the southern margin of the Hurbanovo–Diösjenő Fault and caused burial of the basement in the Late Oligocene–Early Miocene. The Palaeozoic rocks were thrust over the Mesozoic and Oligocene sequences which are located in the eastern side of the Uppony Hills (Schreter, 1952; Pantó, 1954) and so the thrusting along the Darnó Fault is dated to the Kiscellian–Ottnangian time span (30–19 Ma). However, a sinistral strike-slip movement on the Hurbanovo–Diösjenő Fault is assumed the Middle Miocene (Haas et al., 2014).

The kinematics of the Darnó Fault or in an even broader sense referred to the Darnó Zone was justified by the fault-slip analysis (Fodor et al., 2005^{a}). Seismic profile interpretation (Sztanó & Tari, 1993) pointed to a compressional deformation belt. Nevertheless, several authors identified the sinistral strike-slip movement along the Darnó Fault and postulated a 20–30 km of displacement (e.g., Jasko, 1946; Zelenka et al., 1983; Grill et al., 1984; Less et al., 1988; Szentpetery, 1997). According to Fodor

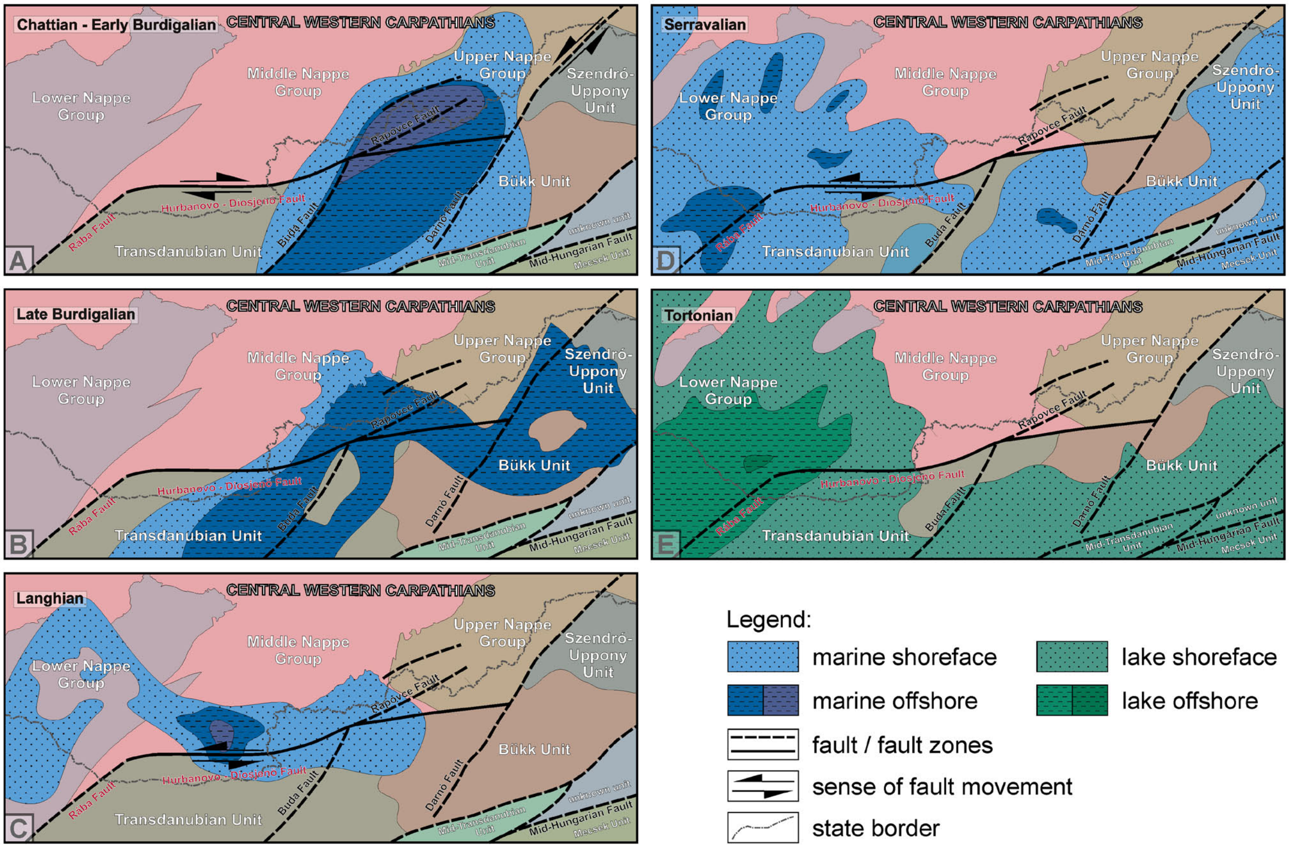

Fig. 5: Model of the Neogene basin evolution (based on Adam & Dlabač, 1969; Vass et al., 1979; Tari et al., 1993; Sztanó, 1994; Magyar et al., 1999[a]; Haas et al., 2012). (A) Chattian early Burdigalian retro-arc basin marine flooding; (B) Late Burdigalian Novohrad–Nógrád basin marine flooding; (C) Langhian Danube and Novohrad–Nógrád basins marine flooding; (D) Serravallian Danube and Novohrad–Nógrád basins marine flooding; (E) Tortonian Lake Panon flooding.

et al. (2005[b]), this sinistral strike-slip movement was probably active during the Ottnangian to Early Badenian (18–15 Ma). Starting from the Late Badenian, normal faulting of this zone can be inferred from the borehole and field evidences (Telegdi Roth, 1951; Radocz, 1966; Fodor et al., 2005[a], 2005[b]). In addition Schmid et al. (2008) assumed that the Darnó Fault could be one of the most important structure separating the mega-units (microplates). They speculated that the fault is a continuation of the Palaeogene–Early Miocene Periadriatic Fault with the dextral strike-slip kinematics. On the contrary, according to Haas et al. (2014), occurrence of different nappes of the same nappe series on each sides of the Darnó Fault was caused by different pre-Cenozoic denudation and deformation.

The aforementioned facts reveal that the tectonic units of the Northern Pannonian Domain were most likely positioned among the Eastern Alpine–Western Carpathian and the Southern Alpine–Dinaride belts before the Palaeogene (e.g., Csontos et al., 1992; Kováč et al., 1994). The Cretaceous–Palaeocene Periadriatic Fault represents a suture zone between the Alpine orogenic system (thrust over the European Platform – northward thrusting) and a nappe pile of the Adriatic Plate – southward thrusting (e.g., Grad et al., 2009). Therefore, the Hurbanovo–Diösjenő Fault could represent a fault zone with a probably similar kinematics and position like the Periadriatic Fault which divides the Central Western Carpathians (similar to the Eastern Alps) in the north from the Northen Pannonian Domain in the south (Transdanubian and Bükk units with affinity to the Southern Alps and Dinarides). If the Darnó Fault would not represent the tectonic contact between the Transdanubian and Bükk units (Haas et al., 2014) the position is almost the same at the present contact of the Southern Alpine and Dinaride units in the Slovenia and northern Croatia.

5. DISCUSSION

The new analysis of deep boreholes, situated in the Želiezovce Depression (Danube Basin), refined refined stratigraphy of the sedimentary record together with the structural and palaeostress field data (e.g., Vass et al., 1993; Marko et al., 1995; Márton & Fodor, 2003; Hass et al., 2014). Based on previous and new data it is possible to discuss geodynamical processes leading to disintegration and opening of several Cenozoic basin systems at the Central Western Carpathian and Northern Pannonian Domain junction in a new way. In this case the behaviour of the Hurbanovo–Diösjenő Fault reflects geodynamical processes leading to (1) individualisation of the Central Western Carpathians, Transdanubian Range, and Bükk units among an older, common Alpine–Western Carpathian–Dinaride domain; (2) provides evidence of tectonic escape of the aforementioned crustal segment of the ALCAPA microplate to north-eastward, and (3) documents the Middle–Late Miocene evolution of the Pannonian Basin during and after soft-docking of the ALCAPA microplate (Western Carpathians) with the European Platform.

(1) Rising compression in the colliding orogen led to the Oligocene exhumation of the Eastern Alpine–Western Carpathian junction area. It is possible to assume that these geodynamic processes most likely reflect a movement along the Periadriatic Fault and its prolongation to the south-east – the Hurbanovo–Diösjenő Fault. In this time the bend parts of the Periadriatic–Hurbanovo–Diösjenő suture zone started to be formed. This process was documented along the Giudicaria Fault area in the west (Pomella et al., 2011, 2012) and similar process we suppose along the future Rába Fault zone in the east (e.g., Balla, 1994). Thus, the Rába Fault formed a boundary between the Eastern Alpine and Transdanubian units (cf. Hass et al., 2014). The Hurbanovo–Diösjenő Fault is considered to be a south-eastward continuation of this boundary based on the calculation with the ~45°–50° counter-clockwise rotation of the Transdanubian Unit during the Early Miocene with respect to stable European Platform (e.g., Márton & Fodor, 2003; Márton et al., 2007).

The proposed model is supported by the following facts: (i) the late Priabonian to early Rupelian sediments of the Hungarian Palaeogene Basin were reached only by boreholes drilled above the Transdanubian Unit; (ii) absences of the early Chattian sediments in the study boreholes support the theory of eastward migration of the basin depocentre (Fig. 5; Tari et al., 1993; Kázmér et al., 2003). (iii) furthermore, exhumation and erosion of the Danube Basin basement together with the Eocene Hungarian Palaeogene Basinis indicated by provenance analysis of clastics and re-deposited Eocene microfauna. This is in accordance with borehole observation which proved that the Central part of the Danube Basin basement is composed of the Tatric and Veporic crystalline rocks almost without any Mesozoic and Palaeogene deposits (e.g., Biela, 1978; Fusán et al., 1987). This model is supported by continual Oligocene to Miocene exhumation revealed in the Western Carpathian crystalline core mountains (Malé Karpaty, southern portion of the Považský Inovec, Tribeč, and/or Žiar Mts.; Danišík et al., 2004, 2008; Kováč et al., 1994; Králiková et al., 2014) and in the easternmost Alps (Rechnitz tectonic window; e.g., Dunkl et al., 1998, 2005; Dunkl & Demény, 1997). In addition, it is also documented by spacious Rupelian hiatus in the Bakony and Buda segments of the Hungarian Palaeogene Basin (e.g., Kázmer et al., 2003; Tari et al., 1993).

(2) The Hurbanovo–Diösjenő Fault and sub-parallel Rapovce Fault on Slovak territory was sealed by the Chattian (Kiscellian and Egerian) deposits located over the Northern Pannonian domain and Central Western Carpathians (Vass, 2002). The elongated shape of the late Chattian to Burdigalian (Egerian to Eggenburgian) depocentre of the Pétervásara Basin (placed above the eastern prolongation of the Hurbanovo–Diösjenő Fault; Tari et al., 1993; Sztanó, 1994) and restriction of the Eocene–earliest Oligocene deposits of the Hungarian Paleogene Basin by the fault, led to assumption that the Hurbanovo–Diösjenő Fault represented a late Oligocene–Early Miocene dextral strike-slip fault zone. Structural data and palaeostress reconstruction document the NW–SE orientation of palaeostress compressional axis (e.g., Vass et al., 1993; Márton & Fodor, 2003). The strike-slip faulting operated during the time when the ALCAPA microplate started to be structurally independent (e.g., Csontos et al., 1992; Kováč et al., 1994; Fodor et al., 1998). This opinion is supported by the sinistral strike-slip movement on the Darnó and Buda faults (Fig. 5), as well as by the dextral displacement of the individual portions of Slovenian–Northern Hungarian Palaeogene Basin more than 200 km to the east after the Oligocene (Báldi, 1984; Báldi & Báldi-Béke, 1985; Fodor et al., 1998).

(3) The Middle Miocene opening of the Danube Basin began in the earliest Langhian. At this time, the Želiezovce Depression represented the western part of the marine flooding spreading along the Hurbanovo–Diösjenő Fault towards the Novohrad–Nógrád Basin in the east (Fig. 5). During the Langhian (Early Badenian) the Hurbanovo–Diösjenő Fault was depicted as sinistral strike-slip zone what is confirmed by as sinistral displacement of the Lower Miocene sedimentary facies (Rapovce delta, Vass et al., 1993) and also by the elongated shape of the depocentre in the Želiezovce Depression (Fig. 5). Additionally, this is denoted by the NW–SE extension which gradually prevailed after the NNW–SSE compression. This paleostress change was revealed in most of the Western Carpathian areas (e.g., Vass et al., 1993; Marko et al., 1995; Kováč, 2000).

Latter depocentres of the Danube Basin were shifted more to the west and north (Hrušecký, 1999; Kováč et al., 2011) and the subsidence was controlled by the NE–SW to NNE–SSW trending normal faults (Fig. 5). The sinistral strike-slip faulting along the Hurbanovo–Diösjenő Fault was accompanied by the early Langhian counter-clockwise rotation of the Central Western Carpathians in association with the north-eastward movement trajectory (e.g., Márton & Márton, 1996; Márton & Fodor, 2003; Márton et al., 2007). This scenario of the basin opening along the southern margin of the ALCAPA microplate fits with the previous models (Fodor et al., 1998; Kováč et al., 1998[a], 1998[b]; Kováč, 2000). After the Langhian (Early Badenian) the Hurbanovo–Diösjenő Fault gradually extinct. The Transdanubian Unit was amalgamated with the Central Western Carpathian structure. The successive early Serravallian stretching of the Western Carpathians (ALCAPA) was placed to the central part of Danube Basin.

During the Late Miocene, the Hurbanovo–Diösjenő Fault was most probably extinct and a significant subsidence in the Danube Basin centre was documented (Fig. 5). Tectonic cessation of the Hurbanovo–Diösjenő Fault associated with the Western Carpathians final docking and partly overthrusting onto the European Platform margin. Moreover, the Hurbanovo–Diösjenő Fault was interrupted by the Pannonian (Tortonian) – Pliocene transverse normal faults (see thickness in the MO-1, NV-1; Figs. 2 and 3). The extensional tectonic regime with the principal minimal palaeostress axis in NE–SW direction was accompanied by conjugate normal faulting (cf. Vojtko et al., 2008; Králiková et al., 2010; Hók et al., 2011). The W–E trending normal faulting along the Hurbanovo–Diösjenő Fault with occasional earthquake occurrence can be considered to be the Pliocene to Quaternary in age (Šefara et al., 1998; Minár et al., 2011).

6. CONCLUSIONS

Cenozoic geodynamics of the Central Western Carpathian and Northern Pannonian domain junction is reflected in disintegration and evolution of different types of basins. Analysis of their sedimentary fill allowed to refine stratigraphy, interpretation of various depositional systems, and verification of the different kinematics of the Hurbanovo-Diösjenő Fault (Figs. 4 and 5):

(1) The Hungarian Palaeogene retro-arc basin disintegration, emersion, and denudation of the pre-Neogene basement in Danube Basin were documented by sedimentological and structural analysis. It is possible to assume that this process can be dated to the Early–Late Oligocene, when the Central Western Carpathians and Northern Pannonian domain began to be independent segments in the Alpine–Carpathian–Dinaride system. This process associated with deformation along the Periadriatic and Hurbanovo-Diösjenő faults between the northern and southern units of the Alpine-Carpathian orogenic system. The restraining/releasing bends of these faults (the Giudicaria and Rába faults) were developed.

(2) The Late Oligocene–Early Miocene eastward migration of the basin depocentre was controlled by compression with the principal NW–SE oriented axis which led to an assumption that the northern restriction of Palaeogene sedimentary strata along the Hurbanovo-Diösjenő Fault is tectonic in origin. The shape of the younger Pétervására Basin, located above the eastern prolongation of the Hurbanovo-Diösjenő Fault, confirms the assumed dextral strike-slip movement along the fault. Opening of the basin depocentre above the transform boundary was in close relation with individualization of the ALCAPA microplate and was followed by its Early Miocene tectonic escape.

(3) Compression at the Early/Middle Miocene boundary led to shortening of the Central Western Carpathian edge, which was followed by partial emersion of the Danube Basin pre-Neogene basement (~17–16 Ma). This tectonic process was documented by sedimentological analysis of the earliest Langhian clastics in the Želiezovce Depression.

(4) The subsequent Middle Miocene rifting of the Danube Basin was linked with onset of volcanic activity and led to deposition of the Langhian (Early Badenian) volcaniclastic sediments in the Želiezovce Depression and Novohrad–Nógrád Basin (15–13.6 Ma). The variations in a thickness of strata and an elongated shape of the basin suggest sinistral strike-slip faulting of the Hurbanovo-Diösjenő Fault. Moreover, a left-lateral offset of the Lower Miocene sedimentary facies in the basin fill is also documented. The evolution of the Western Carpathians and Northern Pannonian domain was coupled with extension trigged by the final movement of the ALCAPA crustal wedge northeastwards.

(5) The Serravalian (Late Badenian–Sarmatian) sedimentation in the Želiezovce Depression represented a syn-to post rift stage of the basin development (~13.6–11.5 Ma). Cessation of the fault activity and filling up in the eastern margin of the basin was documented.

(6) In the Late Miocene, after the soft-docking of the ALCAPA microplate with the European Platform in the north, the wide rifting phase of the Pannonian Basin was affected mostly by the pull (roll back) of ongoing subduction in front of the Eastern Carpathians. Sedimentary record of the eastern margin of Danube Basin (the Želiezovce Depression) revealed the Early Tortonian (Early Pannonian) flooding that was followed by a gradual filling-up of the accommodation space. Tectonic extinction of the Hurbanovo-Diösjenő Fault was evidenced during this time. The restored function of this fault with a normal movement was expected during the basin tectonic inversion phase in the Early Pliocene.

Acknowledgement: This work was supported by the Slovak Research and Development Agency under the contracts APVV-0099-11, APVV-0625-11, APVV-0315-12, APVV-14-0118, Comenius University grant UK/325/2014; European Social Fund grant ESF-EC-0006-07, ES-FEC-0009-07 and by grant VEGA 2/0042/12, 1/0193/13. Our special thanks goes to the company Nafta a.s. management and to Dr. Ľubomír Sliva for allowing access to the borehole core repositories. Mikuláš Hronkovič and Štefánia Pramuková are thanked for help with drill core material and thin section assembly. We are also thankful to both reviewers (Alexander Nagy and Ján Soták) for their constructive reviews, which considerably improved the scientific content of the manuscript.

References

Adam Z. & Dlabač M., 1969: Vysvětlivky k mapám mocností a litofaciálního vývoje Podunajské nížiny. *Zborník geologických vied, Západné Karpaty,* 11, 156–172.

Bada G., Fodor L., Székely B. & Timár G., 1996: Tertiary brittle faulting and stress field evolution in the Gerecse Mountains, northern Hungary. *Tectonophysics,* 255, 3–4, 269–289.

Báldi T., 1984: The terminal Eocene and Early Oligocene events in the Hungary and the separation of an anoxic, cold Paratethys. *Eclogae Geologicae Helvetiae,* 77, 1, 1–27.

Báldi T. & Báldi-Béke M., 1985: The evolution of the Hungarian Paleogene basins. *Acta Geologica Hungarica,* 28, 1–2, 5–28.

Balla Z., 1989: A Diósjenői diszlokációs öv újraértékelése . *A Magyar Állami Eötvös Loránd Geofizikai Intézet 1987. évi jelentése,* 45–57.

Balla Z., 1994: Basement tectonics of the Danube Lowlands. *Geologica Carpathica,* 45, 5, 271–281.

Biela A., 1978: Hlboké vrty v zakrytých oblastiach Vnútorných Západných Karpát. *Regionálna Geológia Západných Karpát,* 10, 224 p.

Catuneanu O., 2006: Principles of Sequence Stratigraphy. Elsevier, Amsterdam, 375.

Csontos L., 1988: Etude geologique d'une portion des Carpathes Internes: le massif du Bükk. Manuscript, These Univ. Lille 1., 250, 327 p.

Csontos L., 2000: A Bükk hegység mezozoos rétegtani újraértékelése [Stratigraphic reevaluation of the Bükk Mts. (N. Hungary)]. *Földtani Közlöny,* 130, 1, 95–131.

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 evolution of the intra-Carpathian area: A model. *Tectonophysics,* 208, 1–3, 221–241.

Cziczer I., Magyar I., Pipík R., Böhme M., Ćorić S., Bakrač K., Sütő-Szentai M., Lantos M., Babinszki E. & Müller P., 2009: Life in the sublittoral zone of long-lived Lake Pannon: paleontological analysis of the Upper Miocene Szák Formation, Hungary. *International Journal of Earth Sciences,* 98, 1741–1766.

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 Journal of Earth Sciences,* 95/96, 60–70.

Danišík M., Kohút M., Dunkl I. & Frisch W., 2008: Thermal evolution of the Žiar Mountains basement (Inner Western Carpathians, Slovakia) constrained by fission track data. *Geologica Carpathica,* 59, 1, 19–30.

Dunkl I. & Demény A., 1997: Exhumation of the Rechnitz Window at the border of the Eastern Alps and Pannonian Basin during Neogene extension. *Tectonophysics,* 272, 2–4, 197–211.

Dunkl I., Grasemann B. & Frisch W., 1998: Thermal effects of exhumation of a metamorphic core complex on hanging wall syn-rift sediments: an example from the Rechnitz Window, Eastern Alps. Tectonophysics, 297, 31–50.

Dunkl I., Kuhlemann J., Reinecker J. & Frisch W., 2005: Cenozoic relief evolution of the Eastern Alps – constraints from apatite fission track age-provenance of Neogene intramontane sediments. *Austrian Journal of Earth Sciences,* 98, 92–105.

Emery D. & Myers K.J., 1996: Sequence stratigraphy. *Blackwell Science*, Oxford, 297p.

Filipovic I., Jovanovic D., Sudar M., Pelikan P., Kovács S., Less Gy. & Hips K.,2003: Comparison of the Variscan – Early Alpine evolution of the Jadar Block (NW Serbia) and "Bükkikum" (NE Hungary) terranes – some palaeogeographic implications. *Slovak Geological Magazine*, 9, 3–21.

Fodor L. & Koroknai B., 2000: Ductile deformation and revised lithostratigraphy of the Martonyi Subunit (Torna Unit, Rudabanya Mts.), Northeastern Hungary. *Geologica Carpathica*, 51, 6, 355–369.

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, 5, 690–709.

Fodor L., Koroknai B., Balogh K., Dunkl I. & Horváth P., 2003: A Dunántúli-középhegységi egység („Bakony") takaros helyzete szlovéniai szerkezeti-geokronológiai adatok alapján. [Nappe position of the Transdanubian Range Unit ("Bakony") based on strctural and geochronological data from NE Slovenia]. *Földtani Közlöny*, 133, 4, 535–546.

Fodor L., Radócz G., Sztanó O., Koroknai B., Csontos L. & Harangi Sz., 2005^{a}: Post-Conference Excursion: Tectonics, sedimentation and magmatism along the Darnó Zone. *Geolines*, 19, 142–162.

Fodor L., Bada G., Csillag G., Horváth E., Ruszkiczay-Rüdiger Z., Palotás K., Síkhegyi F., Timár G., Cloetingh S. & Horváth F., 2005^{b}: An outline of neotectonic structures and morphotectonics of the western and central Pannonian Basin. *Tectonophysics*, 410, 1–4, 15–41.

Fodor L., Sztanó O. & Kovér Sz., 2013: Pre-conference field trip: Mesozoic deformation of the northern Transdanubian Range (Gerecse and Vertes Hills). *Acta Mineralogica-Petrographica, Field Guide Series*, 31, 1–34.

Fordinál K., Nagy A., Zlinská A., Kováčová-Slamková M., Halásová E. & Töröková I., 2002: New knowledge about stratigraphy of eastern part of the Danube basin (Želiezovce Depression). *Slovak Geological Magazine*, 8, 3–4, 259–281.

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

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. *Geophysical Journal International*, 177, 279–295.

Grill J., Kovács S., Less Gy., Reti Zs., Róth L. & Szentpetery I., 1984: Az Aggtelek-Rudabányai-hegység földtani felépítése és fejlődéströrténete. *Földtani Kutatás*, 27, 4, 49–56.

Haas J. & Kovács S., 2001: The Dinaridic-Alpine connection – as seen from Hungary. *Acta Geologica Hungarica*, 44, 345–362.

Haas J., Kovács S., Krystyn L. & Lein R., 1995: Significance of Late Permian-Triassic facies zones in terrane reconstructions in the Alpine-North Pannonian domain. *Tectonophysics*, 242, 1–2, 19–40.

Haas J., Budai T., Csontos L., Fodor L. & Konrad Gy., 2010: Pre-Cenozoic geological map of Hungary, 1:500 000. *A Magyar Állami Földtani Intézet* kiadvanya, Budapest.

Haas J. (Ed.), Hámor G., Jámbor Á., Kovács S., Nagymarosy A. & Szederkényi T., 2012: Geology of Hungary. Regional Geology Reviews, *Springer*, 244 p.

Haas J., Budai T., Csontos L., Fodor L., Konrad Gy. & Koroknai B., 2014: Geology of the pre-Cenozoic basement of Hungary. Explanatory notes for "Pre-Cenozoic geological map of Hungary"(1:500,000). Geological and Geophysical Institute of Hungary, Budapest, 73 p.

Hók J., Kováč M., Kováč P., Nagy A. & Šujan M., 1999: Geology and tectonics NW part of the Komjatice depression. *Slovak Geological Magazine*, 5, 3, 187–199.

Hók J., Vojtko R. & Slaninka I., 2011: Vznik a vývoj klenbovej štruktúry Cerovej vrchoviny. *Acta Geologica Slovaca*, 3, 2, 113–121.

Hók J., Šujan M. & Šipka F., 2014: Tektonické členenie Západných Karpát - prehľad názorov a nový prístup. *Acta Geologica Slovaca*, 6, 2, 135–143.

Horváth F., 1993: Towards a mechanical model for the formation of the Pannonian basin. *Tectonophysics,* 226, 1–4, 333–357.

Horváth F. & Cloetingh S., 1996: Stress-induced late-state subsidence anomalies in the Pannonian basin. *Tectonophysics,* 266, 1–4, 287–300.

Hrušecký I., 1999: Central part of the Danube Basin in Slovakia: Geophysical and geological model in regard to hydrocarbon prospection. *EGRSE Special Issue*, 6, 1, 2–55.

Jaskó S., 1946: A Darnó-vonal. *Beszámoló a Magyar Állami Földtani Intézet Vitaüléseiről,* 7, 63–77.

Kázmer M. & Kovács S., 1985: Permian-Paleogene Paleogeography along the Eastern part of the Insubric-Periadriatic Lineament system: Evidence for continental escape of the Bakony-Drauzug Unit. *Acta Geologica Hungarica*, 28, 71–84.

Kázmér M., Dunkl I., Frisch W., Kuhlemann J. & Ozsvárt P., 2003: The Palaeogene forearc basin of the Eastern Alps and Western Carpathians: subduction erosion and basin evolution. *Journal of the Geological Society*, 160, 3, 413–428.

Kilényi E. & Šefara J. (Eds.), 1989: Pre-Tertiary basement contour map of the Carpathian Basin beneath Austria, Czechoslovakia and Hungary. Eötvös Lóránd Geophysical Institute, Budapest, Hungary.

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 Special Publication,* Serie 1, 105–123.

Kováč M., 2000: Geodynamický, paleogeografický a štruktúrny vývoj karpatsko-panónskeho regiónu v miocéne: nový pohľad na neogénne panvy Slovenska. VEDA, Bratislava, 202p.

Kováč M., Baráth I., Holický I., Mark F. & Túnyi I., 1989: Basin opening in the Lower Miocene strike-slip zone in the SW part of the Western Carpathians. *Geologica Carpathica,* 40, 1, 37–62.

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. *Geologica Carpathica*, 45, 2, 83–96.

Kováč M., Nagymarosy A., Oszczypko N., Csontos L., Slaczka A., Marunteanu M., Matenco L. & Márton E., 1998^{a}: 7.2. Palinspastic reconstruction of the Carpathian - Pannonian region during the Miocene. *In:* Rakús M. (Ed.): Geodynamic development of the Western Carpathians. Geological Survey of Slovak Republic, Bratislava, 189–217.

Kováč M., Baráth I., Kováčová–Slamková M., Pipík R., Hlavatý I. & Hudáčková N., 1998^{b}: Late Miocene paleoenvironments and sequence stratigraphy: Northern Vienna Basin. *Geologica Carpathica,* 49, 6, 445–458.

Kováč M., Bielik M., Hók J., Kováč P., Kronome B., Labák P., Moczo P., Plašienka D., Šefara J. & Šujan M., 2002: Seismic activity and neotectonic evolution of the Western Carpathians (Slovakia). *EGU Stephan Mueller Special Publication Series*, 3, 167–184.

Kováč M., Synak R., Fordinál K. & Joniak P., 2010: Významné eventy v paleogeografii severnej časti Dunajskej panvy – nástroj na upresnenie stratigrafie jej vrchnomiocénnej a pliocénnej výplne. *Acta Geologica Slovaca*, 2, 1, 23–36.

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

Kováč M., Plašienka D., Soták J., Vojtko R., Oszczypko N., Less Gy., Ćosović V., Fügenschuh B. & Králiková S., 2016: Palaeogene palaeogeography and basin evolution of the Western Carpathians: a case study within the scope of the ALCAPA terrane. *Global and Planetary Change,* 140, 9–27.

Králiková S., Hók J. & Vojtko R., 2010: Reorientácia napäťového poľa odvodená z morfoštruktúr a zlomového porušenia pliocénnych sedimentov Hronskej pahorkatiny (Západné Karpaty). *Acta Geologica Slovaca*, 2, 1, 17–22.

Králiková S., Vojtko R., Andriessen P., Kováč M., Fügenschuh B., Hók J. & Minár J., 2014: Late Cretaceous–Cenozoic thermal evolution of the northern part of the Central Western Carpathians (Slovakia): revealed by zircon and apatite fission track thermochronology. *Tectonophysics,* 615–616, 142–153.

Kuhlemann J., 2007: Paleogeographic and paleotopographic evolution of the Swiss and Eastern Alps since the Oligocene. *Global and Planetary Change,* 58, 1–4, 224–236.

Less Gy., Grill I., Szentpetery I., Róth L. & Gyuricza Gy., 1988: Az Aggtelek – rudabányai-hegység fedetlen földtani térképe, 1:25000. *A Magyar Állami Földtani Intézet*, Budapest.

Magyar I., Geary D.H. & Müller P., 1999^{a}: Paleogeograhic evolution of the Late Miocene Lake Pannon in Central Europe. *Palaeogeography, Palaeoclimatology, Palaeoecology,* 147, 3–4, 151–167.

Magyar I., Geary D.H., Sűtő-Szentai M., Lantos M. & Müller P., 1999^{b}: Integrated bio-, magneto- and chronostratigraphic correlations of the Late Miocene Lake Pannon deposits. *Acta Geologica Hungarica*, 42, 1, 5–31.

Magyar I., Lantos M., Ujszászi K. & Kordos L., 2007: Magnetostratigraphic, seismic and biostratigraphic correlations of the Upper Miocene sediments in the northwestern Pannonian Basin System. *Geologica Carpathica*, 58, 3, 277–290.

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

Márton E. & Márton P., 1996: Large scale rotations in Hungary during the Neogene as indicated by palaeomagnetic data. *In:* Morris A. & Tarling D.H (Eds.): Palaeomagnetism and Tectonics of the Mediterranean Region. *Geological Society Special Publication*, 105, 153–173.

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

Minár J., Bielik M., Kováč M., Plašienka D., Barka I., Stankoviansky M. & Zeyen H., 2011: New morphostructural subdivision of the Western Carpathians: An approach integrating geodynamics into targeted morphometric analysis, *Tectonophysics*, 502, 1–2, 158–174.

Pantó G., 1954: Bányaföldtani felvétel az Upponyi-hegységben. *A Magyar Állami Földtani Intézet évi jelentése 1952*-ről, 91–111

Pécskay Z., Lexa J., Szakacs A., Seghedi I., Balogh K., Konečný V., Zelenka T., Kovacs M., Poka T., Fulop A., Márton E., Panaiotu C. & Cvetkovic V., 2006: Geochronology of Neogene magmatism in the Carpathian arc and intra-Carpathian area. *Geologica Carpathica,* 57, 6, 511–530.

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 Geologica Polonica*, 59, 1, 73–91.

Pomella H., Klötzli U., Scholger R., Stipp M. & Fügenschuh B., 2011: The Northern Giudicarie and the Meran-Mauls fault (Alps, Northern Italy) in the light of new paleomagnetic and geochronological data from boudinaged Eo-/Oligocene tonalites. *International Journal of Earth Science,* 100, 8, 1827–1850.

Pomella H., Stipp M. & Fügenschuh B., 2012: Thermochronological record of thrusting and strike-slip faulting along the Giudicarie fault system (Alps, Northern Italy). *Tectonophysics*, 579, 118–130.

Radócz Gy., 1966: A Bükk-hegység környéki helvéti képződmények mélyföldtani térképe, 1:100 000. *A Magyar Állami Földtani Intézet kiadvanya*, Budapest.

Rider M., 1996: Geological interpretation of Well Logs. 2nd edition, Rider French Consulting Ltd., Sutherland, 280 p. [ISBN 0-9541906-0-2]

Rybár S., Halásová E., Hudáčková N., Kováč M., Kováčová M., Šarinová K. & Šujan, M., 2015: Biostratigraphy, sedimentology and palaeoenvironments of the northern Danube Basin: Ratkovce 1 well case study. *Geologica Carpathica,* 66, 1, 51–67.

Schmid S.M., 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 Journal of Geosciences*, 101, 1, 139–183.

Schreter Z., 1952: Újabb földtani felvételek a sajóvölgyi barnakőszén-medencében. *A Magyar Állami Földtani Intézet Evi lelentese* 1949-ről, 115–130.

Szentpetery I., 1997: Sinistrial lateral displacement in the Aggtelek-Rudabanya Mts. (North Hungary) based on the facies distribution of Oligocene and Lower Miocene formations. *Acta Geologica Hungarica*, 40, 265–272.

Sztanó O., 1994: The tide-influenced Pétervására sandstone, early Miocene, northern Hungary: Sedimentology, paleogeography and basin development. *Geologica Ultraiectina,*120, 1–155.

Sztanó O. & Tari G., 1993: Early Miocene basin evolution in northern Hungary: Tectonics and eustacy. *Tectonophysics*, 226, 1–4, 485–502.

Šefara J., Kováč M., Plašienka D. & Šujan M., 1998: Seismogenic zones in the Eastern Alpine–Western Carpathian–Pannonian junction area. *Geologica Carpathica*, 49, 4, 247–260

Šujan M. & Rybár S., 2014: Vývoj pleistocénnych riečnych terás vo východnej časti Dunajskej panvy. *Acta Geologica Slovaca*, 6, 2, 107–122.

Šujan M., Braucher R., Kováč M., Bourlès D.L., Rybár S., Guillou V. & Hudáčková N., 2016: 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 and Planetary Change*, 137, 35–53.

Tari G., 1994: Alpine Tectonics of the Pannonian Basin. PhD Thesis, Rice University, Texas, USA, 501 p.

Tari G. & Horváth F., 2010: A Dunántúli-középhegység helyzete és eoalpi fejlődéstörténete a Keleti-Alpok takarós rendszerében: egy másfél évtizedes tektonikai modell időszerűsége. *Földtani Közlöny*, 140, 4, 463–505.

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

Tari G., Báldi T. & Báldi-Béke M., 1993: Paleogene retroarc flexural basin beneath the Neogene Pannonian Basin: a geodynamic model. *Tectonophysics,* 226, 433–456.

Telegdi Roth K., 1951: A bükkszéki ásványolajkutatás és termelés földtani tanulságai. *A Magyar Állami Földtani Intézet Evkönyve,* 40, 2, 1–21.

Vass D., 2002: Litostratigrafia Západných Karpát: Neogén a budínsky paleogén. Vydavateľstvo ŠGÚDŠ, Bratislava, 202 p.

Vass D., Konečný V., Šefara J., Pristaš J & Škvarka L., 1979: Geologická stavba Ipeľskej kotliny a Krupinskej planiny.*Geologický ústav Dionýza Štúra*, Bratislava, 277p.

Vass D., Hók J., Kováč P. & Elečko M., 1993: Sled paleogénnych a neogénnych tektonických udalostí v juhoslovenských kotlinách vo svetle napäťových analýz. *Mineralia Slovaca,* 25, 2, 79–92.

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

Zelenka T., Baksa Cs., Balla Z., Foldessy J. & Foldessy-Jaranyi K., 1983: The role of the Darnó Line in the basement structure of northeast Hungary. *Geologický Zborník Geologica Carpathica*, 34, 1, 53–69.