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Late Miocene sedimentary record of the Danube/Kisalföld Basin: interregional correlation of depositional systems, stratigraphy and structural evolution

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Abstract: The Danube/Kisalföld Basin is the north-western sub-basin of the Pannonian Basin System. The lithostratigraphic subdivision of the several-km-thick Upper Miocene to Pliocene sedimentary succession related to Lake Pannon has been developed independently in Slovakia and Hungary. A study of the sedimentary formations across the entire basin led us to claim that these formations are identical or similar between the two basin parts to such an extent that their correlation is indeed a matter of nomenclature only. Nemčiňany corresponds to the Kálla Formation, representing locally derived coarse clastics along the basin margins (11–9.5 Ma). The deep lacustrine sediments are collectively designated the Ivanka Formation in Slovakia, while in Hungary they are subdivided into Szák (fine-grained transgressive deposits above basement highs, 10.5–8.9 Ma), Endrőd (deep lacustrine marls, 11.6–10 Ma), Szolnok (turbidites, 10.5–9.2 Ma) and Algyő Formations (fine-grained slope deposits, 10–9 Ma). The Beladice Formation represents shallow lacustrine deltaic deposits, fully corresponding to Újfalu (10.5–8.7 Ma). The overlying fluvial deposits are the Volkovce and Zagyva Formations (10–6 Ma). The synoptic description and characterization of these sediments offer a basin-wide insight into the development of the basin during the Late Miocene. The turbidite systems, the slope, the overlying deltaic and fluvial systems are all genetically related and are coeval at any time slice after the regression of Lake Pannon initiated about 10 Ma ago. All these formations get younger towards the S, SE as the progradation of the shelf-slope went on. The basin got filled up to lake level by 8.7 Ma, since then fluvial deposition dominated.

Keywords: Late Miocene, Tortonian, Pannonian, lithostratigraphy, Pannonian Basin, turbidites, delta, alluvial.

Introduction

The main objective of this study is to establish a correlation between the Late Miocene–Pliocene lithostratigraphic systems of the northern, Slovakian and the southern, Hungarian parts of the Danube/Kisalföld Basin (DKB), a sub-basin of the Neogene Pannonian Basin System. This approximately 200 km long and 120 km wide, NE–SW trending basin is crossed in the middle by the Danube, which marks the international boundary between Slovakia to the north and Hungary to the south (Fig. 1). In Slovakia, the area is known as "Danube Lowland" because it lies adjacent to and was formed mainly by the activity of the Danube and its tributaries. The Hungarian name of the region is Kisalföld ("Little Plain"), as opposed to the Alföld ("Great Plain"), the latter referring to the central part of the Pannonian Basin System located east of the middle course of the Danube. To avoid confusion with other large Miocene to Quaternary depocenters along the course of the Danube, we prefer to name this portion of the system as Danube/Kisalföld Basin.

Lithostratigraphic subdivision of the upper Neogene basin fill evolved independently in Slovakia and Hungary, in spite of the fact that the geological formations are continuous across the political boundary. The attempt of correlation induced re-consideration and re-definition of lithostratigraphic units in both countries, and led to renewed description of the formations. This work was supported by mutual visits of the Slovak-Hungarian team of authors to both parts of the DKB.

In this paper we give parallel description and characterization of each upper Neogene sedimentary formation, and interpret the evolution of their depositional environment within a large-scale tectonic and sedimentary framework.

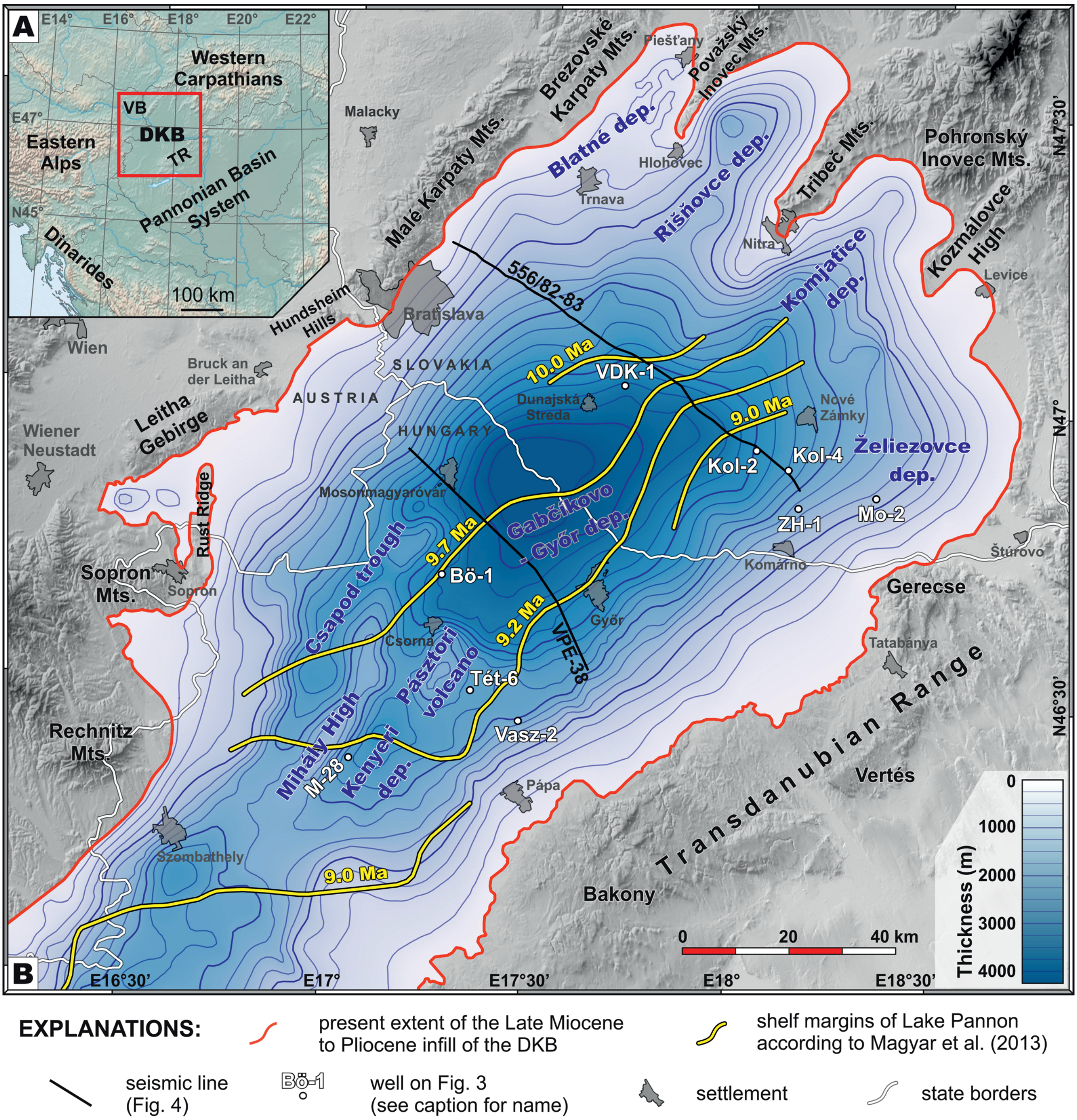

Fig. 1. a — Location of the Danube/Kisalföld Basin (DKB) in the Eastern Alps–Western Carpathians–Pannonian Basin junction area (TR: Transdanubian Range, VB: Vienna Basin). **b** — Map of the DKB with thickness of the Late Miocene to Quaternary succession. Thickness data modified from Atzenhofer et al. (2011). The prograding shelf edge is displayed after Magyar et al 2013. Location of wells and seismic sections shown on Figs. 3 and 4 are indicated.

Geological context and history of lithostratigraphic subdivision

The Neogene Danube/Kisalföld Basin is an extensional basin formed along NE–SW-striking faults in the late Early to Middle Miocene (Tari 1994, 1996; Kováč & Baráth 1995; Lankreijer et al. 1995; Mattick et al. 1996; Hrušecký et al. 1999; Kováč et al. 1999). The sedimentary fill of the DKB, like any other part of the Pannonian Basin System, includes Early to Middle Miocene marine sediments of the Paratethys (Karpatian to Badenian), Middle Miocene restricted marine deposits (Sarmatian), and brackish to freshwater deposits of Lake Pannon and the adjacent fluvial systems (Pannonian, i.e. Late Miocene–Pliocene) (Szádeczky-Kardoss 1938; Kováč et al. 2006, 2011). Results on bio-, chrono-, magnetostratigraphy and geochronology of the non-marine late Neogene sequence of the DKB were recently published by Magyar et al. (2000, 2007, 2013) and Šujan et al. (2016).

The present-day lithostratigraphic subdivision of the lacustrine to fluvial depositional sequence is a result of a historical evolution in both countries. In Hungary, Jámbor (1980) elaborated a lithostratigraphic system for the Pannonian deposits of the Transdanubian Range, Gajdos et al. (1983) for the Pannonian of the Alföld ("Great Plain"), and Bardócz et al. (1987) for the deep basins of western Hungary, including the DKB. The proposal of Juhász (1994) to use a uniform lithostratigraphic subdivision for the basin deposits of the entire country was accepted and implemented by the Stratigraphic Committee of the Hungarian Academy of Sciences (Császár 1997). Recent developments include the correlation and nomenclatural revision of the "basinal" and "marginal" formations and the construction of a comprehensive lithostratigraphic model for the entire Lake Pannon depositional system (e.g., Sztanó et al. 2013a).

In Slovakia, lithostratigraphy was based on correlation of the regional (Central Paratethys) stages, such as the Pannonian, Pontian, and Dacian (e.g., Steininger et al. 1985); these stages were defined as brackish water, brackish to freshwater, and freshwater to terrestrial, respectively. All the three stages were considered as distinct units bounded by transgressions (e.g., Buday et al. 1967; Adam & Dlabač 1969; Biela 1978). A formation system was introduced during the late 80's, but only the names changed: the Ivanka Fm. corresponded to the same sequence as the previous "Pannonian", the Beladice Fm. to the "Pontian", and the Volkovce Fm. to the "Dacian" (e.g., Priechodská & Harčár 1988; Vass et al. 1990; Vass 2002). By definition, each formation contained several depositional systems (e.g., basinal, deltaic, alluvial) and variable lithology, which led to difficulties in correlation. Recent efforts have focused on establishing a genetic definition of depositional systems in the lithostratigraphy of the northern DKB, and on obtaining new geochronological constraints (Kováč et al. 2006, 2010, 2011; Šujan et al. 2016), which resulted in lithostratigraphic redefinitions included in this study.

Description of Formations

Kálla Formation/Nemčiňany Formation

Lithology, facies: Kálla Formation (Fig. 2) is made up of coarse siliciclastics. Grain size varies from very well-sorted fine sand to coarse gravel. Colour is usually whitish grey or yellow-brown depending on rate of limonitic cementation. Its type locality is in the Kál Basin, located ca. 40 km south of the DKB, where it is matured quartz-sand or "pearl" gravel made up of well-rounded quartzite pebbles with only a minor amount of metamorphics and local Mesozoic constituents (Jámbor 1980). The composition of the formation, however, strongly depends on the geology of the source area. For instance, in the western part of the DKB (south of the Sopron Hills) the clastics are shed from a local source; most probably from the Rosalia Mts. (Permo-Triassic metasediments, medium-grade metamorphics). The Kálla Formation is usually characterized by a steep depositional dip up to 15–25°, as the beds comprise clinoforms. Small-scale cross-bedding, cross-lamination and plane lamination may occur in horizontal topset beds. Low angle dip differences in foreset beds, shallow scours or chutes, and backsets are rather common. The height of individual clinoforms is variable up to 20 m, but stacking of two or three clinoform sets is a common feature. Small-scale syn-sedimentary faults, more often deformation bands are present (Schmid & Tari 2015); they are, at least partly, due to gravity-driven deformation along clinoforms. There are also locations where only very well sorted sand is present without any observable sedimentary structures other than a few vertical burrows and limonitic or quartz cementation features.

The Nemčiňany Gravel Formation (Kutham et al. 1963), the potential equivalent of the Kálla Formation in the northern DKB, is also a coarse siliciclastic succession. Its type area is the Komjatice Depression, as seen in the Nemčiňany quarry, where the rounded to well-rounded pebbles contain mainly quartzite and volcanites, followed by metamorphics, quartz, and variable content of carbonates. Again, the petrographic composition mirrors the source area, including the proximal Central Slovakian Neovolcanic Field and the Central Western Carpathians. Clinoform foresets are built up by 10–30 cm thick tabular beds of matrix-supported gravels with normal or reverse gradation, and have a dip of 10–20°. Their height may exceed 30 m. Channels with imbricated clast-supported gravels are incised into the foresets, and trough-cross stratified gravels in lenticular bodies up to 12 m wide occur in the topset units. Several-metre-thick sandy-gravelly layers interfingering with open-water mudstones may still be part of the Nemčiňany Formation (northern margin, well Bernolákovo-1).

In well logs, coarse clastics may appear at the base of the Pannonian succession as low gamma ray blocky units. Resistivity is usually moderate to low due to varying rate and type of cementation (cf. Csillag et al. 2010).

Stratigraphic position, thickness: The Kálla Formation either directly overlies pre-Pannonian rocks or follows above the Szák Formation. The interfingering of the Kálla and Szák Formations was also documented (Csillag et al. 2010). The Kálla Formation is usually overlain by shallow water deltaic deposits of the Újfalu Formation. Its average thickness is 10–20 m, with a maximum of about 40 m.

The Nemčiňany Formation in the Želiezovce Depression forms the several tens of metre thick basal part of the Pannonian succession (well Dubník-1). In the Komjatice Depression it overlies a several tens of metres thick clayey-silty succession with brackish mollusc fauna, corresponding to the lower part of the Ivanka Formation, which is an equivalent of the Szák Formation. The overall thickness of the formation in this part of the basin reaches 80 to 100 m, according to borehole data.

Fossils, age: The coarse clastics of the Kálla and Nemčiňany Formations rarely contain fossils. In the type area at the Kál Basin, however, both molluscs and plant remains were found

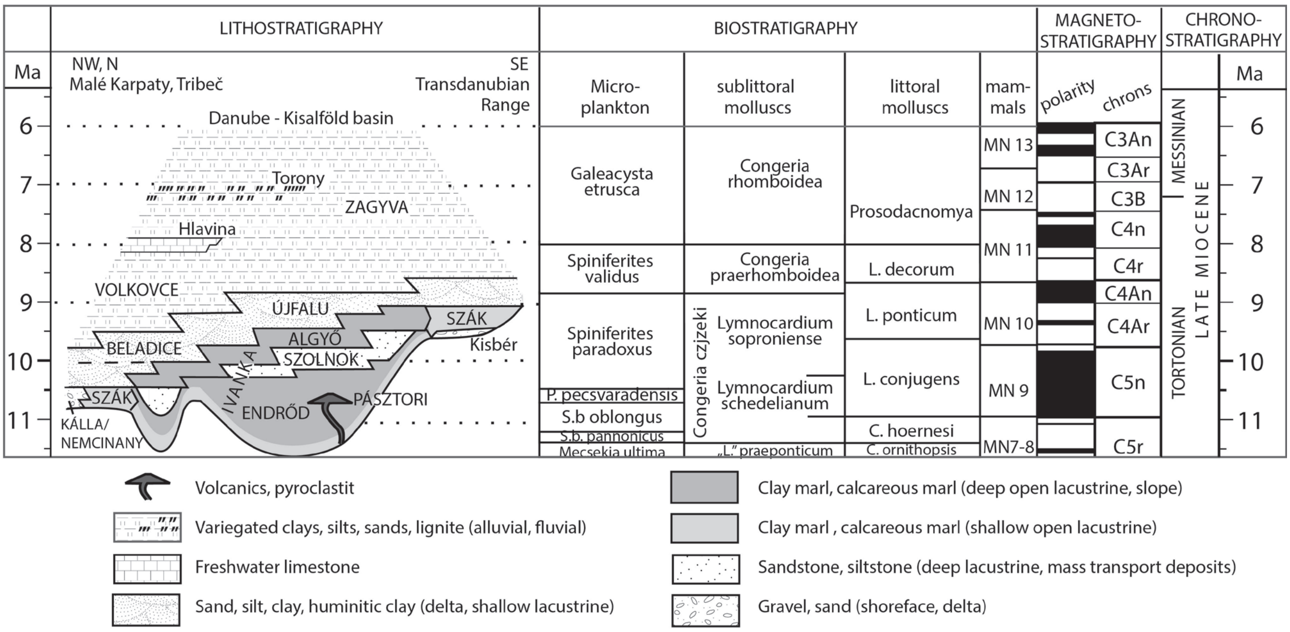

Fig. 2. Litho-, bio-, magneto- and chronostratigraphy of the Late Miocene sedimentary fill of the Danube/Kisalföld Basin.

in the sand layers of the formation (Magyar 1988). The species *Lymnocardium schedelianum, Congeria pancici, Unio atavus,* and *Melanopsis fossilis* indicate the upper part of the *Lymnocardium conjungens* littoral mollusc zone, which means an age of 9.5–10.5 Ma (Fig. 2).

In the eastern Komjatice Depression, the Nemčiňany Gravel was originally considered as part of the Volkovce Formation of early Pliocene age (Priechodská & Harčár 1988; Baráth & Kováč 1995). This assumption, however, contradicts both the interpretation of the depositional environment and new stratigraphic data. Biostratigraphic and magnetostratigraphic constraints from the ŠVM-1 Tajná borehole indicate the age of these deposits younger than 10.0 Ma (Kováč et al. 2006, 2008), while five authigenic $^{10}Be/^{9}Be$ ages point to deposition between 9.5 and 11.0 Ma (Šujan et al. 2016).

Depositional environments: The gravelly and gravelly to sandy occurrences with clinoforms are interpreted as locally-fed Gilbert-type deltas arriving into 10–30 m deep water along the margin of Lake Pannon (Sztanó et al. 2010; Tóth et al. 2010). Indications of fluvial transport and wave agitation are present in the topsets. The steep foresets were formed by grain avalanches, grain flows, and sandy debris flows with the common occurrence of sliding. Transport of coarse clastics was limited in the bottomsets, where decoupling of the suspended material occurs, therefore the Gilbert-type delta deposits interfinger with sublittoral clays (i.e. Szák Formation, Ivanka Formation) in a very short distance. Longshore currents may have transported part of the sand into embayments along the shore, where it was deposited on the shoreface (Budai et al. 1999; Babinszki et al. 2003). The somewhat larger bodies along the northern shore of Lake Pannon may have developed as fan-deltas. In these cases a structurally active basin margin and the lack of shallow shelf is supposed, therefore fan-deltas may have provided some clastics into the deeper part of the basin directly (e.g., Bernolákovo; Šujan et al. 2016).

Representative outcrops and boreholes: The Kálla and Nemčiňany Formations are exposed in gravel and sand pits along the western margin of the DKB between Weppersdorf and Lackendorf (Mostafavi 1978; Schmid & Tari 2015), near the boundary of the Sopron-Eisenstadt basin in the upper part of the gravel pit of Sopronkőhida-Piuszpuszta (Rosta 1993), and in the north-eastern margin of the DKB in the gravel pits of Volkovce, Nemčiňany, and Tajná. Important classical localities south of the DKB include Szentbékálla and Mindszentkálla (Magyar 1988) and Tapolca-Billege (Sztanó et al. 2010). From boreholes within the DKB these formations were reported either as a basal conglomerate of crystalline rocks above the Mihályi High (e.g., well Mihályi-22; Kőrössy 1987), or as coarse intercalations in the northern margin of the basin from the well Bernolákovo-1 (several layers between 1050 and 820 m; Šujan et al. 2016), and the Dubník-1 well (1250–1200 m) in the Želiezovce Depression.

Szák Formation/part of Ivanka Formation

Lithology, facies: The Szák Formation (Fig. 2) is made up of bluish grey silty clay marl. Occasionally it is laminated, but most commonly it is structureless. Very thin, lenticular sandy intercalations of a few mm may occur locally (Jámbor 1980). In the bottom of the formation, a 0.2–2 m thick sandy gravel occurs, with well-sorted and well-rounded pebbles, mostly quartzite (Jámbor 1980). The grain size of the sandy, gravelly beds rapidly decreases and they are sharply overlain by the clay marl. Along the SE margin of the DKB ("Tata Horst", western Gerecse Hills) well-rounded gravel derived from local Mesozoic carbonates also occur, some along eroded fault scarps with abrasional reworking. It is supposed that these are also interfingering with the basal layers of the clay marl. These coarse basal units were formerly referred to as the Kisbér and Diás Formations, respectively (Budai et al. 1999, 2008); they are now classified as the Kisbér Member of the Szák Formation. In well logs the Szák Formation appears as a homogeneous shale unit with high gamma-ray and low resistivity response.

Stratigraphic position, thickness: The thickness of the formation varies between 10–100 m, increasing basinward, but the average is less than 50 m. The formation unconformably overlies pre-Pannonian rocks. Towards the basin margins it may interfinger with locally-sourced coarse-grained deltas of the Kálla/Nemčiňany Formation. At the same places the Kálla Formation may serve as its stratigraphic cover as well. In basinward direction it interfingers with the Endrőd Formation. The separation of these two formations can be based on fossil content (more profundal forms in Endrőd), and on location within the basin. The Szák Fm. occurs above local basement highs, therefore even cm thick sandy intercalations are rare. Their stratigraphic position is also different: the Szák Clay Marl is covered by the shallow-water deltaic deposits of the Újfalu Formation, whereas the Endrőd Marl is overlain by the Szolnok or Algyő Formations.

An enigmatic situation occurs in well ŠVM-1 on the eastern margin of the Komjatice Depression, where a continuous transition between Sarmatian and Pannonian marls was documented by an endemic nannoplankton. An angular unconformity of 25° appeared ca. 30 m above the Sarmatian/Pannonian boundary. The fossils of the Pannonian marls indicate a relatively shallow depositional depth similar to the Szák Formation and are covered by the Nemčiňany Fm. (Kováč et al. 2008).

Fossils, age: The formation is rich in fossils. Endemic dreissenids (most commonly *Congeria czjzeki*, *C. ungula-caprae*, *C. partschi*), cardiids, and deep-water pulmonate snails (lymnaeids, planorbids) constitute the mollusc fauna. The ostracod assemblages are dominated by Candonidae (*Bakunella*, *Lineocypris*, *Serbiella*, *Camptocypria*, *Caspiocypris*, *Typhlocyprella*, *Zalanyiella*) and Leptocytheridae (Cziczer et al. 2009). As to fish, sciaenid otoliths and skeletal elements of percids were reported. Trace fossils (*Spirosiphonella*, *Minisiphonella*, *Diplocraterion*) are locally abundant. Endemic dinoflagellates, coccolithophorids and cosmopolitan green algae also occur (Kováč et al. 2006; Cziczer et al. 2009). The formation is usually rich in spores and pollen (Jámbor 1980; Korpás-Hódi 1983; Nagy 2005; Cziczer et al. 2009; Barna et al. 2010). In the DKB, this formation belongs to the *Congeria czjzeki* or *Lymnocardium soproniense* sublittoral mollusc zone and the *Spiniferites paradoxus* dinoflagellate zone (Sütő-Szentai 1991; Nagy et al. 1995; Cziczer et al. 2009; Magyar & Geary 2012). Magnetostratigraphic correlations suggest that its age in the western margin of the DKB is older than 9.7 Ma, whereas in the eastern margin it is 9.4–8.9 Ma (Magyar et al. 2007; Cziczer et al. 2009).

The calcareous nannoplankton (zones *Praenoelaerhabdus banatensis* and *Noelaerhabdus bozinovicae/N. jerkovici*) and magnetostratigraphic data (chrons C5r2r to C5n1n) from the ŠVM-1 well on the eastern margin of the Komjatice Depression and from the SE edge of the Malé Karpaty Mts. Ma-1 well in Bratislava dates the shallow open lacustrine deposits in the time span of ca. 9.9 to 11.6 Ma (Nagy et al. 1995; Kováč et al. 2006, 2008).

Depositional environments: The Szák Formation is an open-water lacustrine deposit, formed in non-agitated waters below storm wave base. Palaeoecology of sublittoral molluscs and other considerations (Cziczer et al. 2009) point to a depth of about 20–30 to 80–90 m. The formation marks transgression of Lake Pannon over elevated basement blocks, either along the shore or inside the lake, which were inundated later during the evolution. There is no significant clastic input other than muds from the interfingering coarse-grained deltas. The lack of coarse clastic intercalations of mass gravity flow origin confirms the relatively elevated position, where shelf-slope could not develop due to restricted water depth. The gravels at the base of the formation are of local origin, marking either the abrasion of rocky coasts, most probably controlled by faults (along the SE basin margin, in the western Gerecse Hills, Tata block etc.) or winnowing of older clastic sediments forming the substratum (i.e. Oligocene Csatka Formation; Jámbor 1980). Thus the Kisbér Member of the Szák Formation represents a transgressive lag, the large areal extension of which reveals the continuous retreat of the shoreline.

Representative outcrops and boreholes: Brickyard claypits in Sopron — Balfi-út (Balázs et al. 1981; Barna et al. 2010) in the western margin of the basin, and in Tata, Szák, Kisbér, Pápateszér, Bakonyszentlászló, Tapolcafő, Devecser along the eastern margin (Cziczer et al. 2009). Shallow boreholes along the eastern margin were analysed by Korpás-Hódi (1983). In the northern DKB, no outcrop occurrence can be correlated with the Szák Fm. A number of wells penetrated the succession formerly assigned to the Ivanka Fm., such as Tajná ŠVM-1, Bernolákovo-1, Diakovce-1, as well as Trakovice together with the Madunice well series in the Blatné Depression.

Endrőd Marl Formation/Lower part of Ivanka Formation

Lithology, facies: The lower part of the Endrőd Formation usually consists of calcareous marl and marl. Upwards the carbonate content decreases, the sediment becomes dark grey to light grey, laminated to structureless clay marl, alternating with mm to cm-thick siltstone interbeds. In the upper part of the formation, thin sandy intercalations may occur (Bardócz et al. 1987; Juhász 1994). Series of thin andesitic-trachytic tuff layers or altered tuffs are also reported in the DKB (Kőrössy 1987; e.g., in Tét-6; Fig. 3). In well logs, the upward decreasing carbonate content is reflected in a characteristic bell shape. The clay marl shows a rather smooth curve of high GR, positive SP, and low resistivity. The seismic facies of the formation is characterized by relatively continuous, moderate to high amplitude reflections.

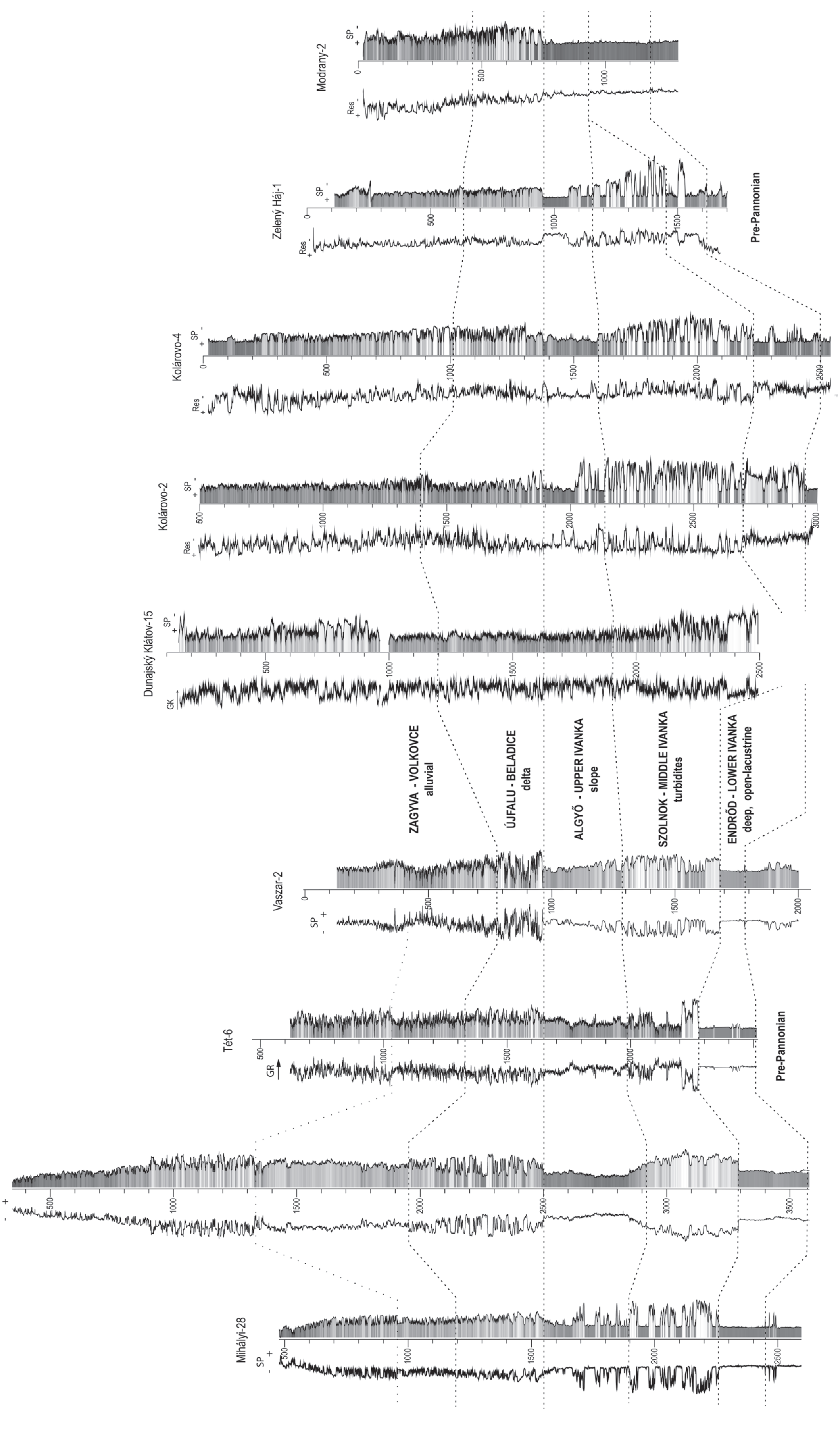

Fig. 3. Selected examples of well logs demonstrate the lithological character and variability of the formations. For location of wells, see Fig.1.

Stratigraphic position, thickness: The formation is supposed to develop continuously from Sarmatian marls only in the deepest parts of the basin (Zala Member; Gyalog & Budai 2004). Elsewhere it unconformably overlies pre-Pannonian rocks, therefore its base is commonly marked by onlaps on seismic profiles (Fig. 4). The calcareous marls are often mentioned as Belezna or Tótkomlós Members (Kőrössy 1987; Juhász 1994). In the deep basins, Endrőd Formation is overlain by turbidite sandstones of the Szolnok Formation or, above moderate basement highs, by the Algyő Formation. The transition towards the overlying deposits can be sharp or gradual depending on the appearance of turbidites. Its thickness varies between 50–400 m, with an average of 200 m. Over the basement highs its thickness is often below seismic resolution.

Fossils, age: The lowermost part of Endrőd Formation often contains a specific mollusc fauna with "*Lymnocardium" praeponticum, "L." cekusi, Radix croatica*, and *Gyraulus praeponticus*, indicating the *"Lymnocardium" praeponticum* Zone (Korpás-Hódi 1992). With the deepening of the water, a low-diversity profundal assemblage becomes dominant with *Paradacna abichi, Congeria banatica, C. partschi maorti, Velutinopsis sp., Undulotheca sp*. The age of the formation in the DKB spans from 11.6 to ca. 9.5 Ma. The intercalated tuff layers were related to the 11–10 Ma activity of the Pásztori Volcano (Harangi et al. 1995, 2015; Zelenka et al. 2004), which was an island in the middle of the basin (Fig. 5).

Depositional environments: The clay marls were deposited mostly in several hundred metre deep profundal waters of Lake Pannon. Above flooded basement highs, such as the Mihályi High, the colour of the marl is usually light grey (cf. Magyar et al. 2004). It is supposed that the oldest/lowermost beds were formed below wave base in sublittoral depth, but deepening occurred rapidly, and usually it is not possible to distinguish the sublittoral and profundal deposits in well data.

Representative outcrops and boreholes: The Endrőd Formation does not have a surface occurrence in the vicinity of the DKB. Calcareous marls at the base were reported from Vaszar-1 and Gönyü-1 (Kőrössy 1987), tuffs are common in Tét-6. The presence of Endrőd Marl in the northern part of the DKB is expected, but very little information about its distribution and composition is known. It was identified in well Kolárovo-4 (Fig. 3) and in nearby wells close to the foothills of the Transdanubian Range.

A 400 m thick succession with brackish fauna in the wells Nová Vieska-1 and Modrany-1 (Fig. 3) was considered by Šujan et al. (2016) as shallow water Szák-type mudstone according to fossil dinocysts (Baranyi et al. 2014). However, the thickness and location indicates a much deeper environment. Now it is suggested that these strata represent deep water marls followed by shelf-slope deposits, classified as lower and upper Ivanka Formation, equivalent to Endrőd and Algyő Formations, respectively, with redeposited fossils. Unequivocal interpretation of this issue is hampered by the absence of seismic sections in this area.

Szolnok Sandstone Formation/Middle part of Ivanka Formation

Lithology, facies: The Szolnok Formation comprises alternations of fine to very fine sandstone and siltstones/marls, with the dominance of sandstones. Graded beds, laminated to cross-laminated or convolute beds, as well as massive amalgamated sandstones occur. The sand-prone strata are interpreted mostly as turbidites. Bed thickness is highly variable, from a few cm to metres. Coarsening and thickening upwards series alternate with fining and thinning up ones. Thickness of the shale units is also variable (5–40 m). In well logs, the sandy character with respect to the under- and overlying muddy formations is spectacular. A few-metre-thick blocky and several-tens-of-metre-thick barrel-shaped units alternate (Fig. 3, Mihályi-28 and Tét-6). The thickness of these sand bodies is typically 10–50 m in the central part of the DKB and 80–180 m in the north (Fig. 3). Its seismic facies is also highly variable from low to high amplitude reflections with moderate continuity. Short reflections with downlaps or onlaps are common (Fig. 4). Because of the sandy composition, this formation is mentioned in old Slovak literature as the Great Lower Pannonian Sand (Vass 2002).

Stratigraphic position, thickness: The Szolnok Formation is always underlain by the Endrőd Marl and is overlain by the Algyő Clay Marl. The latter may also contain some (10–30 m thick) sandstone bodies in its lower part, so the boundary of the two formations can be gradual. Therefore, if depicted from well log data, the thickness of the Szolnok Formation is often overestimated. The characteristic thickness is only a few metres in the Csapod Trough. East of the Mihályi High it attains 300 m, and it onlaps and pinches out on the Endrőd Formation on the flank of the Transdanubian Range in the eastern part of the DKB (Fig. 4). In the central depression its thickness may exceed 1000 m (area of the Dunajská Streda-1 and Kolárovo wells, Fig. 3). Further to the north, above highs in the north-western side of the Ripňany-Galanta fault system, it is missing or very thin, whereas in the Rišňovce Depression it accumulated up to a thickness of almost 500 m, seemingly without accumulation of older deepwater marls, above the Sarmatian deltaic Ripňany Formation (Fordinál & Elečko 2000).

Fossils, age: The formation contains a typical, low-diversity deep-water assemblage of Lake Pannon molluscs with thin-shelled cardiids (*Paradacna abichi, Paradacna sp., "Pontalmyra" otiophora*), dreissenids ("*Dreissenomya" digitifera, Congeria banatica*), and deep-water-adapted pulmonate snails (planorbids and lymnaeids). Deposition of the formation is basically connected to the advance of the shelf-margin slope, thus it spans a relatively short time period between 10–9.2 Ma. Older (ca. 10.5 Ma) turbidite successions were detected only in the northernmost Rišňovce Depression (Šujan et al. 2016), where they form separate sandy units. On the other hand, turbidites related to the 9.5–9.2 Ma old slope probably deposited further to the south, as in the Zala Basin (Uhrin et al. 2009).

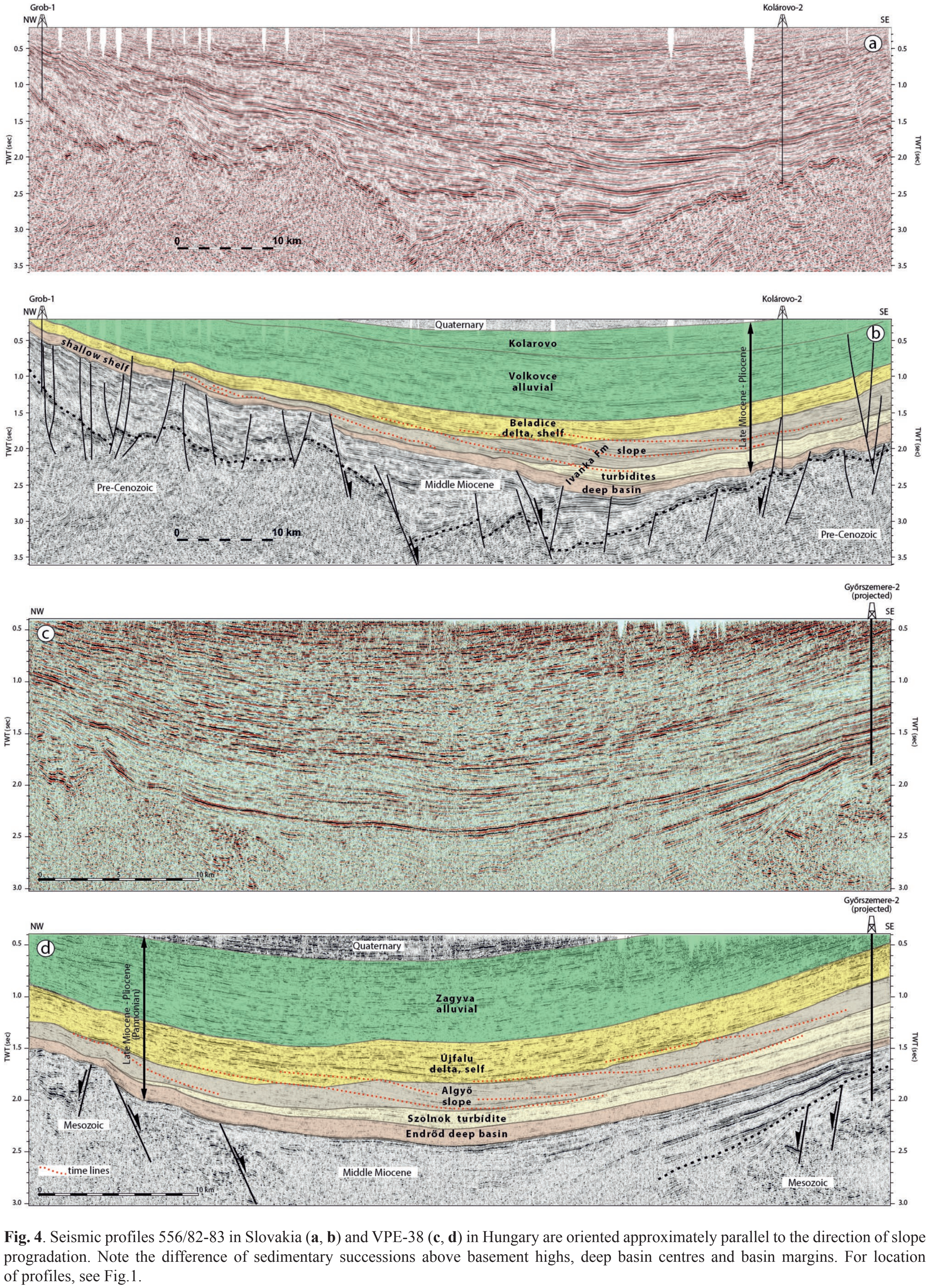

Fig. 4. Seismic profiles 556/82-83 in Slovakia (**a**, **b**) and VPE-38 (**c**, **d**) in Hungary are oriented approximately parallel to the direction of slope progradation. Note the difference of sedimentary successions above basement highs, deep basin centres and basin margins. For location of profiles, see Fig.1.

Depositional environment: Szolnok Formation was formed as part of an extensive turbidite system. Sediments arriving through the major fluvial feeder systems were partitioned between the deltaic lobes (Újfalu/Beladice Formation) on the shelf and the turbidite lobes in the deep basins. Locally sourced coarse-grained deltas (i.e. Kálla/Nemčiňany Fms.) did not contribute to the turbidite systems. The bulk of the sand spread in the form of large flat lobes far from the slope, indicating no or only minor confinement, as the centre of the DKB was large enough. The elongated troughs to the south, mostly parallel to the transport direction (i.e. slope progradation, cf. Uhrin 2011), might have produced lateral confinement. Some of the minor depressions, bounded by fault-related highs or volcanic edifices in downcurrent direction also might have acted as local sediment traps. This might have been the case of the Rišňovce Depression, where during a very short period of time a very thick turbidite succession was stacked in a neccesarily confined setting. Another interesting, probably confining, situation might have caused the deposition of ca. 800 m thick turbidite series in the Želiezovce Depression (Kolárovo wells, Fig. 3), where the prograding slope itself partly blocked the "entrance" to the elongated embayment surrounded by terrestrial to sub-lacustrine highs on three sides (i.e. 9.2–9.0 Ma shelf edge, Fig. 1).

Representative outcrops and boreholes: The Szolnok Formation does not have a surface exposure. Characteristic well logs include those of Mihályi-22, -28, Bősárkány-I, Vaszar-1-2, Gönyű-1, Kolárovo well series (1–4), Ripňany-1, Vráble-1 (Fig. 3, Šujan et al. 2016).

Algyő Formation/Upper part of Ivanka Formation

Lithology, facies: Dark grey clay marl, siltstone with sandy intercalations. Few to 10s of metres thick sandstones may occur near its top, but usually they are common in the lower third of the formation. The claystones are often thin bedded to structureless. Sandy-silty intercalations can be graded, laminated or cross-laminated. Convolution, soft-sediment deformation structures, sedimentary folds or cm-scale en-echelon faults may occur in cores pointing to turbidity currents, slides, slumps. In well logs, high gamma values, positive SP and low resistivity are typical. The log shape is smooth to finely serrated, the sand bodies appear as sharp peaks (Fig. 3). It is easy to identify Algyő Formation on seismic profiles (Fig. 4): it comprises clinoforms of 200–400 ms height, representing 300–630 m decompacted thickness (Balázs et al. 2015), which can correspond to the same water depth in the DKB. The dip angle of the original slope surfaces might have been 2–5°. The upper, steep portions of clinoforms usually show low amplitude, poor continuity seismic facies, while high amplitude, long reflections are common in their basal part.

Stratigraphic position, thickness: The Algyő Formation overlies the main turbidite bodies of the Szolnok Formation in the deep basins or the Endrőd Marl above the sub-lacustrine basement highs (e.g. Mihályi). The distinction between the Szolnok and the Algyő-type turbidites is commonly disputable; thickness of the sand bodies, sand/mud ratios, and the seismic character may offer a key (cf. Sztanó et al. 2013b), however that may depend on the rate of confinement among many other factors. It is also difficult to mark the Endrőd/Algyő boundary, although the appearance of thin sandstone bodies near the base of the Algyő Formation may help. The muddy Algyő Formation is overlain by the sandy Újfalu Formation; their boundary is fairly well constrained both lithologically and geometrically (Figs. 3 and 4). Although this boundary is widely and incorrectly referred to as the "Lower/Upper Pannonian boundary", it get consistently younger towards the S, SE and obviously has no chronostratigraphic meaning. Thickness of the Algyő Formation is smaller near the margins (150–250 m), and is larger (may attain 700 m) above the deepest depocentres in the DKB.

Fossils, age: Fossils of the formation represent low-diversity, deep-water mollusc assemblages of Lake Pannon. Typical forms include *Paradacna abichi, Paradacna sp., Congeria cf. czjzeki, Dreissenomya digitifera, Valenciennius sp*., and planorbid snails. The age of the formation within the DKB is estimated as 10–9 Ma (Magyar et al. 2000, 2007).

Depositional environment: This formation represents the shelf-margin slope bridging the few tens of metres deep shelf with the several hundred metre deep basins. Its progradation is related to the high clastic sediment input arriving via fluvial and deltaic feeder systems to Lake Pannon. Cyclic variations of sediment input and lake level influence the rate of slope progradation vs. aggradation (Uhrin & Sztanó 2012; Sztanó et al. 2013b). On the upper part of the slope, sand bodies related to shelf-edge deltas and sandy canyon-fills may occur. Towards the base of the formation, where inclination of the clinoforms is already low, simple turbidite lobes or sheets and chaotic slump units are common. More complex channel-levees to turbidite lobes might have developed a few tens of km in front of the slope; these can still be correlated to slope surfaces.

Representative outcrops and boreholes: The Algyő Formation does not have a surface exposure. Representative boreholes include Bősárkány-I, Vinár-1, Celldömölk-1, Tét-3, Tét-6, Gönyű-1, Mosonszolnok-1, Kolárovo well series, Zelený Háj-1. SE of the Mihályi High thin packages of turbidite sandstones deposited high on the slope (Fig. 3).

Újfalu Formation/Beladice Formation

Lithology, facies: The formation is made up of cyclic repetition of sands, silts, clays and huminitic to lignitic clays on two scales. Well logs display a series of 20–50 m thick coarsening upward units (Fig. 3), whereas in outcrops only 5–10 m thick coarsening upward and a few 1–5 m thick fining upward cycles can be observed. Mudstones contain shell beds, lenticular to thin-bedded intercalations of fine, very fine sands, small horizontal burrows and minor slump folds. Sandy beds show symmetrical and asymmetrical cross-lamination, various types of cross-bedding, vertical burrows, and clay-clast conglomerates over numerous erosional surfaces. All types of cycles are topped by organic rich, bio/pedoturbated or variegated silty beds. Higher up in the formation, the cycles become thinner, lithological heterogeneity and abundance of thick sandstones decreases and logs still reflect frequent alternations of various grain size. The seismic facies of the formation is characterized by moderate to high amplitude reflections with fairly good continuity (Fig. 4).

Stratigraphic position, thickness: The formation overlies the undifferentiated Ivanka Formation, or, in the more detailed Hungarian nomenclature, either the Algyő slope shales (above deep basins) or the shallow open-lacustrine Szák Formation (above sublacustrine basement highs). In the former case, the coarsening up cycles and the overlying muddy-silty strata are stacked up to a thickness of 300–500 m, whereas in the latter case, they are usually not thicker than 200 m. These thinner developments were formerly regarded in Hungary as the Somló or Tihany Member/Formation (Jámbor 1980, 1989; Sztanó et al. 2013a). The stratigraphic cover is everywhere the Zagyva/Volkovce Formation. It is not easy to pick the upper boundary as the upper delta plain and the alluvial plain might show similarly heterogeneous lithology. Commonly their boundary is assigned where the first large channel-fill sand bodies appear or where the brackish fauna disappears. Change in abundance of lignite layers is also indicative for this transition. In the southern part of the DKB, however, between the delta plain succession and the appearance of the large sandy channel bodies there is a 250–600 m thick muddy, silty interval with only subordinate thin sand beds (Fig. 3). Seismic correlation indicates that far to the south no slope can be related to this electrofacies. Therefore finally this interval is assigned to the Zagyva instead of the upper Újfalu Formation.

Fossils, age: The formation is rich in fossils representing diverse shallow-water and freshwater mollusc and ostracod faunas. The most common mollusc species include *Unio atavus, Congeria spathulata, C. pancici, Lymnocardium schedelianum, L. brunnense, L. conjungens, L. edlaueri, "L." desertum, Caladacna steindachneri*, *Melanopsis fossilis* in the western margin of the DKB ("Burgenland"), representing the *Lymnocardium conjungens* Zone. In the eastern margin (Transdanubian Range), *Unio mihanovici, Congeria simulans turgida, C. ungulacaprae, Dreissena auricularis, L. variocostatum, L. penslii, L. ponticum, Caladacna steindachneri, Euxinicardium schreteri, Melanopsis caryota*, etc. are the most characteristic species, representing the *Lymnocardium ponticum* Zone (Magyar et al. 2000). The oldest occurrence of the formation within our study area had a Carpathian source area (possible palaeo-Nitra river) and, according to $^{10}Be/^{9}Be$ dating, might be as old as 10.0–10.5 Ma (Šujan et al. 2016). The bulk of the formation, however, was deposited on the palaeo-Danube shelf (cf. Magyar et al. 2013) between ca. 10 and 8.7 Ma (Magyar et al. 2000). On the foothills of the Malé Karpaty Mts., mammal fauna from the Pezinok clay pit indicates MN9 to lower MN10 biozones with expected deposition in the age range 9.5 to 10.5 Ma (Kováč et al. 2011; Joniak 2016; Šujan et al. 2016).

Depositional environments: The Újfalu/Beladice Formation was formed by the progradation of deltaic lobes on the shallow shelf of Lake Pannon. This interpretation was first proposed by Mucsi & Révész (1975) in the Algyő hydrocarbon field in the central part of the Pannonian Basin. Later descriptions, however, identified the formation with the delta-plain deposits only (e.g., Juhász 1992; Juhász & Magyar 1993). The Somló and Tihany Members were originally considered as local sand bodies on coasts of islands rather than parts of a major deltaic feeder system (Jámbor 1989). Return to the delta concept of Mucsi and Révész (1975) was partly a consequence of high-resolution seismic studies in Lake Balaton (Sacchi et al. 1999) and correlation of the high-resolution seismic profiles with nearby outcrops (Sztanó & Magyar 2007). The major coarsening up units comprise prodelta shales, delta front sands and reflect the lithological variability of the delta plain. The thickness of such cycles mirrors the water depth at the place of deposition as 20–50 m on the shelf. Their stacking indicates repeated flooding of the shelf and recurring progradation of deltas, an overall rise of lake level due to subsidence and climatic factors. Minor units are mouth bars, interdistributary bay fills or distributary channel fills. Some incised valleys may also occur to a depth of 20–30 m, pointing to base level drops below the resolution of industrial seismics (Sztanó et al. 2013a).

Representative outcrops and boreholes: The formation has a general distribution in the entire DKB. Outcrops are located along the present-day basin margins: from Pezinok (Baráth et al. 1999) through the region of Lake Neusiedl/Fertő-tó as far south as Stegersbach (Magyar et al. 2000) in the western margin, and from Chlaba in the north to the Somló Hill in the south along the eastern margin (Strausz 1942; Bartha 1963; Szilaj et al. 1999; Magyar et al. 2000; Bartha et al. 2015). All deep boreholes in the basin have penetrated the Újfalu/Beladice Formation, from Bratislava (Fordinál 1995) to the Transdanubian Range (Korpás-Hódi 1983).

Zagyva Formation/Volkovce Formation

Lithology, facies: Zagyva/Volkovce Formation is characterized by 4–8 m thick cross-bedded sandstones, usually comprising fining-upward units, which alternate with m- or 10-m scale silt and clay sections. Some of the sandstones are amalgamated into 10–20 m thick bodies. The clay beds are partly variegated, and may contain carbonatic nodules. Cm- to dm-scale lignite seams occur subordinately. Lithology within the formation is highly variable, because floodplain deposits can locally dominate over several hundred metres of stratigraphic thickness, whereas in other parts of the basin (e.g., southern Želiezovce Depression) the formation is composed of up to 60 % sandy channel belt sediments. Locally, alluvial fans were formed by rivers entering the basin, with an example located in the northern Blatné Depression. This alluvial fan consists of up to 100 m thick gravels gradually passing towards the south to the dominantly clayey succession of a meandering river. The electrofacies character is spatially heterogeneous, a consequence of uneven channel belt distribution. The stacking of several upward fining and blocky 8–15 m thick units usually alternate with long sections of low amplitude serrated trends (Fig. 3). Freshwater limestones of the Hlavina Member appear on margins of the recently uplifted Považský Inovec and Tribeč Mountains and interfinger smoothly through calcareous clays with the mainly floodplain fines dominated Volkovce Fm. (Fordinál & Nagy 1997; Kováč et al. 2011). From the western margin towards the central parts of the DKB a series of stacked lignite seems occur, which were locally called the Torony Member (Jámbor 1980).

Stratigraphic position, thickness: The Zagyva/Volkovce Formation overlies, and interfingers with, the Újfalu/Beladice Formation. The transition is gradual, thus it is difficult to pick the exact position of the boundary. The thickness of the formation may attain 1500 m in the area of the basin centre; it is especially thick in the northern part of the DKB. In the central and southern part of the basin deposition of the Zagyva/Volkovce Formation continued through the Pliocene and is overlain by Quaternary fluvial deposits. The stratigraphic boundary is usually marked by the appearance of gravelly beds (Janáček 1971; Kőrössy 1987; Gábris & Nádor 2007; Kováč et al. 2011). In the "Little Hungarian Plain Volcanic Field" (Martin et al. 2003), latest Miocene to Pliocene volcanic bodies of the Tapolca Basalt Formation occur locally above or within the Zagyva/Volkovce Formation. In the northern part of the basin, a significant stratigraphic gap was demonstrated between the Zagyva/Volkovce Formation and the overlying Pliocene Kolárovo Formation. The unconformity is not exposed in outcrops, but the log response of the under- and overlying formations is sometimes sharply different. At such localities the rather fine-grained floodplain succession of the Zagyva/Volkovce Fm. does not show pronounced grain-size variations, whereas the alluvial suit of the Kolárovo Fm. often appears as a lithologically variable unit with dominance of channel fills. In the Kolárovo Fm. blocky to fining up channel bodies alternate with less frequent serrated floodplain fines, reflecting alternations of thin clay, silt and sand layers. Variegated and reddish colours are typical for the Kolárovo Fm. and probably resulted from erosion of the uppermost Volkovce Fm., which was deposited during the more arid Messinian times (Böhme et al. 2011).

Fossils, age: The formation contains freshwater and terrestrial molluscs, such as *Margaritifera flabellatiformis*, various species of *Unio, Planorbarius, Bythinia, Melanopsis, Theodoxus,* etc. (Halaváts, 1925). Mammal remnants representing MN11 to MN14 are relatively common (Gasparik 2001; Kováč et al. 2006, 2010; Tóth 2010; Pandolfi et al. 2016). Authigenic $^{10}Be/^{9}Be$ ages obtained from the Volkovce Fm. range from 10 Ma up to 6 Ma (Šujan et al. 2016). The Hlavina Freshwater Limestone, important as a correlative horizon in the Volkovce Fm., was dated using small mammals to ca. 8.0 Ma (Kováč et al. 2010). The age of the lignite-bearing Torony Member within the Zagyva Formation is 7.3–6.7 Ma. Note that this interval equals the age of the lignite-bearing Bükkábrány Member of the Újfalu Formation, which occurs in the NE part of the Pannonian Basin (foothills of the Mátra, Bükk region and the Eastern Great Plain, Juhász et al. 2007; Magyar 2010).

Depositional environments: Alluvial plain with meandering or anastomosing channels (cf. Uhrin & Sztanó 2007; Uhrin et al. 2011), which discharged into the Újfalu/Beladice delta system along the shore of Lake Pannon. The sandstones represent channel fills, while thin beds of sand, silt and clay were deposited on the floodplains. Variegated clays and carbonate nodules are interpreted in terms of palaeosols, suggesting sustained periods of subaerial exposure under relatively arid conditions. The extended lignite seams have been formed in floodplain ponds and marshes, and mark a more humid period at about 7 Ma ago (Magyar 2010; cf. Böhme et al. 2011). Connected lake-level rise influencing deposition in the Drava Basin and the eastern part of the Great Plain area did not reach directly the DKB. A rise of the ground-water table, however, might have resulted in development of an extended floodbasin. The "channel-poor" portion of the Zagyva/Volkovce Formation might coincide with this stage. The relatively fine grained composition of the formation continues up to the youngest strata (ca. 6 Ma) in the northern part of the DKB, what indicates no changes in sediment supply and therefore no significant tectonic activity on basin margins. Hlavina Freshwater Limestone was formed along marginal faults of the mountains, suggesting enhanced spring activity connected to Mesozoic karstic aquifers.

Representative outcrops and boreholes: The formation has a large number of outcrops, especially in the northern part of the basin. This is a result of denudation connected with basin inversion. Outcrops are mostly artificial sandpits, representing channel fills, whereas floodplains are exposed less frequently. Important outcrops include Hlohovec, Bernolákovo (Blatné Depression), Veľké Ripňany (Rišňovce Depression), Semerovo, Veľké Lovce and Bátorove Kosihy (Želiezovce Depression) in the northern part of the basin. It also crops out at the elevated Pannonhalma area and a few locations along the SE margin of the DKB (i.e. Hosszúpereszteg; Balázs et al. 1981). Typical borehole sections include, for instance, Abrahám-1, Diakovce-1, Kolárovo-2, Mosonmagyaróvár K-136, Abda K-12, Bősárkány-I, Bük-1, Csapod-1, Gönyü-1, Tét-6. The alluvial fan in the northern Blatné Depression is penetrated by the counterflush well series Piešťany and Bučany.

Basin evolution

Structural background

The onset of Late Miocene sedimentation might have been preceded by latest Sarmatian basin inversion, an idea long thought to be supported by the lack or very thin development of Sarmatian sediments in the southern part of the DKB (Kőrössy 1987; Horváth 1995). However, there are examples along the western (Rosta 1993) and northern basin margin (Kováč et al. 2008) that the Sarmatian and Pannonian sequences are continuous. Locally Sarmatian strata reach a thickness of up to 300–400 m (Adam & Dlabač 1961; Vass et al. 1990; Kováč et al. 2011). Continuous Sarmatian to Pannonian sequences were also observed in the southernmost DKB and Zala Basin (Fodor et al. 2013b).

The origin of the Late Miocene subsidence and basin formation is still a matter of debate. In one view the major subsidence of the basin can be attributed to a crustal-scale process and not mainly to basin-margin faulting. This interpretation is confirmed by the relatively uniform thickness of several formations, and by the fact that the Late Miocene basin evolution followed crustal faulting of the syn-rift phase of ca. 19–11.6 Ma and largely represents a post-rift thermal cooling episode (Royden et al. 1983; Vass et al. 1990; Lankreijer et al. 1995; Kováč & Baráth, 1996; Kováč et al. 2010, 2011; Horváth et al. 2015; Majcin et al. 2015; Hók et al. 2016). Other processes, like magmatic underplating could also play a role (Konečný et al. 2002). Localized (flexural) subsidence due to sediment loading contributed to the deepening of the central zone of the basin as well (Lankreijer et al. 1995).

Middle Miocene basin subsidence occurred in a simple shear regime in the upper crust (Györfi 1992; Tari et al. 1992; Lankreijer et al. 1995; Hók et al. 2016). Re-evaluation of biostratigraphy, palaeoecology and sedimentology of deep borehole cores in the northern part of the DKB suggest that accommodation was filled up in the Sarmatian in most places (Rybár et al. 2015; Kováč et al. in review). This may imply that the rapid deepening of several depressions (e.g., Komjatice and Gabčíkovo-Győr Depressions) at the beginning of the Pannonian can represent a new rifting phase acting in a pure shear regime — an idea that is supported also by the results of thermal modelling (Majcin et al. 2015). In the interpretation of Tari (1994) it was probably a "wide rift stage", when earlier distributed syn-rift faulting concentrated into a few fault zones in the northern and southern parts. An increasing number of documented Late Miocene faults support the idea that faults also contributed to basin subsidence, although their displacement remained modest, not reaching 500 m separation. Such faults influenced sedimentation and deposition pattern (see below).

Fault kinematics varied from normal to transtensional strike-slip (mostly sinistral oblique-slip) although it can mostly be deduced from outcrop-scale fault-slip data (e.g., Fodor 1991; Vojtko et al. 2011; Sipos-Benkő et al. 2014; Klučiar et al. 2016). Stress calculations would suggest E–W to SE–NW tension although it is not clear if the different values indicate spatial or temporal variations (see Marko et al. 1995; Fodor et al. 1999; Hók et al. 1999; Marko 2012; Sipos-Benkő et al. 2014, Kovács et al. 2015). The Late Miocene extensional tectonic regime with NW–SE directed Sh_{min} persisted in the northern part of the basin up to the Middle Pleistocene.

Basin-fill history

During deposition of the earliest Late Miocene sediments (i.e. Endrőd/Lower Ivanka Formation in the basin centres) continued subsidence was "inherited" from the syn-rift phase (or renewed subsidence in case of Sarmatian inversion) at about 11.6 to 10.5 Ma ago. In the Gabčikovo-Győr Depression a notable displacement and tilting was documented along the Ripňany-Galanta fault system (e.g., Hrušecký 1999; Bielik et al. 2002; Kováč et al. 2011; Synak 2013; Kronome et al. 2014). Continuing fault control at Mihályi High is probable (see Fig. 5). The subsidence history in the northernmost area, namely the Rišňovce Depression, is surprisingly long (Figs. 2 and 5). It seems to be continuous with deep water clays and with the occurrence of the oldest turbidites, which, however, might have been confined by the mid-Miocene Kráľová volcano and the southern tip of the Tribeč block, as local highs. In the same way the oldest deltas of the Beladice Formation fed by northerly rivers are recorded. Synak (2013) recognized significant activity of the Ripňany-Galanta fault (Bielik 2002) during deposition of lowermost Pannonian strata using seismic stratigraphy. This fault probably contributed to subsidence of the Rišňovce Depression. The angular unconformity within Ivanka Fm. (Tajná ŠVM-1 well) probably represent an early Pannonian fault activity (Kováč et al. 2008) which resulted in diversified lake bottom morphology.

Development of the Szák and Kálla/Nemčiňany Formations was a consequence of a lacustrine base-level rise. Flooding of the northern–north-eastern margin about 11 Ma ago and inundation of the western basin margin ca. 10.5 Ma ago was probably the joint effect of a climatically induced lake-level rise and overall subsidence. In addition, the Kálla/Nemčiňany Formation clearly indicates the existence of a fault-related lake margin relief, however small the fault offset might have been. Such faults were detected near the Sopron Hills in the west (Vendel 1973; Fodor et al. 1989; Fodor 1995), and based on other evidence along the Gerecse Hills in the east (Fodor et al. 2013a). In contrast to the overall deepening and transgression, the locally sourced Gilbert-type deltas led to normal regression of the shoreline within a short time (cf. Sztanó et al. 2010), while deposition of the Endrőd Formation continued in the deep basin centres (Fig. 5).

About 10 Ma ago, or shortly before, the palaeogeography significantly changed: the main fluvial feeder system (i.e. the palaeo-Danube and its major distributaries) entered the DKB from the W-NW, and the sediments accumulated partly in large delta systems. Where water depth was less than 100 m (i.e. areas where formerly the Szák Formation was deposited) prograding deltas filled accommodation rapidly, while towards the area of the deep basin centres a shallow shelf was constructed (Magyar et al. 2007, 2013). Progradation of the shelf-margin slope resulted in the formation of the Algyő/Upper Ivanka Formation, and deposition of turbidite sandstones (Szolnok/Middle Ivanka Formation) at the toe-of-slope and in the basin proper (Fig. 5). Meanwhile the confined northern Rišňovce Depression was filled up as well, therefore turbidity currents may have "escaped" to the deepest parts of the basin to the south (Dunajská Streda area). Finally, deltas of the north dumped their sediments into the central depression as well approximately 9 Ma ago (Šujan et al. 2016).

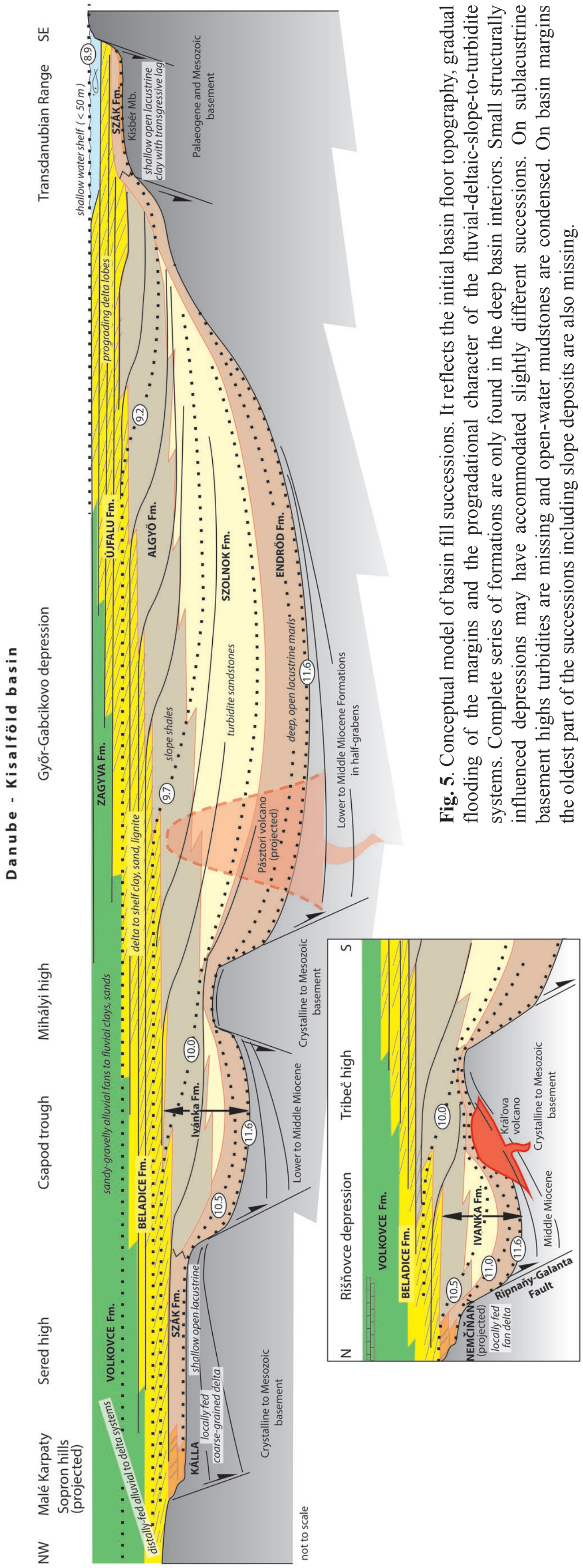

Fig. 5. Conceptual model of basin fill successions. It reflects the initial basin floor topography, gradual flooding of the margins and the progradational character of the fluvial-deltaic-slope-to-turbidite systems. Complete series of formations are only found in the deep basin interiors. Small structurally influenced depressions may have accommodated slightly different successions. On sublacustrine basement highs turbidites are missing and open-water mudstones are condensed. On basin margins the oldest part of the successions including slope deposits are also missing.

The shelf-slope generally prograded towards the SE until the elevated block of the Transdanubian Range deviated the transport to the south. The blocking and ultimate confinement is also indicated by the thick accumulation of turbidite sands in the Kolarovo area. The later development of the slope and transport direction of turbidites was turned towards the local depocentres often controlled by minor fault activity (Uhrin et al. 2009; Törő et al. 2012). For example, modest displacement and tilting along the Mihályi High clearly diverted slope progradation parallel to the elongated high (Uhrin 2011; Fodor et al. 2013a). Flexural subsidence due to sediment loading continuously contributed to deepening in front of the prograding shelf-slope system, thus created ample space for the accumulation of turbidites. Eventually the same flexural subsidence resulted in the progressive (and gradual) flooding of the south-eastern, Transdanubian Range basin margin ca. 9.2 Ma ago. Limited faulting locally contributed to subsidence (e.g. western Gerecse margin). Faulting was maintained even during delta sedimentation a few 100 ka later; tilted and raised fault blocks locally deflected sediment transport to N-NE, thus delta channels and lobes got around the block of Gerecse instead of passing straight though it (Bartha et al. 2015).

Progradation of the fluvial to delta to shelf-slope system led to a long term normal regression (Sztanó et al. 2013b), as the shelf edge and delta fronts gradually shifted to the south. Regardless of the original topographic differences, basin floor morphology, structural evolution etc. the DKB got filled up by ca. 9 Ma within the *Congeria czjzeki* and *L. ponticum* biochrons (Magyar 2010). Afterwards only fluvial sedimentation occurred, most likely influenced by compactional subsidence and potential prolonged fault activity. By 8.6 Ma the feeder system overcame the mostly flooded Transdanubian Range and the shelf margin was located far to the south (Magyar et al. 2013).

The Late Miocene sedimentary fill of the DKB is similar to that in other parts of the Pannonian Basin System. It hosts one of the thickest successions in the basin centre with all five lacustrine formations representing deep-water marls, turbidites, slope shales, deltas to fluvial deposits. There are also internal highs and large marginal areas with less complete successions, reflecting later flooding or filling up of only shallow water depth in Lake Pannon. As the basin margins got uplifted during the Pliocene to Quaternary inversion these latter types can be studied at several locations. The DKB was large enough to develop good examples of different rates of turbidite confinement or to demonstrate how basin floor morphology influenced slope progradation. The basin-fill succession, however, is unique in a sense that it is the first major basin along the NW feeder system to be filled in the history of Lake Pannon, thus all the formations, which developed everywhere else later in the Pannonian Basin are the oldest in the DKB. Part of the fluvial feeder system is also special as alluvial fans occur along the northern basin margin. Except for the rapidly subsiding basin centre, overall water depth might have been less than 100 m over vast NW areas and only a few hundreds of metres in the southern parts, therefore slope progradation and overall regressive filling up of the large DKB occurred rapidly, during less than two millions year (Magyar et al. 2013).

Conclusions

In spite of the significant local differences in the structural background of the individual depressions and basement highs, the overall basin fill history and thus the sedimentary successions are uniform across the Danube/Kisalföld Basin, allowing a robust correlation of the formation from S to N or W to E. The Hungarian lithostratigraphic system is more detailed, closely reflecting the depositional systems, therefore it can be easily integrated into the Slovak system which, in turn, does not discriminate between various deep-water deposits. The most important aspect of correlation is that all formations are time-transgressive, which means that their boundaries cannot be characterized with a single precise datum even within the DKB (Fig. 2).

Late Miocene lacustrine sedimentation started where the basin deposits are deepest today with deposition of the Endrőd Marls, corresponding to the lower Ivanka Formation. At about 10.5 Ma ago several marginal highs were flooded, and the shallow offshore Szák Formation and the coarse-grained deltas of the Kálla/Nemčiňany Formations were deposited. These small volume, locally derived clastics were soon overlain by the enormous fluvial input from the N-NW, indicating the commencement of long term normal regression. Turbidite systems (Szolnok/middle Ivanka Fm.) and shelf-margin slope (Algyő/upper Ivanka Fm.) formed in the several hundred metre deep basin, while deltas (Újfalu/Beladice Fm.) developed on the few tens of metre deep shelf, being fed by different fluvial systems (Zagyva/Volkovce Formations). The turbidite systems rapidly spread all over the deep basin floor with different rates of confinement. Except for the northernmost, oldest occurrences there is not much age difference within the turbidites (10.5–9.5 Ma). With the gradual progradation of the shelf-margin slope towards the S and SE between 10 and 9 Ma, each formation became increasingly younger in the same direction. After 9 Ma only the alluvial Zagyva/Volkovce Formation was deposited in the DKB. In the northern part of the basin a major unconformity is recorded at about 6 Ma, marking a significant change in the style of alluvial deposition. In the central part of the basin (Győr-Gabčíkovo Depression), however, deposition was uninterrupted until the Quaternary as a consequence of continued subsidence. These long lasting fluvial systems acted as sediment conduits and recorded climatic and structural events until the entire Pannonian Basin was filled up with sediments.

Although confined in space and time, the lacustrine to fluvial sedimentary fill of the Danube/Kisalföld Basin offers a model of depositional system development and formation distribution for the entire Late Miocene to Pliocene Pannonian Basin system.

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