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Late Miocene and Pliocene history of the Danube Basin: inferred from development of depositional systems and timing of sedimentary facies changes

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Abstract: The development of the northern Danube Basin (nDB) was closely related to the Late Miocene geodynamic evolution of the Pannonian Basin System. It started with a wide rifting which led to subsidence of several basin depocenters which were gradually filled during the Late Miocene and Early Pliocene. In the Late Pliocene the subsidence continued only in the basin's central part, while the northern marginal zone suffered inversion and the uplifted sedimentary fill began to be eroded. Individual stages of the basin development are well recorded in its sedimentary succession, where at least three great tectono-sedimentary cycles were documented. Firstly, a lacustrine cycle containing Lower, Middle and lowermost Upper Pannonian sediments (A–F Zones; *sensu* Papp 1951) deposited in the time span 11.6–8.9 Ma and is represented in the nDB in Slovakia by the Ivanka and Beladice Formations. In the Danube Basin of the southern part in Hungary, where the formations are defined by the appearance of sedimentary facies in time and space, the equivalents are: (1) the deep-water setting marls, clays and sandy turbidites of the Endrőd and Szolnok Formations leading to the overlying strata deposits of the basin paleoslope or delta-slope represented by the Algyő Formation, and (2) the final shallow-water setting deposits of marshes, lagoons and a coastal and delta plain composed of clays, sands and coal seams, represented by the Újfalu Formation. The second tectono-sedimentary cycle was deposited in an alluvial environment and it comprises the Upper Pannonian (G and H Zones; *sensu* Papp 1951) and Lower Pliocene sediments dated 8.9–4.1? Ma. The cycle is represented in the nDB, by the Volkovce Formation and in the southern part by the Zagyva Formation in Hungary. The sedimentary environment is characterized by a wide range of facies from fluvial, deltaic and ephemeral lake to marshes. The third tectono-sedimentary cycle comprises the Upper Pliocene sediments. In Slovakia these are represented by the Kolárovo Formation dated 4.1–2.6 Ma. The formation contains material of weathering crust preserved in fissures of Mesozoic carbonates, diluvial deposits and sediments of the alluvial environment.

Key words: Late Miocene, Pliocene, Lake Pannon, Danube Basin, tectono-sedimentary cycles.

Introduction

The Danube Basin is situated in the territories of Slovakia, Hungary and Austria; it is located in the NW part of the Pannonian Basin System (Fig. 1). A large part of this basin system was covered by a Late Miocene lake which represented one of the most extensive flooded areas in Central Europe (Harzhauser & Mandič 2008; Magyar 2009).

Lake Pannon (Magyar et al. 1999), surrounded by the East Alpine–Western Carpathian and Dinaride mountain chains, developed due to the isolation of this part of the Central Paratethys Sea from the Eastern Paratethys and the Mediterranean (Royden & Horváth 1988; Horváth 1993; Rögl 1998; Kováč et al. 1999, 2006, 2010; Magyar et al. 1999; Konečný et al. 2002; Popov et al. 2006; Harzhauser & Mandič 2008). The specific environmental conditions of the lake are confirmed by an enormously diversified endemic mollusc fauna, which suffered selective rapid phylogenetic radiation (Magyar et al. 1999; Harzhauser et al. 2004; Harzhauser & Mandič 2008; Magyar 2009). From the Late Miocene to the Pliocene, Lake Pannon was continuously filled by sediments, generally from the W–NW to E–SE (Meulenkamp et al. 1996; Magyar et al. 1999). Gradual infilling of the individual depocenters or basins is reflected in the extent of specific sedimentary facies and their change over time and space. Evaluation of hundreds of seismic lines and electrical logs from boreholes penetrating the sedimentary fill of the lake's individual depocenters documents the presence of a great number of depositional systems in shallow- and deep-water settings whose positions varied over time and space (Juhász 1991; Pogácsás & Seifert 1991; Csató 1993; Vakarcs et al. 1994; Magyar et al. 1999; Sacchi & Horváth 2002; Kováč et al. 2006; Csató et al. 2007; Juhász et al. 2007; Uhrin et al. 2009; Magyar 2009; Leever et al. 2011).

These individual depocenters have their own tectono-sedimentary history and the main factors which influenced the development of their depositional systems were climatic

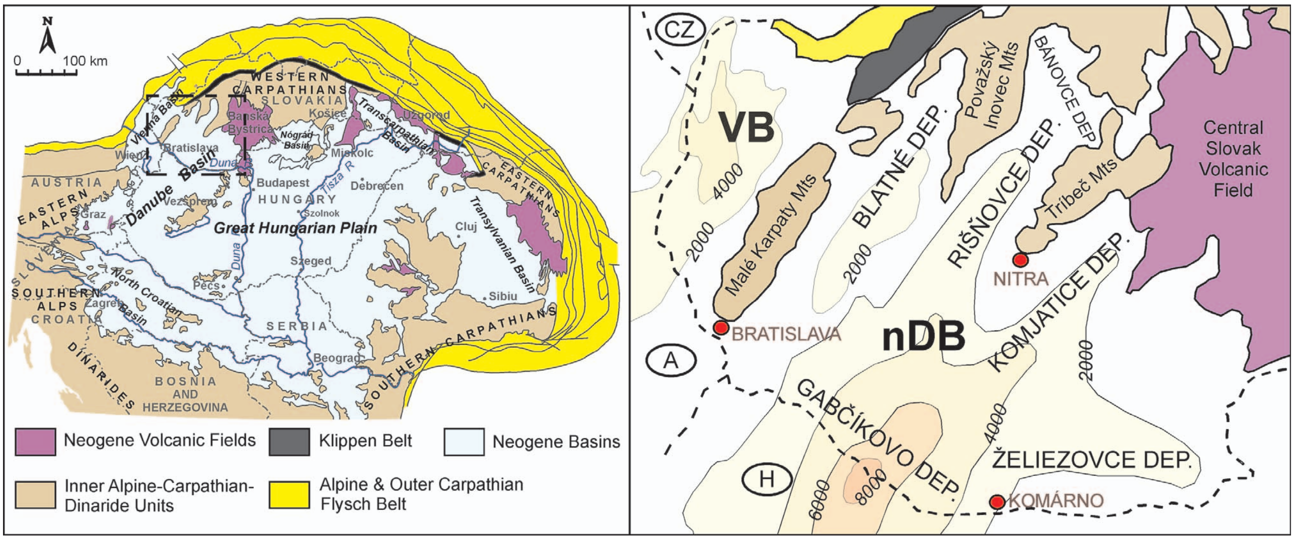


Fig. 1. Position of the Danube Basin within the Alpine-Carpathian-Pannonian region. The northern part of the Danube Basin (nDB) — position of basin depocenters: Blatné, Rišňovce, Komjatice, Želiezovce and Gabčíkovo Depressions.

changes controlling humidity and evaporation and also local tectonics which influenced uplift and subsidence, and consequently the development of the river network and burial history (Kováč et al. 2006, 2010; Uhrin et al. 2009; Leever et al. 2011). The sedimentary record of individual basins normally started with brackish to freshwater lacustrine deposits changing in the overlying strata to lagoonal, deltaic, fluvial and alluvial facies with a great thickness of often more than 2000–4000 m. This deposition was mostly in an alluvial environment and it was followed by tectonic inversion of the basin margins during the Pliocene and Quaternary era (Cloetingh et al. 2005; Jarosinski et al. 2011).

The predominantly lacustrine to alluvial character of the Late Miocene and Pliocene sedimentation in individual depocenters of Lake Pannon gave rise to many problems in correlative lithostratigraphy between the Carpathian, Pannonian, and Dinaride regions (Magyar 2009; Kováč et al. 2010). Although, the thick piles of lacustrine deposits are mainly correlated on the basis of fossil records using endemic aquatic fauna and flora, the biostratigraphy of alluvial sequences relies on scarce results from mammalian fossils. The biostratigraphical data are only supported by magnetostratigraphy or numerical dating of interbedded volcanic rocks in some places (Vasiljev et al. 2004; Kováč et al. 2006; Magyar et al. 2007). Therefore the correlation of sedimentary formations existing between individual depocenters over greater distance is sometimes difficult.

The more important second problem is the confidentiality of data which can be acquired by the Oil and Gas Industry. Previously, this has led to many problems in the exchange of geological and geophysical information on the sedimentary records of basins encompassing the territories of more than one country. An excellent example of the different approaches in geological investigation can be found in the Danube Basin which encompasses both a northern Slovak portion and a southern Hungarian part.

A complete re-evaluation of geophysical and geological data obtained in the northern Danube Basin (nDB), together with new field-work and laboratory results formed the ground-work for a new determination of particular sedimentary facies and their changes in time and space. This allowed a new model of the development of the basin's depositional system and an inter-regional correlation of the sedimentary fill and formations within the northern Slovak and the southern Hungarian portions of the Danube Basin.

Late Miocene and Pliocene biostratigraphy of the northern Danube Basin

The biostratigraphy of the nDB Upper Miocene sediments (Fig. 2), similar to that in the Vienna Basin, is predominantly based on the following; (1) brackish to freshwater mollusc fauna (A–F Zones, *sensu* Papp 1951, 1953; Fordinál 1997, 1998; Magyar et al. 1999; Harzhauser et al. 2004; Kováč et al. 2006, 2008), (2) refined mammalian biozonation (Harzhauser et al. 2004; Joniak 2005; Kováč et al. 2005, 2006, 2008, 2010; Vlačiky et al. 2008; Magyar 2009; Tóth 2010a,b), and (3) dinoflagellates and sporadic calcareous nannoplankton (Hudáčková 1995; Hudáčková & Slamková 2000; Andrejeva-Grigorovich et al. 2003a,b; Kováč et al. 2006, 2008).

The shallow-water mollusc associations (Fig. 2) documented during the Early Pannonian (A, B, C Zones; *sensu* Papp 1951) belong to the *Mytilopsis ornithopsis* and *Mytilopsis hoernesi* Biozones (Harzhauser et al. 2004; Kováč et al. 2005, 2006, 2008). In the Middle Pannonian sediments (D, E Zones; *sensu* Papp 1951), in the *Lymnocardium conjugens* Biozone associations with *Congeria partschi* and *Congeria subglobosa* were found (Fordinál 1997; Kováč et al. 2006, 2008). The Early and Middle Pannonian deep-water mollusc fauna has previously only been recognized in

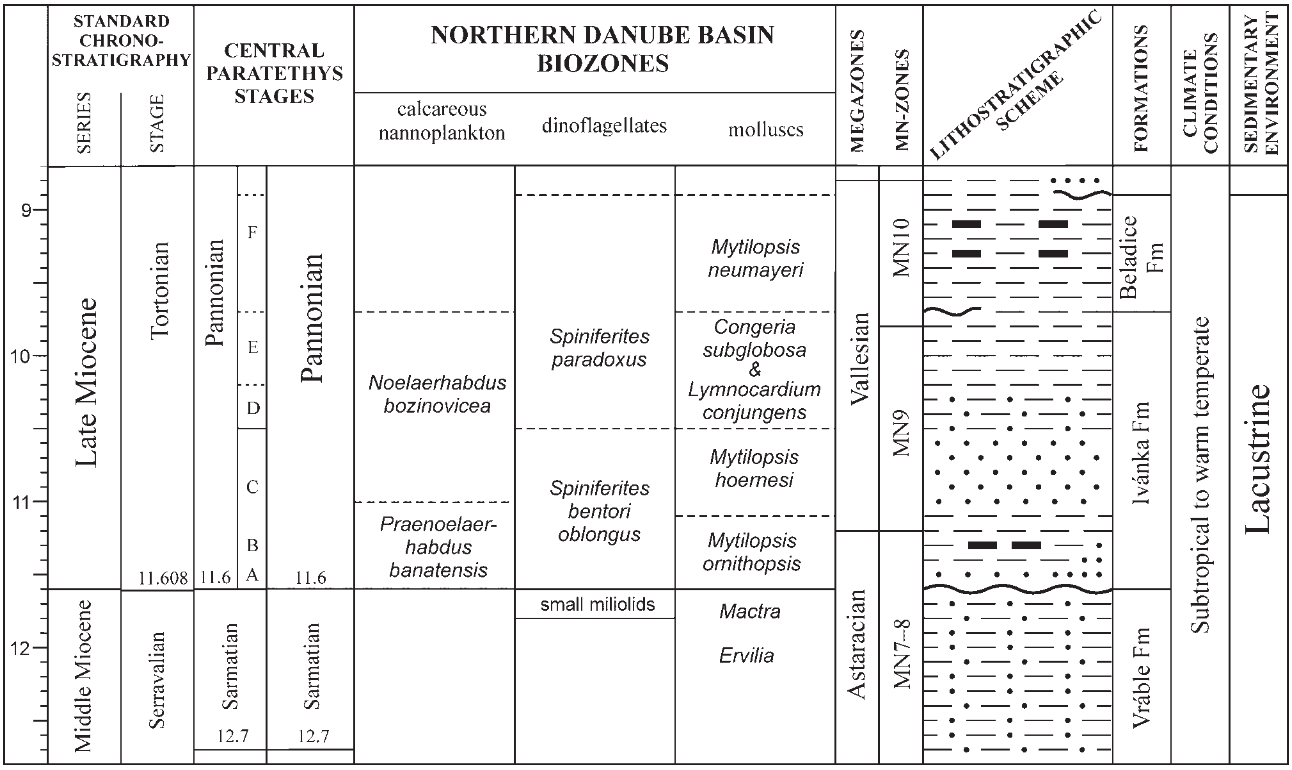


Fig. 2. Biostratigraphy of the northern Danube Basin. Central Paratethys stratigraphy *sensu* Kováč et al. (1998), Rögl (1998), Gradstein et al. (2004), Harzhauser et al. (2004), Vasiliev (2006), Harzhauser & Mandic (2008). Calcareous Nannoplankton *sensu* Martini (1971), Marunteanu (1997), Kováč et al. (2008). Dinoflagellates *sensu* Sütő-Szentai (1988, 1990), Magyar et al. 1999, Szuromi-Korecz et al. 2004. Molluscs and mammals *sensu* Kováč et al. 2006; Vlačiky et al. 2008; Tóth 2010a,b.

Hungary and it is characterized by the *Congeria banatica* Biozone (Magyar et al. 1999).

The beginning of the Late Pannonian (F Zone; *sensu* Papp 1951) represents a time interval when the lacustrine environment of the Vienna Basin changed into an environment of marshes and alluvial plains, and it is characterized by the *Mytilopsis neumayri–Mytilopsis zahalkai* Biozone (Harzhauser et al. 2004). A similar environment was also detected on the western flanks of the nDB and it is documented by the *Mytilopsis neumayri* Biozone in the Ivánka Formation's uppermost part (Fordinál 1997). In the basin center which is documented only on seismic lines and also on the basin's SE Hungarian margin, a lacustrine environment defined by the *Congeria czjzeki* and *Lymnocardium ponticum* Biozone was still present during this time (Magyar et al. 1999; Cziczer et al. 2009; Magyar 2009). For the following Late Pannonian to Pliocene predominantly alluvial sedimentary record of the nDB, we are unable to use further correlation based on mollusc assemblages. The biostratigraphy of these sediments is therefore based only on scarce findings of mammalian fossil associations (Figs. 3, 4).

Biostratigraphy using "small mammals" helped us to determine not only the Ruscinian MN15b Biozone, but also the Vallesian MN9 and MN10 Biozones (*sensu* Harzhauser et al. 2004; Harzhauser & Tempfer 2004; Daxner-Höck et al. 2004; Joniak 2005). The proboscideans teeth of "big mammals", constituted the main evidence used to solve the chronological succession from the Turolian to Villanyian deposition in the studied area (MN12, MN13, MN14, MN15a, MN16, and MN17; *sensu* Tóth 2010a,b). The results of this research simultaneously helped us to deduce important facts about changes in paleoecology and paleogeography of the broader nDB area.

The oldest Late Miocene mammalian fossil associations (MN10 and MN9 mammal Biozones) were discovered at the Pezinok brickyard (Blatné Depression of the nDB) where *Deinotherium giganteum* was found together with other fossils (Holec 2005; Tóth 2010a,b). The sediments form the uppermost part of the Ivánka Formation and the lowermost part of the Beladice Formation. The local fauna of the Vallesian mammalian stage document an open landscape on the Lake Pannon shoreline (Holec 1981, 1986; Sabol & Holec 2002; Joniak 2005). Climate can be characterized by a gradual change from subtropical to warm temperate, with evidence of the sporadic presence of thermophilous and evergreen taxa (Kvaček et al. 2006).

The fossil fauna of the overlying Volkovce Formation forms part of the MN11 to MN14 mammal Biozones and they cover the Turolian and Lower Ruscinian mammalian stage of the Late Miocene and Early Pliocene epochs (Fig. 4). The fauna and characteristics of the sediments document the change from lacustrine to prevailingly alluvial and fluvial environments.

The Turolian shift of the Lake Pannon shoreline from the nDB towards the southeast confirms seismic data (Magyar

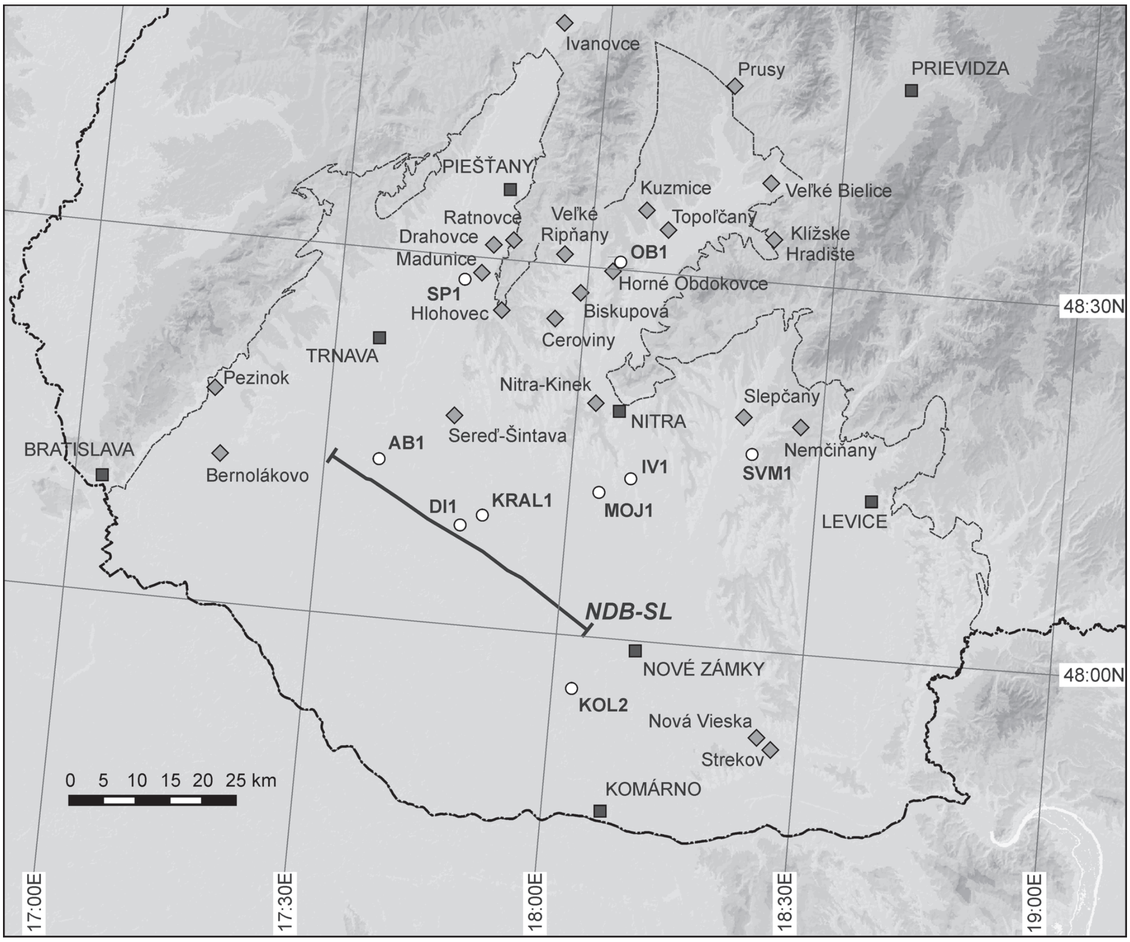


Fig. 3. Northern part of the Danube Basin; localization of the sites with mammal fossil occurrences and figured outcrops (see Fig. 5); localization of seismic profile and boreholes (white circles: AB1 — Abrahám 1, DI1 — Diakovce 1, IV1 — Ivánka 1, KRAL1 — Králová 1, KOL2 — Kolárovo 2, MOJ1 — Mojmírovce 1, OB1 — Obdokovce 1 and SP1 — Špačince 1, SVM1 — Tajná).

2009) and also mammalian fossil sites at Nyárád, Tihany and Csákvár in Hungary (Bernor et al. 1987; Kordos 1987; Nargolwalla et al. 2006). The associations document an increase in species diversity during the MN11 mammal Biozone. The findings, represented by "large" and "small" mammals are characterized by a murid-cricetid dominated assemblage and by an increase in carnivores, ruminants and proboscideans. The fauna points to relatively open woodland environments and drier conditions with seasonal climate changes — compared to the Vallesian (Daxner-Höck 1996). The Turolian MN11 Zone which is also well known from the Eichkogel limestone in the Vienna Basin (Wenz & Edlauer 1942; Daxner-Höck 1996; Harzhauser & Binder 2004; Nargolwalla et al. 2006) can be partly correlated with the Hlavina Member (Fordinál 1994; Fordinál & Nagy 1997) a freshwater limestone described from the western foothill of the Tribeč Mts or with the Ratnovce limestone appearing at the western foothill of the Považský Inovec Mts. The Hlavina limestone is positioned in the Volkovce Formation basal portion (Fig. 4).

Discovery of the *Deinotherium proavum* (originally described as *D. gigantissimum*) at the Madunice locality in the Blatné Depression refers to the presence of the MN12 Biozone in the nDB (Musil 1959; Tóth 2010a,b). The first occurrence of a primitive *Anancus* (*Anancus* sp.) comes from the Topoľčany-Kalvária site. Various proboscidean taxa such as "*Mammut*" aff. *borsoni*, *Anancus* sp., and *Tetralophodon* sp., which can be dated at MN12–13? Biozones have also been reported at the Veľké Bielice, Klížske Hradište, Prusy, and Horné Obdokovce localities on the basin's northern margin, in the Bánovce and Rišňovce Depressions (Figs. 1, 3). All the aforementioned Turolian *Anancus* teeth have a small to extremely small size, a complex morphology and very low hypsodonty. The remains of the Vallesian species *Tetralophodon longirostris* were also documented at the Topoľčany-Kalvária site. The taphonomy of this locality is therefore extremely difficult and the remains of two taxa were presumably excavated from two separate or mixed strata.

The MN12–13 Biozone mammalian fauna is also known from the Hungarian part of the Danube Basin at Tardosbánya (Kordos 1987; Daxner-Höck 1996; Van Dam 2006; Nargolwalla et al. 2006), Györszentmárton (Hugeney 1999) and Baltavár localities (Kordos 1987; Bernor et al. 1987; Nargolwalla et al. 2006). The Baltavár site has the best preserved faunal assemblage of the "Middle Turolian" in Central Europe, with paleoenvironments of open country woodlands in a warm, temperate climatic zone with seasonal changes (Bernor et al. 1996; Solounias et al. 1999; Kaiser & Bernor 2006).

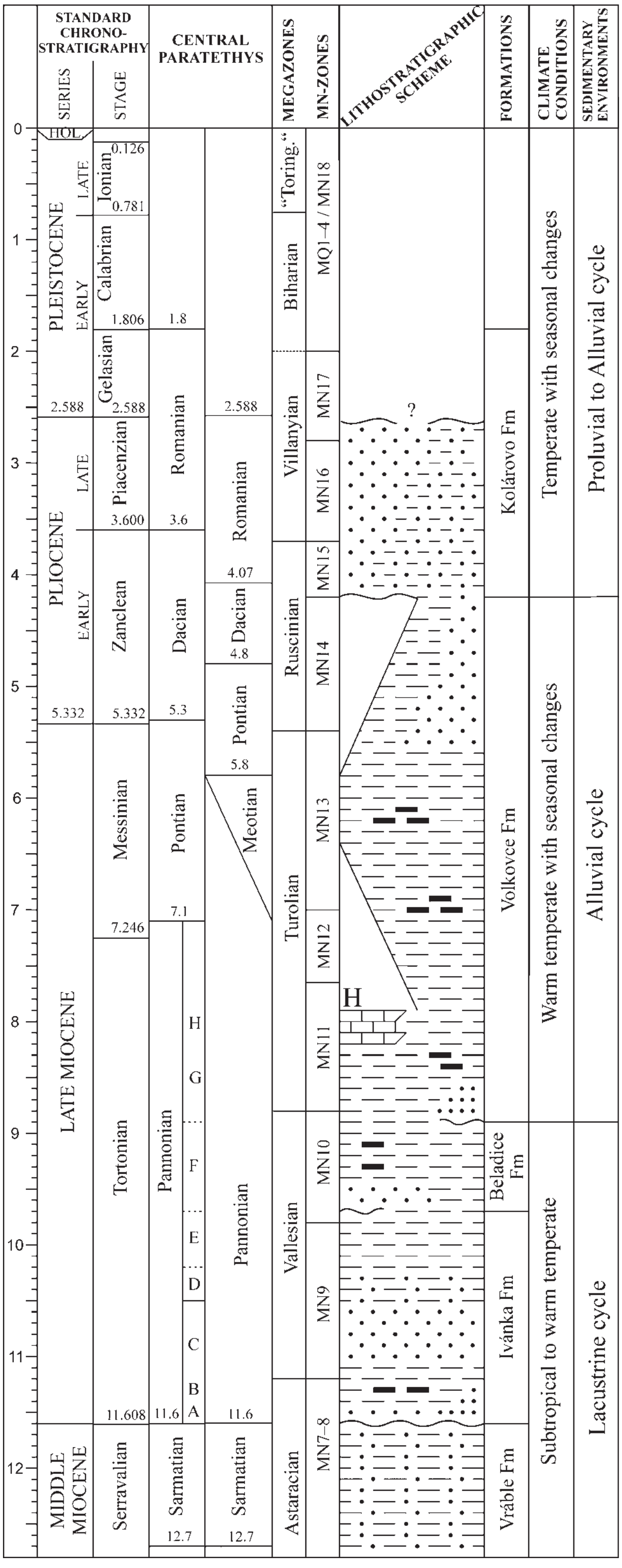


Fig. 4. Lithostratigraphic scheme of the northern Danube Basin formations; Standard Neogene stages and Central Paratethys stratigraphy *sensu* Rögl (1998), Kováč et al. (1998), Gradstein et al. (2004). Explanatory notes: **dots** — coarse clastics, sand and conglomerate; **lines** — fine-grained deposits, clays and silts; **black rectangles** — coal seams and coalificated plant remnants; **H** — Hlavina Member freshwater carbonates. Time span of the Late Miocene formations after Kováč et al. (2010).

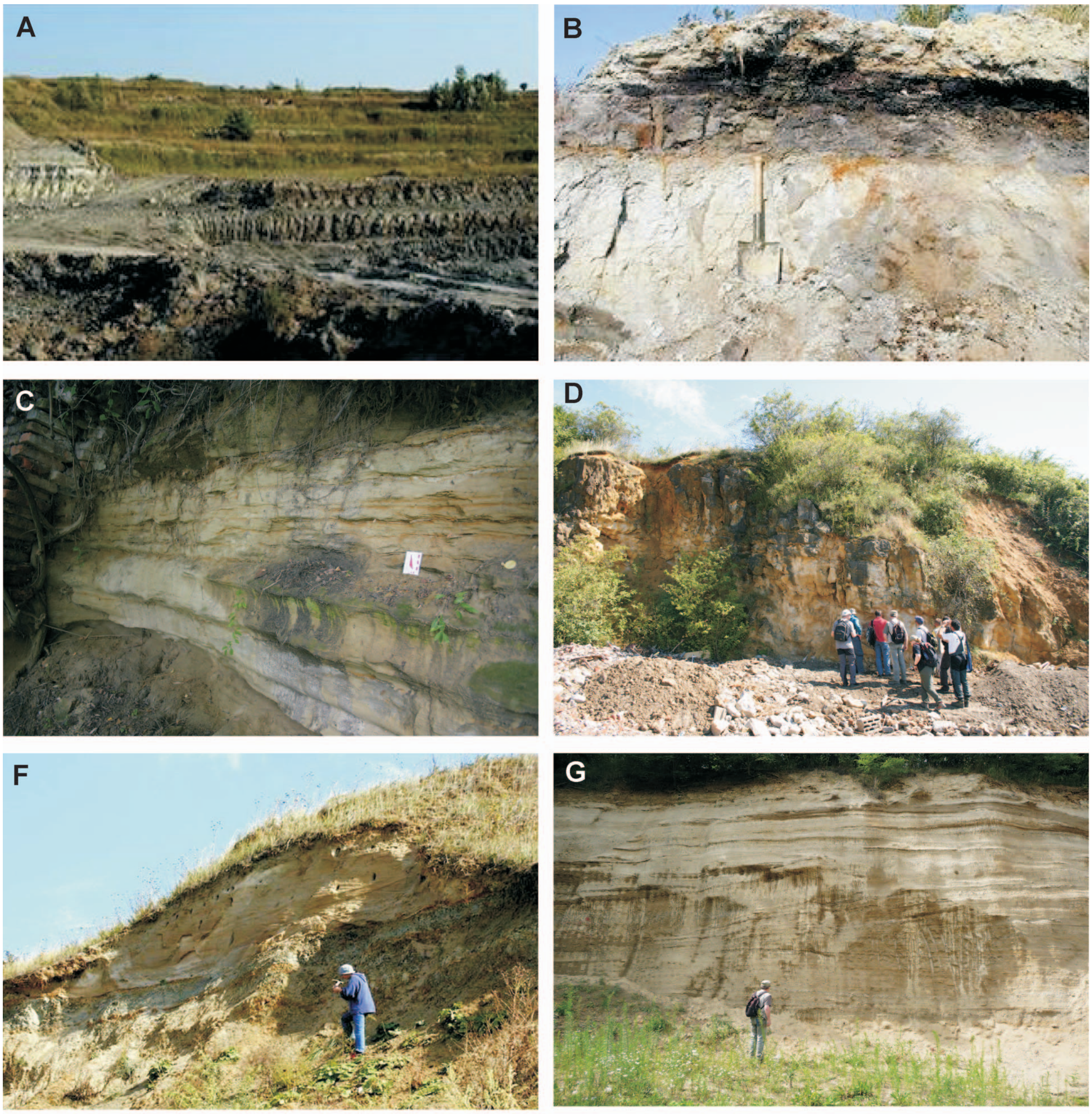
The findings of fossil remains of large mammalians from the Volkovce Formation at the Slepčany site in the Komjatice Depression of the nDB (Holec 1981) belong to the MN13–14? Biozones (Figs. 1, 3). The teeth of *Anancus* aff. *arvernensis* have a more complex morphology and are more hypsodont in comparison with the *Anancus* from previous Turolian localities (MN12–13? Biozones).

The first appearance of the "typical" *Anancus arvernensis* was recognized from the Kuzmice (MN13?–14), Nitra-Kynek and Biskupová (both MN14) localities. These findings document the Early Pliocene age of the sediments. The molars are large with a less complex morphology and low hypsodonty. There is a progressive trend of hypsodonty, shortening and morphological simplification of the molars (*sensu* Metz-Muller 1995). This is clearly observable in the fossil record from Slovakia from the Early Pliocene to the Early Pleistocene; and the final appearance of the *"Mammut"* aff. *borsoni* taxon is reported at the Kuzmice site (Fig. 3).

The Late Pliocene fauna located in the "red beds" of the Kolárovo Formation, cover a wide area of the Považský Inovec Mts and the uplifted margin of the nDB in the Rišňovce and partly Komjatice Depressions, and this documents an abrupt change at the Early and Late Pliocene boundary, which is clearly visible in the sedimentary record. The Ruscinian mammalian stage (MN15 Zone) documents the first occurrence of the typical *"Mammut" borsoni* from the Velké Ripňany and Drahovce (Tóth 2010a) and also from the Ceroviny sites (Holec et al. 2002) placed in the MN15–16 Zones (the Ruscinian-Villanyian boundary). At the Ivanovce site near Trenčín, a Late Pliocene small mammal faunal association of the Late Ruscinian (MN15b) was documented (Fig. 3). This fauna points to humid forests with scarce open land near rivers or local lakes in a temperate climatic zone (Fejfar 1961a,b, 1970; Fejfar & Heinrich 1985).

The Early Pleistocene mammalian faunal associations (*Anancus arvernensis*, "*Mammut*" *borsoni*, *Mammuthus* cf. *meridionalis*) were found in the SE part of the nDB at Nová Vieska and Strekov localities (Figs. 1, 3). This mammal fauna is represented mainly by large mammals and belongs to the MN16–17 Zones of the Villanyian mammalian stage (Holec 1996; Vlačiky et al. 2008). The fossil fauna points to open woodlands in temperate climatic zone with seasonal changes; however, the sedimentary environment and composition of fauna indicate allochthonous and probably also heterochthonous origin of the assemblage.

The rare foraminifers identified in pelitic deposits at the base of the Late Miocene sedimentary record of the nDB — *Miliammina subvelatina* Venglinskij, *Trochammina kibleri* Venglinskij (Jiříček 1974; Jámbor et al. 1985; Kováč et al. 2008) confirm an initially brackish environment. The endemic nannoplankton (Fig. 2) of the *Praenoelaerhabdus banatensis* and *Noelaerhabdus bozinovicae* Biozones (Andrejeva-Grigorovich et al. 2003a,b; Kováč et al. 2008) correlated with NN9 and NN10 Zones (*sensu* Martini 1971; Marunteanu 1997) partly support a brief connection with the Eastern Paratethys, at least during the very early stage of the Lake Pannon on the Middle/Late Miocene boundary. After 9 Ma, the nDB was almost totally isolated from the rest of the lake.



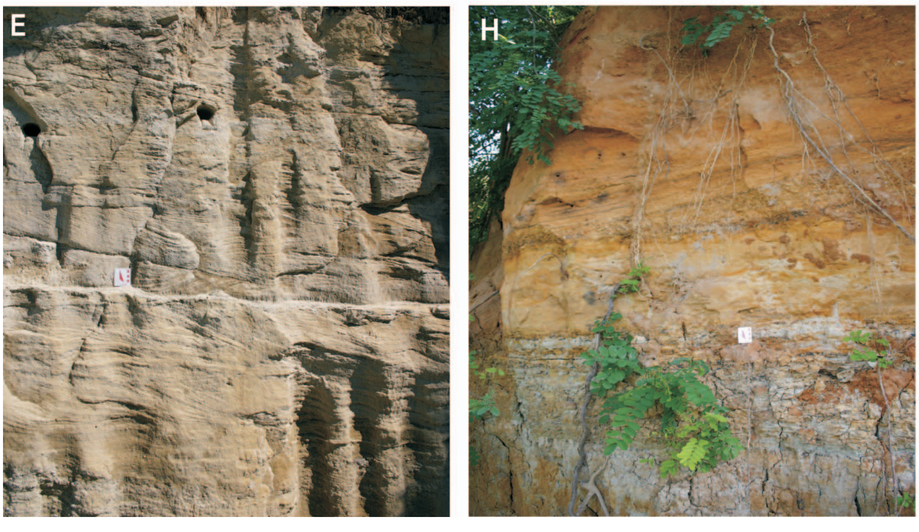


Fig. 5. A — Brackish to freshwater lacustrine deposits, Ivánka Fm, Pezinok. **B** — Coal seams in nearshore swamps and alluvial plain deposits, Ivánka Fm, Pezinok. **C** — Shallow-water fluvial to lacustrine deposits with ripple marks, Beladice Fm, Bernolákovo. **D** — Freshwater limestones, Hlavina Mb, Ratnovce. **E** — Coarse-grained to fine sand, braided to meandering river deposits, Volkovce Fm, Hlohovec. **F** — Overbank alluvial clays overlain by deposits of small point bar, Volkovce Fm, Hlohovec. **G** — "Hron River" deltaic sandstones and conglomerates, Volkovce Fm, Nemčiňany. **H** — Erosional contact between grey alluvial fine-grained deposits of the Volkovce Fm and red or variegated clays, sand and fine- to medium-grained gravel of the alluvial sediments of the Kolárovo Fm, Veľké Ripňany.

Lithostratigraphy of the Upper Miocene and Pliocene northern Danube Basin fill

The Danube Basin (DB), situated in the Western Carpathians hinterland between the Eastern Alps on the west and the Mid-Hungarian Range on the east, began to open at the end of the Early Miocene (Tari et al. 1992). The initial rifting was followed by the Middle Miocene subsidence of individual depocenters (Lankreijer et al. 1995; Kováč et al. 1999). The Late Miocene to Pliocene represents a separate chapter in the basin's history, during which more than 4500 m sediments were deposited in the basin center (Kilényi & Šefara 1989; Lankreijer et al. 1995; Kováč 2000).

In the nDB (Slovakia), the lower part of the Upper Miocene basin fill (Early and Middle Pannonian A–E Zones; *sensu* Papp 1951) is represented by the Ivánka Formation, originally correlated with the time range of 11.6–7.1 Ma (Priechodská & Harčár 1988; Vass 2002). New results from paleomagnetic dating and biostratigraphy proved its Vallesian age and a time range of approximately 11.6–9.7 Ma (Kováč et al. 2006, 2010; Magyar et al. 2007). The formation, with a maximal thickness of up to 2000 m, was deposited in a brackish to freshwater lacustrine environment (Fig. 5A). It consists predominantly of calcareous clays (claystones) and silts (siltstones) intercalated with sand bodies (sandstones). Occasionally, gravels (conglomerates), coal-clays and coal seams are present on the basin margin (Fig. 4, Fig. 5B).

The Beladice Formation (Priechodská & Harčár 1988) was deposited towards overlying strata and this correlated with the Late Pannonian Zone F (*sensu* Papp 1951) described as Pontian in the time range of 7.1–5.3 Ma (Vass 2002). It is formed by clays and silts with various sand contents attaining a thickness from 30 to 500 m. The Beladice Formation was originally defined as occurring only in shallow-water to alluvial environments containing typical coal-clays and coal seams deposited in marshes, oxbows of meandering rivers and ephemeral lakes (Fig. 5C). However, it is clear from the seismic lines crossing the basin center (Fig. 6a) that the accepted lithostratigraphical definition of this formation is valid only for the basin margins. Toward the basin center, in the southeast, the alluvial to shallow-water facies continuously pass into deep-water lacustrine facies. Therefore, the formation can be correlated with the Szák Formation located on the NE margin of the Mid-Hungarian Range in Hungary (Cziczer et al. 2009). The formation represents high stand deposits of the *Congeria czjzeki* and *Spiniferites paradoxus* Biozones (Magyar et al. 1999 or Zone F *sensu* Papp 1951), in the time span of 9.4–8.9 Ma, and therefore the upper boundary of deposition of the Beladice Formation can be placed at approximately 8.9 Ma (Figs. 2, 4).

In the southern (Hungarian) part of the DB, Upper Miocene sediments identical to the Ivánka and Beladice Formations can be approximately correlated to at least four formations (*sensu* Juhász 1991, 1994; Juhász et al. 2007). The Újfalu Formation is formed of sediments deposited in a shallow-water setting as shelf deposits, alluvial and deltaic sediments of marshes, lagoons, coastal and delta plains. The Algyő Formation is composed of fine-grained sediments, mostly clays, and marls in the area of the basin or delta slope. The deep-water sandy turbidites form the Szolnok Formation and the clays and marls of the distant basin floor are part of the Endrőd Formation (Fig. 6b).

The Upper Miocene to Lower Pliocene basin fill of the nDB (G and H Zones; *sensu* Papp 1951) is represented by the Volkovce Formation described as Dacian and correlated with the time range of 5.3–3.6 Ma (Priechodská & Harčár 1988; Vass 2002). The formation was deposited in an alluvial environment and contains fluvial deposits and also sediments of marshes, ephemeral lakes and small deltas (Fig. 5E,F, and G). The formation is more than 1200 m in the central part of the basin, and it consists predominantly of variegated clays and silts with sand bodies, often with a lot of plant detritus. At the basin margin, fluvial and deltaic sands and gravels are present as well; on tectonic lines (in the case that carbonate rocks form the pre-Neogene basement) freshwater limestone and "lake chalk" were deposited (Fig. 5D). The freshwater limestone bodies represent the Hlavina Member with an estimated age of approximately 8 Ma (Fordinál & Nagy 1997; Kováč et al. 2010; Tóth 2010a,b). The base of the Volkovce Formation has been newly dated to 8.9 Ma (Kováč et al. 2010) with its upper part approaching the Upper Pliocene base, which is about 4.1 Ma old (*sensu* Gradstein et al. 2004). This new time span of the formation is proved by findings of mammal fossils ranging between the MN11 and MN14 Biozones (Turolian and Early Ruscinian; 8.9–4.1 Ma).

In the southern, Hungarian part of the basin, the same package of sediments represents the Zagyva Formation with a thickness of 1000–1200 m (Juhász 1991, 1994; Juhász et al. 2007). Its sedimentary sequence is composed of sandstones, siltstones, clays and marls deposited in lacustrine, alluvial and fluvial environments, similar to the northern part of the basin. This formation contains a lot of plant remnants, coal clays, and coal seams. Sandy bodies of 10–20 m thickness are interpreted as alluvial plain channel fill or deposits of point bars.

Upper Pliocene sediments in the nDB are represented by the Kolárovo Formation (Priechodská & Harčár 1988). The age of the formation base has conventionally been stated as the base of the Romanian regional stage (Vass 2002) at present dated to 4.1 Ma (Vasiliev et al. 2004). The age of the formation upper boundary was also stated conventionally to be at base of the Quaternary 2.6 Ma (Gradstein et al. 2004). Findings of mammal fossils have currently proved the time span of the MN15, 16 and 17 mammalian Zones (Ruscinian and Villanyian; 4.1–2.6 Ma; Fejfar 1966; Vlačiky et al. 2008). The maximum thickness of 200–300 m the Kolárovo Formation has been determined only from boreholes (Kováč 2000; Vojtko et al. 2008). The sedimentary environment of the deposition was proluvial to alluvial; the sequence is composed mostly of red or variegated clays, sand, and fine- to medium-grained gravel (Fig. 5H). The pebble material is represented by quartz, chert, sandstone, and crystalline schists (Priechodská & Harčár 1988).

In the southern, Hungarian part of the basin, the Hanság Formation (Császár et al. 1997) may be the equivalent of the Kolárovo Formation in Slovak territory. The formation is formed by lacustrine to fluvial variegated clays and sands with gravel bodies, lignite layers and basalt tuffs occurring in some places.

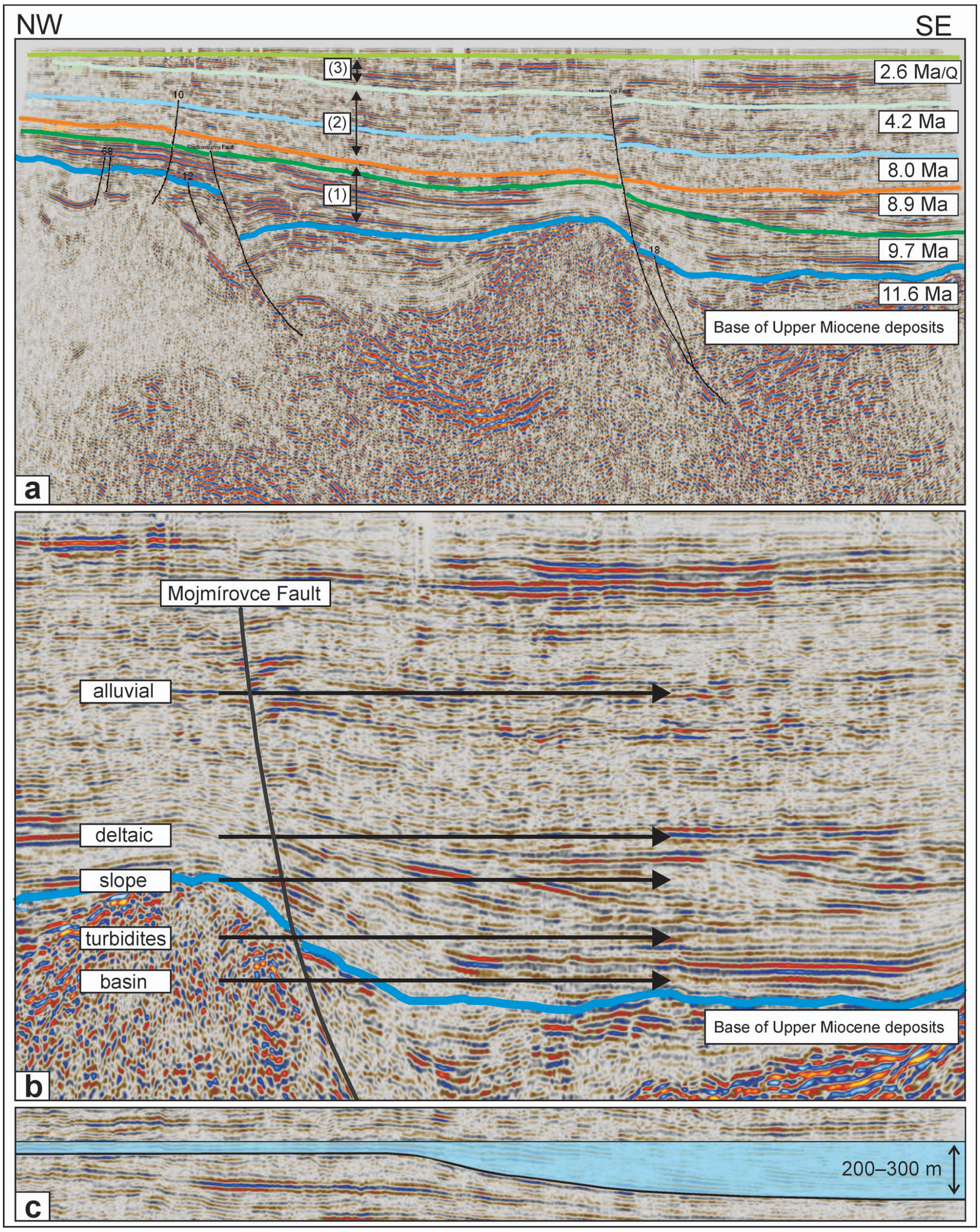


Fig. 6. NW–SE oriented seismic profile in the central part of the northern Danube Basin, situation at Fig. 3: **a** — Seismic profile with marked time lines dividing individual tectono-sedimentary cycles; 1 — Late Miocene lacustrine tectono-sedimentary cycle, 11.6–8.9 Ma, Ivánka and Beladice Fms; 2 — Late Miocene to Early Pliocene alluvial tectono-sedimentary cycle, 8.9–4.2 Ma, Volkovce Fm; 3 — Late Pliocene proluvial to alluvial tectono-sedimentary cycle, 4.2–2.6 Ma, Kolárovo Fm. **b** — Distribution of sedimentary facies on seismic line (e logs of the same facies are marked on Fig. 7). **c** — Paleodepth of Lake Pannon in the northern Danube Basin.

Late Miocene and Pliocene depositional cycles in the northern Danube Basin

The nDB Late Miocene and Pliocene tectono-sedimentary evolution commenced with a phase of subsidence around the Middle–Late Miocene boundary. The "wide-rifting" of the basin was followed by its gradual infill which lasted until the Early Pliocene (Lankreijer et al. 1995; Kováč et al. 2010). During the Late Pliocene a shift of subsidence in the central Gabčíkovo Depression was documented. This occurred simultaneously with uplift and denudation at the basin's northern margins (Lankreijer et al. 1995; Kováč et al. 2006). Three periods of deposition (tectono-sedimentary cycles) have been recorded in the basin sedimentary fill and these are observable in outcrops, and especially on seismic lines and well logs.

The first, Late Miocene lacustrine tectono-sedimentary cycle began approximately 11.6 Ma (Magyar et al. 1999; Kováč et al. 1999, 2006; Kováč 2000) and it can be approximately correlated with the base of the global TB3.1 cycle (*sensu* Haq et al. 1988; Haq 1991), or the Ser4/Tor1 cycle (*sensu* Hardenbol et al. 1998; 11.7–9.4 Ma). The coincidence in timing of the depositional cycle lower boundary with the global cycles, and more or less also with the lower boundary of all depositional cycles in the whole Pannonian Basin System can be related to the existence of a short period of connection with the Eastern Paratethys during this time. The possibility of such a connection is also supported by the presence of marine nannoplankton in the Lower Pannonian deposits as far as the Danube and Vienna Basins (Andrejeva-Grigorovič et al. 2003a,b).

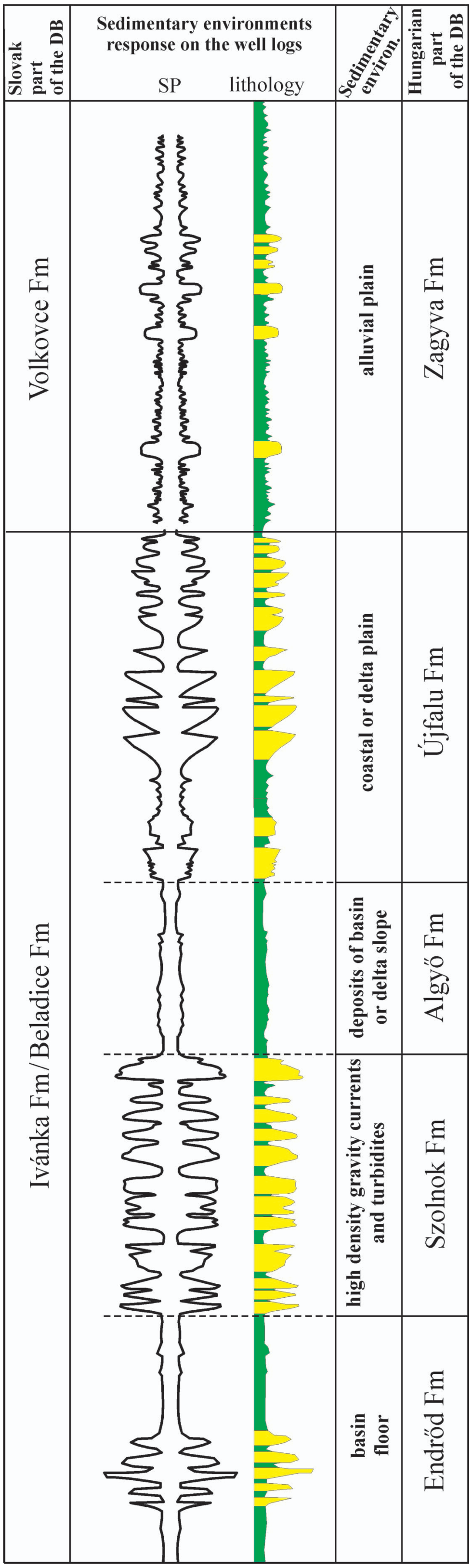


Fig. 7. Sedimentary environments and facies of the northern Danube Basin and their response on the composite spontaneous potential (SP) well log, correlation between the formations used in the northern (Slovak) and southern (Hungarian) parts of the Danube Basin (*sensu* Juhász 1991, 1994; Juhász et al. 2007 and Kováč et al. 2010).

During this sedimentary cycle, the Ivánka and Beladice Formations (Priechodská & Harčár 1988; Vass 2002) were deposited in the nDB (Fig. 4). Reinterpretation of data from the outcrops, boreholes, and geophysical measurements helped in the detection of the upper boundary of this cycle, which we placed on seismic lines to the distinct level where a change in character of seismic reflexes appears from "a typical lacustrine to an alluvial pattern" (Fig. 6b). This change in seismic signal also coincides with the change in shape of the boreholes' electrical logs in many places (Fig. 7). Timing of this boundary is based on the age of the Szák Formation at 8.9 Ma (Cziczer et al. 2009). Thus, our definition of the first Pannonian lacustrine depositional cycle upper boundary can also be correlated with the uppermost portion of the "Pannonian cycle PAN2" defined in the southernmost part of the DB by Sacchi & Horváth (2002).

The base of the second, Late Miocene to Early Pliocene alluvial tectono-sedimentary cycle was confirmed on the surface at the DB northern margin: in the Blatné Depression (clay pit Hlohovec; Kováč et al. 2006) and in the Komjatice Depression (Kováč et al. 2008), where the borehole ŠVM-1 near the town of Vráble (Fig. 3) reached below the sediments of the Volkovce Formation on the erosion surface, lying on the Ivánka Formation clays (E Zone, *sensu* Papp 1951). The upper boundary of this depositional cycle is located at the contact with the overlying Upper Pliocene Kolárovo Formation, which is divided from the Volkovce Formation mainly by an angular discordance. Erosion surfaces and incised valleys were often present at the outcrops in the Rišňovce Depression (Fig. 5H).

The third, Late Pliocene proluvial to alluvial tectono-sedimentary cycle is formed by the Kolárovo Formation (Fig. 3). The age of this cycle's lower boundary is close to the lowermost part of the Late Ruscinian age at approximately 4.1 Ma where the base of the Romanian stage is established according to Vasiliev (2006). The upper boundary of the cycle is conventionally placed at the bottom of the Quaternary at 2.6 Ma (*sensu* Gradstein et al. 2004). During this cycle, massive erosion of sediments of the older formations began in the nDB marginal parts and fluvial sedimentation survived only in the central Gabčíkovo Depression. The thickness of the Quaternary deposits does not exceed 500 m (Janáček 1969; Scharek et al. 2000).

Correlative lithostratigraphy between the northern and southern Danube Basin

The lithostratigraphy of the Upper Miocene and Pliocene sediments of the DB and the consequent definition of formations in the northern Slovak and southern Hungarian portions of the basin is totally different because various methods and aspects of their definition have been used up to now. In the Slovak part, the formations were defined following the vertical "age" stratification of the sedimentary record (Priechodská & Harčár 1988; Vass 2002), similar to that in the Vienna Basin (*sensu* Papp 1951), while in the Hungarian portion the formations were defined as various depositional systems, independent of age and characterized by their sedimentary environment which was predominantly conditioned by the paleo-geomorphology of the basin. This included the shelf, basin slope, and deep basin floor (Juhász 1991, 1994; Császár et al. 1997; Magyar et al. 1999; Juhász et al. 2007; Magyar 2009). However, the Hungarian formations were mainly defined in the Great Hungarian Plain basins and not in the Little Hungarian Plain area of the Danube Basin.

The new reevaluation of borehole archival data and seismic lines from the nDB in Slovak territory, together with reinterpretation of the electrical log patterns from the basin's deepest parts show that the northwestern shelf of Lake Pannon did not exceed a paleo-depth of 20–50 m. However, the floor of the basin depocenters in Slovak territory initially had depths of 200–300 m (Fig. 6c).

When the Hungarian definition of formations is considered, a very approximate correlation can currently validly divide the Upper Miocene Ivánka and Beladice Formations into sediments deposited in shallow- and deep-water settings. Shelf deposits such as alluvial and deltaic sediments of the marshes, lagoons, coastal and delta plains are present in the Újfalu Formation. Further subdivision include the fine-grained and mainly clay marl sediments in the basin paleo-slope or delta slope of the Algyő Formation and the Szolnok Formation's deep-water sandy turbidites and the Endrőd Formation's clays and marls on the distant basin floor. When these facts were considered, a partial correlation of the deep-water sedimentary record of the nDB was performed between the still used "Papp zones" sense and the "Hungarian" definition of formations in the sense of depositional environments (Fig. 7).

The Upper Miocene deep-water sediments, which can be correlated with the Endrőd Formation, correspond to the A and B zones (*sensu* Papp 1951) and they reach a thickness of 50–100 m. The calcareous clays and claystones, represent the base of the sequence and these were deposited in a basin floor environment (Figs. 6b,c, 7). The overlying strata have a thickness of 200 to 600 m and mainly contain fine- to medium-grained massive sands and sandstone bodies separated by layers of basin clays (C Zone; *sensu* Papp 1951). On the basis of electrical log interpretations (Fig. 7) from drill holes crossing these sediments in the central part of the basin we can assume the presence of sandy high-density gravity currents and turbidites localized at the foot of the basin or delta slope and on the adjacent basin floor (Figs. 6c, 7). This part of the sedimentary sequence can be correlated with the Szolnok Formation.

According to the studied electrical logs, clays and silts, 100–200 m thick in the D Zone (*sensu* Papp 1951), capping the sandy sediments of the "C Zone" show a distinct fining upward trend of grain size again followed by a gradual increase in sandy component towards the overlying strata (Figs. 6c, 7). We can interpret this part of the sedimentary record as deposits of the basin or delta slope, and also as the facies of the lower basin or delta front in some places, and correlate them with the Hungarian Algyő Formation.

Sediments of the DB marginal portion, as well as lake deposits above the deep-water sedimentary record were generally deposited in much shallower environments (E and F Zones; *sensu* Papp 1951). These sediments represent deposits of the coastal or delta plain including marshes, lagoons and delta front. The sedimentary record is composed of cyclic deposition of sands, silts and clays, and the presence of coal-clays and coal seams is very common, especially in outcrops at the basin margins. We correlate these with the Hungarian Újfalu Formation (Figs. 6c, 7).

The Upper Miocene to Lower Pliocene basin fill (Zones G and H; *sensu* Papp 1951) of the nDB is represented by the Volkovce Formation (Priechodská & Harčár 1988; Vass 2002) which has a serrated pattern on electrical logs documenting the alluvial sedimentary environment of this part of the basin fill (Figs. 4c, 6).

Late Miocene and Pliocene geodynamics and development of the nDB

Due to new results of multidisciplinary geological and geophysical research, progress in biostratigraphy, definition of tectono-sedimentary cycles, and correlative lithostratigraphy, we can better understand the Late Miocene and Pliocene evolution of the nDB. This evolution was influenced by a geodynamic background set up by asthenospheric mantle upheaval in the back arc basin acting together with the overriding slab pull — caused by the subduction retreat in front of the Eastern Carpathians during this time (Horváth 1993; Csontos 1995; Lankreijer et al. 1995; Bada et al. 1996, 2001; Fodor et al. 1999; Konečný et al. 2002).

The current shape of the nDB, with characteristic digit like depocenters in a NE–SW direction: the Blatné, Rišňovce, and Komjatice Depressions (Fig. 1) is a result of the Middle Miocene structural pattern development which controlled the opening of these depressions from west to the east during the Badenian and Sarmatian ages.

At the Middle–Late Miocene boundary no marked change in the basin sedimentary fill architecture was observed along the seismic lines in the basin center. However, frequent angular discordance between the Sarmatian and Lower Pannonian sediments on the basin margin document an accelerated subsidence of the basin.

The Late Miocene "wide rifting" of the nDB (*sensu* Lankreijer et al. 1995) was controlled by a fault pattern similar to the Middle Miocene one (Marko et al. 1990, 1991, 1995; Fodor et al. 1999; Kováč 2000). The Pannonian halfgrabens and grabens subsided predominantly along NNE–SSW to NE–SW trending fault zones operating in a paleostress field with a NE–SW oriented maximal compression axis. Following the thickness of sediments and average sedimentation rates (m/Myr) during individual time spans at selected boreholes, a gradual increase in the Late Miocene deposition can be observed from the basin margins toward its center (Fig. 8). The Beladice Formation (9.7–8.9 Ma) gained maximum thickness and an accelerated sedimentation rate during this time in the Gabčíkovo Depression.

The following Late Miocene and Early Pliocene sedimentation of the Volkovce Formation (8.9–4.1 Ma) document a more moderate deposition. The tectonic background of subsidence during this time span is not satisfactorily solved. However, it is proposed that the origin of the accommodation space was initiated due to thermal subsidence of the

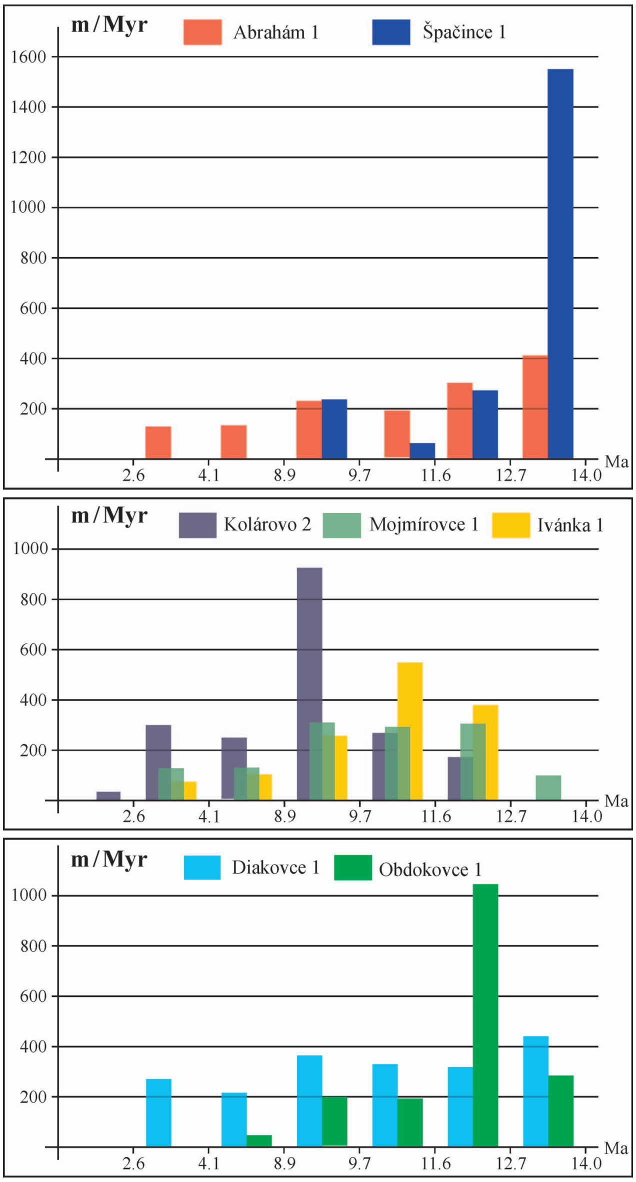


Fig. 8. Sedimentation rates (m/million years) from boreholes in the Blatné (Špačince 1, Abrahám 1); Rišňovce (Obdokovce 1, Diakovce 1); Komjatice and Gabčíkovo Depressions (Ivánka 1, Mojmírovce 1 and Kolárovo 2).

back arc basin (Horváth 1993; Hrušecký et al. 1996). It appears that the mechanism of subsidence could also be mainly controlled by the deep sub-crustal erosion above the mantle diapir, allowing the sinking of the thinned overheated crust of the nDB below the load of a massive sedimentary pile of more than 4000 m at this time.

The thermal subsidence (*sensu* Horváth 1993), due to cooling of the overheated lithosphere, may have started in the nDB originally during the Early Pliocene (Konečný et al. 2002). This fact documents the change of lithosphere elastic properties towards a more brittle condition (Lankreijer et al. 1995, 1999; Lankreijer 1998; Bada 1999; Dérerová et al. 2006). A northward advance of crustal deformations from southern regions began at the end of the Late Miocene and during the Early Pliocene. This is dated by folding of the Pannonian sediments — "Sava folds"; *sensu* Fodor et al. (1999) and it first reached the northern regions during the Late Pliocene (indicated by the transpressive tectonic regime in the Western Carpathians causing their accelerated uplift; *sensu* Minár et al. 2011). All these tectonic events were induced by the movement of the Adriatic plate northward (Sacchi & Horváth 2002; Ruszkiczay-Rüdiger et al. 2005; Horváth et al. 2006).

In the nDB, this considerable change in tectonic regimes is marked by angular discordance between the Upper Pliocene sediments and underlying strata, and also by increased deposition during this time period (Fig. 8) in the central Gabčíkovo Depression (Kolárovo Formation; 4.1–2.6 Ma).

Inversion of the DB northern margin, due to the accelerated uplift of the Western Carpathians led to the basin inversion which persisted into the Quaternary, and was associated with erosion of the uplifted nDB sedimentary formations (Kováč et al. 2006; Minár et al. 2011). This yielded sediments for subsiding depocenters in its central part. The following Late Quaternary subsidence of the Gabčíkovo Depression along NW–SE trending normal faults (Herrmann et al. 1998) was possibly connected with the change of transpressive tectonic regimes to transtensional by the NW–SE orientation of the principal maximum paleostress axis by the final stage of the basin's evolution (Vojtko et al. 2008; Králiková et al. 2010).

The Pliocene to Quaternary basin inversion of the Pannonian-Carpathian system is related to changes in the regional stress field leading to differential vertical movements associated with a laterally variable folding mechanism which was active in the entire system (*sensu* Cloetingh et al. 2005). The lateral variability was a result of marked contrast in rheology between various areas, directly related to the crustal configuration, thermal properties and late-stage collision kinematics of the Carpathians. The finite-element numerical-modelling study by Jarosinski et al. (2011) also predicted a successive development in surface undulations caused by crustal and/or lithosphere folding and a change in the stress state along the flanks of the basin, due to the development of a weak basin lithosphere in their vicinity.

Discussion

The Late Miocene and Pliocene paleogeography of the Western Carpathians and the northern Danube Basin (nDB), located in the hinterland of the mountain chain (Kováč et al. 1993; Magyar et al. 1999) can also be judged from a qualitative mass balance relationship viewpoint. An example of this is the relationship between the uplifting source and the sinking areas. The tectonically active periods of the mountain chain uplift are recorded in the basin fill, with the deposition of coarse-grained sedimentary bodies and the tectonically quiet periods are characterized by predominantly fine-grained sediments deposition.

The nDB sedimentary history documents a Late Miocene lacustrine cycle (Early and Middle Pannonian) followed after 8.9 Ma by a second cycle (Late Pannonian to Early Pliocene) with an environment of alluvial plains. The absence of greater amounts of coarse-grained sediments such as gravels and conglomerates in the majority of the sedimentary fill during both cycles indicates the development of a moderate landscape in the hinterland of the basin. This agrees with the documented development of the Mid-mountain level — main planation surfaces of the Western Carpathians (Mazúr 1963; Minár 2003), dated between 10–6 Ma (Minár et al. 2011; Kováč et al. 2011).

The commencement of a rapid uplift in the Western Carpathian mountain chain documented between 6–4 Ma (Kováč et al. 2011) is not visible in the sedimentary record of the basin center, and no abrupt change or erosion surface is to be found on the seismic lines crossing the basin. This tectonic event can be supported only by the onset of coarser deltaic sedimentation in the upper part of the Volkovce Formation (Late Turolian MN13(14?) mammalian Biozone), when a fan delta of the paleo-Hron river entered the basin in the Komjatice Depression (Baráth & Kováč 1995; Fig. 5G).

The Late Pliocene (4.1–2.6 Ma) and Quaternary acceleration of the Western Carpathian chain uplift (Minár et al. 2011), which was associated with tectonic inversion of the nDB margins, was tectonically controlled and it led to the current landscape and development of the river network. Eroded material from the mountains was transported by the rivers towards the lowlands (Fig. 5H); the paleo-Váh river entered the basin and the Kolárovo Formation was deposited (Kováč et al. 2006). The Quaternary nDB was divided into uplifting hilly lands and subsiding plains.

Conclusions

The significant results of the nDB study and its correlation with the southern Hungarian portion can be summarized as follows:

• A new biostratigraphical and lithostratigraphical concept of the Upper Miocene and Pliocene nDB fill:

(a) The time range of the Volkovce Formation (Priechodská & Harčár 1988; Vass 2002) previously dated as the Early Pliocene (Dacian), was shifted from 5.3–3.6 Ma to the time span of 8.9–4.1 Ma due to new paleomagnetic and biostratigraphical data, and also new analysis of borehole logs and seismic profiles;

(b) The time range of the Beladice Formation (Priechodská & Harčár 1988; Vass 2002) previously correlated with the Pontian regional stage, was shifted from 7.1–5.3 Ma to 9.7–8.9 Ma due to new paleomagnetic, biostratigraphical data, and also new analysis of borehole logs and seismic profiles;

(c) The time range of the Pannonian Ivánka Formation (Priechodská & Harčár 1988; Vass 2002), previously dated 11.6–7.1 Ma, was shifted to 11.6–9.7 Ma due to new paleomagnetic, biostratigraphical data, and also new analysis of borehole logs and seismic profiles.

• Three tectono-sedimentary cycles were documented in the Upper Miocene and Pliocene fill of the nDB (Slovakia):

(a) The first Late Miocene (Pannonian) tectono-sedimentary cycle (11.6–8.9 Ma), representing a lacustrine to alluvial depositional system, comprising the Ivánka and Beladice Formations, was deposited on the prograding margin of the Lake Pannon in various environments. We can define this succession as deposits of alluvial, lagoonal, and deltaic to basin slope and basin floor facies shifting over time and towards the basin center. Just as in the southern part of the basin in Hungary, the individual depositional systems based on sedimentary facies changes can be defined and named as lithostratigraphic entities uniformly in the southern, as well as in the northern DB. (1) The shallow-water setting deposits of alluvial and delta plain (marshes, lagoons, coastal, and delta plain) are represented by the Újfalu Formation. (2) Deposits of the paleo-slope or delta-slope of the Lake Pannon comprise the Algyő Formation. (3) Sandy turbidites form the Szolnok Formation and (4) the deep-water setting marls and clays make up the Endrőd Formation;

(b) The second Late Miocene to Early Pliocene tectono-sedimentary cycle (8.9–4.1 Ma), representing a predominantly alluvial depositional system, began to develop after loss of accommodation space. The alluvial package of sediments is represented by the Volkovce Formation in Slovakia, and by the Zagyva Formation in Hungary. The depositional environments can be characterized as alluvial — with a wide range of facies — from fluvial, deltaic, ephemeral lake to marshes, and dry land deposits;

(c) Third Late Pliocene tectono-sedimentary cycle (4.1–2.6 Ma), predominantly represented by the proluvial to alluvial depositional system, comprises deposition at the nDB margins and in the basin "remnant depocenters" which are mainly situated in its central part. The third cycle comprises the Kolárovo Formation in Slovakia.

• The Late Miocene to Pliocene geodynamic development of the nDB, with two important changes of structural pattern (paleostress field orientation), was documented:

(a) The Late Miocene to Early Pliocene synrift stage with paleostress field with maximal compression axis of NE–SW orientation;

(b) The Late Pliocene and Quaternary stage of inversion with a Quaternary paleostress field change. Here, the maximal compression axis changed orientation from NE–SW to NW–SE.

• Qualitative mass balance relations, such as relations between the uplifting source and sinking areas can be characterized as follows:

(a) The Late Miocene tectonically quiet period with the absence of a greater amount of coarse-grained sediments in the majority of the nDB sedimentary fill (10–6 Ma) indicates the development of a moderate topography in the hinterland of the basin. These facts agree well with the documented development of the main planation surfaces of the Western Carpathians, at the Mid-mountain level;

(b) The uplift of the Western Carpathians mountain chain documented between 6–4 Ma is not visible in the basin sedimentary record, and no abrupt change or erosion surface can be found on seismic lines crossing the basin center. This tectonic event is supported only by the onset of coarser deltaic sedimentation in the Volkovce Formation upper part, when a fan delta of the paleo-Hron river entered the basin;

(c) Tectonically controlled Late Pliocene (4.1–2.6 Ma) and Quaternary acceleration of the mountain chain uplift led to the current landscape and development of the river network.

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