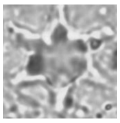
Neogene changes in palaeogeography, palaeoenvironment and the provenance of sediment in the Northern Danube Basin

Samuel Rybár, Michal Kováč, Katarína Šarinová, Eva Halásová, Natália Hudáčková, Michal Šujan, Marianna Kováčová, Andrej Ruman & Tomáš Klučiar



The Danube Basin is situated between the Eastern Alps, Central Western Carpathians and Transdanubian Range. The northwestern embayment of the basin is represented by the Blatné depression with deposits ranked into the Langhian–Serravallian (Badenian, Sarmatian) and Tortonian–Pliocene (Pannonian–Pliocene). They are documented by the NN4, NN5 and NN6 calcareous nannoplankton zones; the CPN7 and CPN8 foraminiferal zones (equivalent to N9, N10 and N11 of global foraminiferal zones and to the MMi4a, MMi5 and MMi6 of Mediterranean foraminiferal zones) and by the mammalian zones MN9, MN10, MN13 and by Be isotopes. Sedimentation in basin began with basal conglomerates formed by local fan-deltas short before and during the initial rifting phase. Early Langhian conglomerates are composed of Mesozoic rocks derived from the sedimentary cover and nappe units of the Eastern Alps and Central Western Carpathians. The content of crystalline rocks increases upwards, which documents a continual denudation of the emerged source area (at present forming the pre-Neogene basement of the Danube Basin). The middle to late Langhian synrift stage of the basin development was accompanied by volcanic activity. Gravity transport of sediment took place on the basin slopes formed by pronounced fault activity. The basin floor reached the deep neritic zone. During the early Serravallian shelfal offshore sedimentary conditions prevailed and gradually passed into the late Serravallian regressive coastal plains with normal to brackish salinity. Tortonian transgressive sedimentation on the muddy shelves of Lake Pannon followed and was subsequently replaced by a relatively short-living deltaic environment and later by deposition on an alluvial plain. Final Pliocene to Quaternary fluvial sedimentation is characterized by gravel and sand beds. • Key words: Neogene, biostratigraphy, sedimentology, depositional systems, provenance of clastics, palaeogeography.

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Samuel Rybár (corresponding author), Michal Kováč, Eva Halásová, Natália Hudáčková, Michal Šujan, Marianna Kováčová, Andrej Ruman & Tomáš Klučiar, Department of Geology and Paleontology, Faculty of Natural Sciences, Comenius University in Bratislava, Mlynská dolina, Ilkovičova 6, 842 15 Bratislava, Slovakia; samuelrybar3@gmail.com • Katarína Šarinová, Department of Mineralogy and Petrology, Faculty of Natural Sciences, Comenius University in Bratislava, Mlynská dolina, Ilkovičova 6, 842 15 Bratislava, Slovakia

The presented study follows the previous research of Rybár *et al*. (2015) and is based on re-evaluation of the deep petroleum wells drilled in the Blatné depression of the northern Danube Basin. All wells were re-analysed by modern biostratigraphical, palaeoenvironmental, sedimentological and petrological methods with a special focus on provenance analysis. The key wells Trakovice-1 and Trakovice-4 penetrated the Miocene sedimentary record in the thickness of 1510 to 1600 m and were analysed in high resolution. The results were additionally crosschecked with data obtained from the Ratkovce-1, Špačince-5 and Krupá-5 wells. The Trakovice-1 (48° 26´ 31˝ N, 7° 43´ 19˝ E), Trakovice-4 (48° 25´ 13˝ N, 17° 42´ 31˝ E; Fig. 1), Ratkovce-1 (48° 28´ 9˝ N, 17° 43´ 23˝ E), Špačince-5 (48° 29´ 28˝ N, 7° 37´ 38˝ E) and Krupá-5 (48° 30´ 55˝ N, 17° 31´ 16˝ E) wells were drilled in the late 60s and 70s of the last century and were technically documented in well reports by Gaža (1963, 1965, 1968). The cores were collected in selected depth levels (spot samples) within the Langhian and Serravallian (Badenian) stage and from the pre-Neogene basement. The Late Miocene to Quaternary development of the study area had already been compiled in the past by using shallow and moderately deep structural wells with a total depth range of 300 to 600 m. However, existing analyses of these wells were not satisfactory. Therefore, the presented study contains a reinterpretation of counter-flush well data, which improve the definition of the Upper Miocene and Pliocene depositional systems and also the associated palaeoenvironments (*sensu* Kováč *et al.* 2010, 2011).

Geological setting

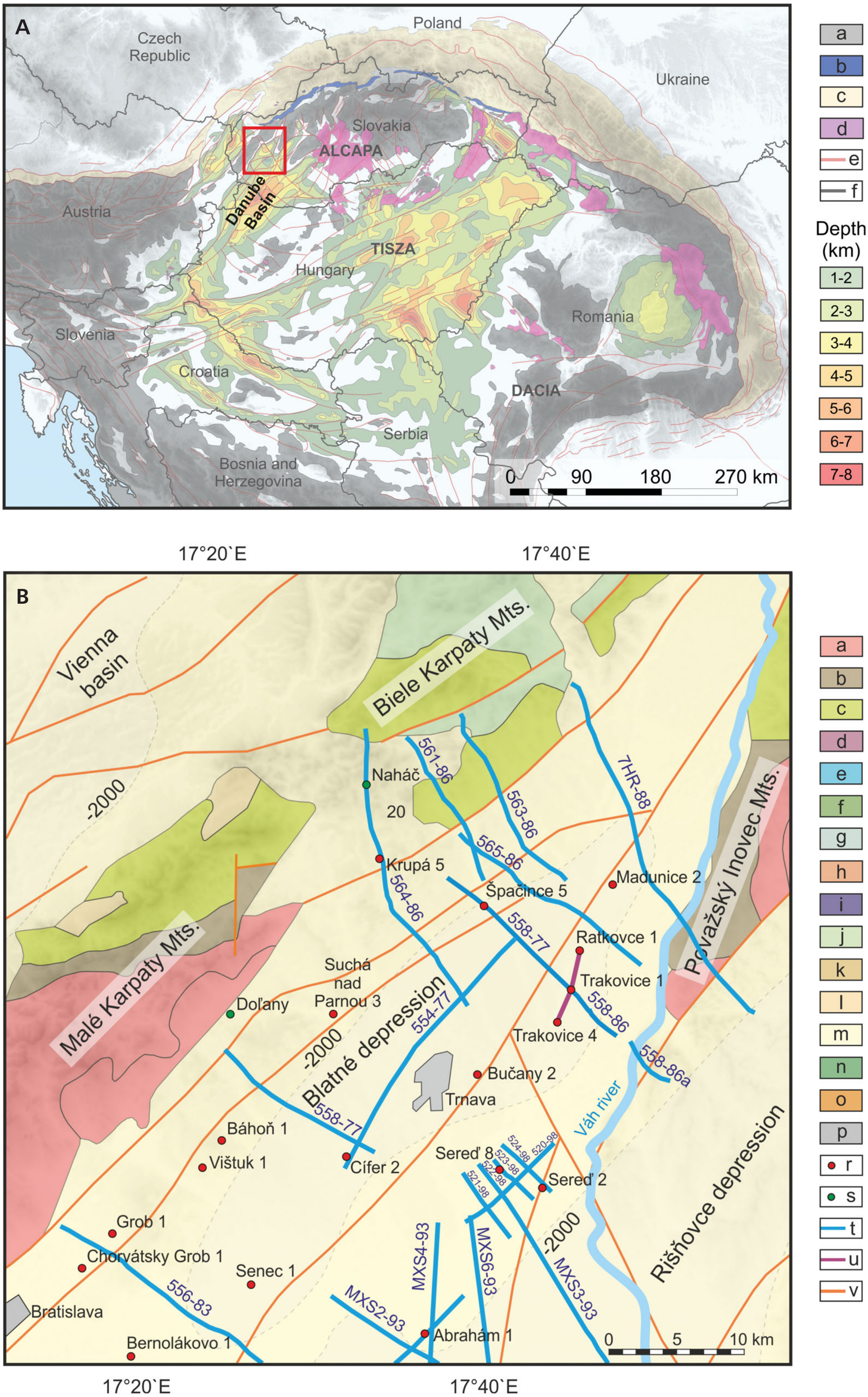
The Danube Basin is situated between the Eastern Alps, Western Carpathians and Transdanubian mountain range. The northern margin of the basin is represented by three branches from west to east known as: the Blatné, Rišňovce and Komjatice depressions with Middle to Upper Miocene-Pliocene fill. The study area – the Blatné depression – is located between the Malé Karpaty Mts in the west, and Považský Inovec Mts in the east (Fig. 1). The pre-Middle Miocene basement of the depression (sub-basin) is formed by the Western Carpathian crystalline complexes, Mesozoic cover and nappe units, and rare Paleogene to Lower Miocene strata occurring only in the northernmost part (Fusán *et al.* 1987). The Trakovice-4 well reached Mesozoic carbonates and the Trakovice-1 well penetrated alternating Mesozoic carbonates and Permian arkoses (Gaža 1965, 1968; Biela 1978).

The Middle Miocene sedimentation in the northern Danube Basin started during the earliest Langhian (Karpatian–earliest Badenian, according to Špička & Zapletalová 1964). In the late Langhian and early Serravallian (Lower and Upper Badenian) rifting followed and was in close relation to the asthenospheric bulge which developed in the hinterland of the Carpathian arc – in the Pannonian domain (Lankreijer *et al.* 1995, Konečný *et al.* 2002). The Langhian Špačince and Báhoň formations were formed by shallow to deep marine deposits (Vass 2002). Subsequently, a gradual transition to sedimentation of the brackish Vráble Formation (Vass 2002, Kováč *et al.* 2007) followed in the late Serravallian (Sarmatian). The Middle Miocene transtensional to extensional tectonic regime (Tari *et al.* 1992, Horváth 1995, Kováč 2000, Horváth *et al.* 2006) was replaced by thermal subsidence during the late Tortonian (Pannonian). The Late Miocene lacustrine sediments of Lake Pannon (Magyar *et al.* 1999) are represented by the Ivánka Formation and swamp deposits of the Beladice Formation (Vass 2002). By the end of the Late Miocene, alluvial Volkovce Formation was deposited and was occasionally overlain by the Pliocene to Pleistocene deluvial to alluvial Kolárovo Formation (Kováč *et al.* 2011). Isopach maps of the basin sedimentary fill were elaborated by Adam & Dlabač (1969), and the selected well data were later summarized by Biela (1978) without revision of sedimentology and only with scarce refining of existing biostratigraphy. Reinterpretations of older geophysical data were carried out in the past by Hrušecký *et al.* (1993, 1996, 1999). Complex studies aimed on palaeogeography, geodynamic evolution, and sequence stratigraphy of the Carpathian-Pannonian region during the Miocene were published by Kováč *et al.* (1998) and Kováč (2000). The Miocene landscape, palaeoclimate and palaeoflora were analysed in papers of Kvaček *et al.* (2006) and Kováč *et al.* (2006, 2011). Integrated stratigraphy of the Central Paratethys was enriched by Andrejeva-Grigorovič *et al.* (2001, 2003), Harzhauser *et al.* (2007), Harzhauser & Mandič (2008) and Hohenegger *et al.* (2014).

Material and methods

The well core material was obtained in a repository of the Nafta a.s. petroleum company situated in Gbely town (Slovakia). For the micropalaeontological analysis, 74 rock samples from the Trakovice-1 well were compared with 14 samples from the Trakovice-4 well, 24 samples from the Špačince-5 well and with 18 samples from the Krupá-5 well. All samples were collected and processed by standard preparation methods (for details see Kováčová & Hudáčková 2009). To obtain foraminiferal assemblages, 100 g of rock sample was diluted in H_2O_2 (5%), and then sieved using the 0.071 and 1 mm mesh sieves. Dried residue was split into *ca* 500 foraminifera shells. Foraminifers were then collected and identified using a Olympus SZ61 binocular stereoscopic microscope. Determination of foraminifers followed Kennet & Shrinivasan (1983), Loeblich & Tappan (1992) and Turco *et al.* (2011). Biostratigraphic interpretations of foraminiferal associations followed standard zonations of Grill (1941) and Cicha *et al.* (1975). The

Figure 1. A – schematized geological map with the geographical position of Danube Basin. Explanatory notes: a – Inner Alpine, Carpathian and Dinaric mountains; b – Klippen Belt; c – Foredeep and Flysch belt; d – Miocene volcanic fields; e – faults; f – state boundaries; *sensu* Horváth. • B – location map of the northern Danube Basin. Explanatory notes to the geological map: a – Tatricum; b – Fatricum; c – Hronicum; d – Veporicum; e – Silicicum; f – Andesitic volcanic rocks (Neogene); h – Magura units; i – Oravicum; j – Cretaceous to Paleogene sediments of the Brezová and Myjava; g – Bükkicum and Pelsonia; k – sediments of the Inner Carpathian Paleogene Basin; l – Paleogene sediments of the Buda Basin; m – Neogene to Quaternary sediments; n – Vahicum; o – Rhyolitic volcanic rocks (Neogene); p – towns; r – deep wells; s – outcrops; t – 2D reflection seismic grid; u – well correlation profile; v – faults. Modified after Fusán *et al.* (1987), Hók *et al.* (2014), Horváth *et al.* (2015).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Vienna basin
Biele Karpaty Mts.
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Sereď 2
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Rišňovce depression
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Chorvátsky Grob 1
Senec 1
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stratigraphical foraminifera ranges were explored from Papp (1951), Cicha *et al.* (1998), Wade (2011), Iaccarino *et al.* (2011), Turco *et al.* (2011) and Gradstein *et al.* (2012). The calcareous nannofossils were analysed quantitatively in standard smear slides prepared from all lithologies. Nannofossils were then counted using a polarizing microscope Olympus BX 50 at 1250× magnification. Calcareous nannoplankton biostratigraphical data were compared with standard nannoplankton zonation of Martini (1971), taxonomy followed Perch-Nielsen (1985), Young (1998) and Young *et al.* (2014). Additionally, subdivision of the NN5 Zone in sense of Andrejeva-Grigorovič *et al.* (2001) was applied.

The current status of the Miocene Central Paratethys stratigraphy, the correlation between the Central Paratethys regional stages and the Mediterranean scale summarized by Piller *et al.* (2007), Kováč *et al.* (2007) and Hohenegger (2014) was used to range stratigraphically important taxa found in the Trakovice-1, Trakovice-4, Špačince-5 and Krupá-5 wells. Palaeoecological parameters were evaluated for samples containing at least 200 individuals of benthic foraminifers with the presence and dominance of taxa exhibiting special environmental significance. For better interpretations of distributional patterns, species with similar environmental significance were grouped. Taphonomic analysis of the foraminiferal assemblage was identified and evaluated according to methods described by Holcová (1997, 1999).

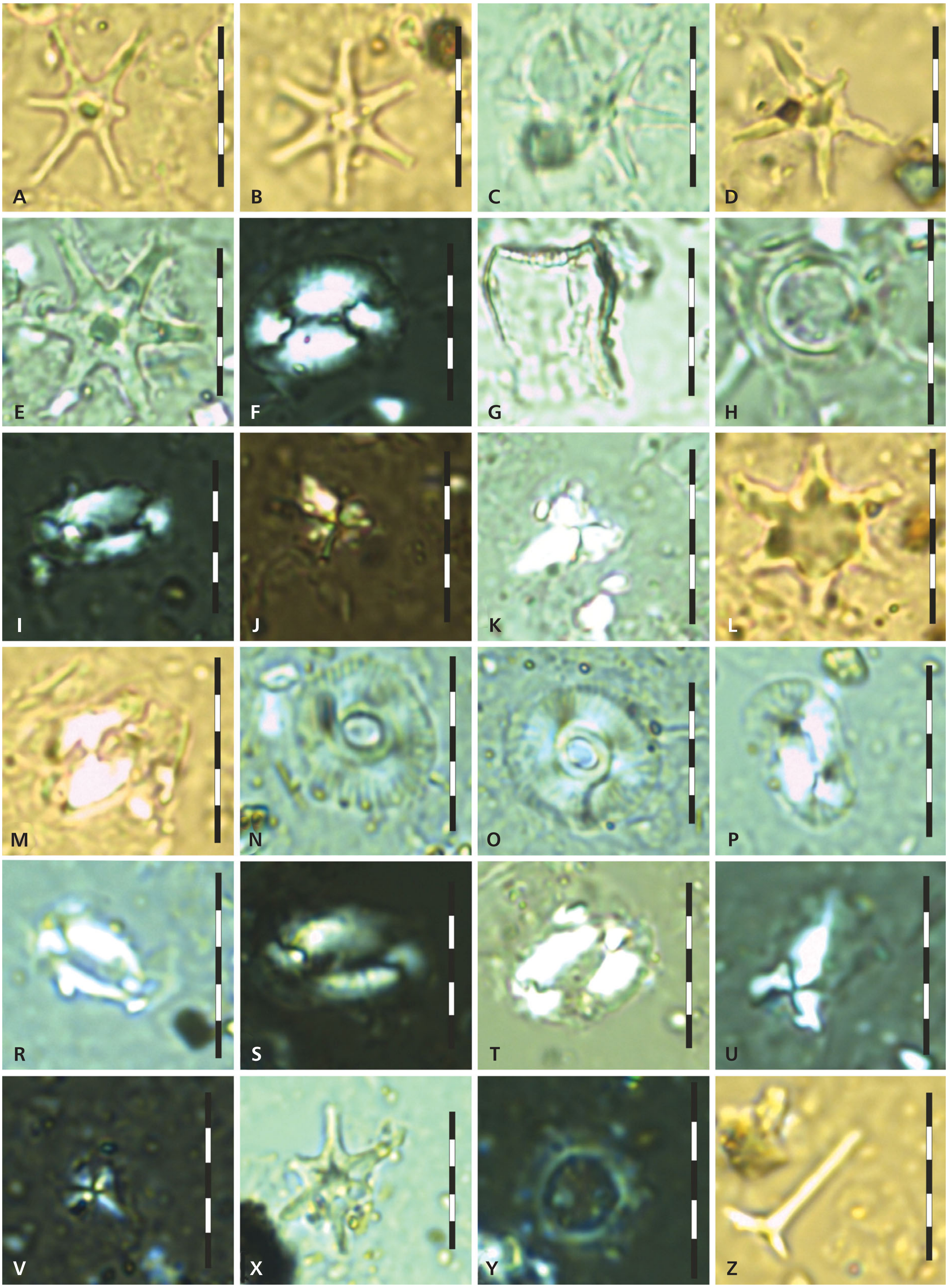
Palynological samples preparation followed standard laboratory methods (*e.g.* Erdtman 1943, Faegri & Iversen 1989, Moore *et al.* 1991). During the procedure, 20 g of dry sediment was treated with cold HCl (35%) and HF (70%) to remove carbonates and silica. Usage of $ZnCl_2$ (heavy liquid with density = 2 g/cm^3) in the centrifuge allowed the extraction of palynomorphs.

For sediment provenance analysis, coarse-grained samples were selected and studied under a polarizing microscope. Heavy mineral analysis was conducted using a 0.25–0.10 mm fraction and studied under a binocular microscope. The mineral associations were confirmed by an EDAX analysis (microprobe Cameca SX-100). Garnets and plagioclases were analysed by WDS quantitative analysis. Measurement conditions were: 15 keV, 20 nA. The chemical composition of garnet was calculated on the basis of 12 anions. The Fe^{3+} garnets were calculated to ideal stoichiometry. Plagioclases from volcanic lithoclasts were calculated on the basis of 8 anions. From the handpicked lithoclasts chemical composition of volcanic material (Trakovice-4 well, depth 985–980 m) was analysed using ICP-ES (major oxides) in Acme Laboratories (Vancouver, Canada). The results were compared with volcanic lithoclasts from the Ratkovce-1 well. To display the whole rock analysis, the diagram after Pearce (1996) was utilised, where the volcanic rock classification is based on immobile elements. Mineral abbreviations follow Whitney & Evans (2010). Photo documentation of separated clasts was made by a trinocular stereomicroscope (Olympus KL 1500 LCD) and QuickPHOTO MICRO 3.0 software.

For the purpose of the sedimentological analysis well core samples were collected, cut in half perpendicularly to the bedding plane, washed and treated for preservation with dispersive glue. The samples were later scanned and digitized. Sedimentary textures and structures were documented mainly in sense of Boggs (2006), Nichols (2009), and Miall (2010). Further evaluation was conducted based on well logs using spontaneous potential (SP) and resistivity (RT). The well curves and reflection seismic lines were originally acquired by the company Moravské naftové doly. The available data was re-interpreted in this study based on Mitchum *et al.* (1977), Sangree & Widmier (1979), Rider (1986), Vail (1987), Light *et al.* (1993), Emery & Myers (1996), and Catuneanu *et al.* (2006).

Lithology of the Upper Miocene to Quaternary sequences was studied on 130 counter-flush wells of the Bučany series. Trends of facies changes and depositional environment transitions were interpreted with support of SP and RT logs from the Ratkovce, Trakovice, and Madunice well series. Biostratigraphy and the definition of correlated formations are based on Harzhauser *et al.* (2004), Kováč *et al.* (2004, 2006, 2011), and Magyar *et al.* (2007).

Figure 2. Calcareous nannoplankton found in the studied well cores. • A – *Discoaster broweri* Tan, emend. Bramlette & Riedel; Ratkovce-4, core 2, box 1, 50–60 cm. • B, C – *Discoaster exilis* Martini & Bramlette; Trakovice-4, core 2, box 1, 50–60 cm. • D – *Discoaster pentaradiatus* Tan; Trakovice-4, core 2, box 1, 50–60 cm. • E – *Discoaster variabilis* Martini & Bramlette; Trakovice-4, core 2, box 1, 50–60 cm. • F – *Helicosphaera wallichii* (Lohmann) Okada & McIntyre; Trakovice-4, core 2, box 1, 50–60 cm. • G – *Scyphosphaera pulcherrima* Deflandre; Trakovice-4, core 2, box 1, 50–60 cm. • H – *Umbilicosphaera rotula* (Kamptner) Varol; Trakovice-4, core 2, box 1, 50–60 cm. • I – *Helicosphaera waltrans* Theodoridis; Trakovice-4, core 10, box 1, 50–60 cm. • J, K – *Sphenolithus heteromorphus* Deflandre; Trakovice-4, core 10, box 1, 50–60 cm. • L – *Discoaster musicus* Stradner; Trakovice-4, core 13, box 1, 50–60 cm. • M – *Helicosphaera waltrans*, Theodoridis; Trakovice-4, core 13, box 1, 50–60 cm. • N – *Calcidiscus premacintyrei*, Theodoridis; Trakovice-1, core 4, box 4, 50–60 cm. • O – *C. premacintyrei* Theodoridis; Trakovice-1, core 1, box 3, 0–15 cm. • P – *Helicosphaera walbersdorfensis* Müller; Trakovice-1, core 3, box 3, 80–85 cm. • R – *H. scissura* Müller; Trakovice-1, core 16, box 5, 50–60 cm. • S – *H. waltrans* Theodoridis; Trakovice-1, core 16, box 5, 50–60 cm. • T – *H. ampliaperta* Bramlette & Wilcoxon; Trakovice-1, core 16, box 5, 50–60 cm. • U – *Sphenolithus heteromorphus* Deflandre; Trakovice-1, core 16, box 5, 50–60 cm. • V – *S. abies* Deflandre *in* Deflandre & Fert; Trakovice-1, core 6, box 3, 50–60 cm. • X – *Discoaster variabilis* Martini & Bramlette; Špačince-5, core 6, box 3, 50–60 cm. • Y – *Hayella challengeri* (Müller) Theodoridis; Špačince-5, core 22, box 1, 50–60 cm. • Z – *Rhabdosphaera sicca* Stradner; Špačince-5, core 6, box 3, 50–60 cm. Scale bars equal 10 µm.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Results

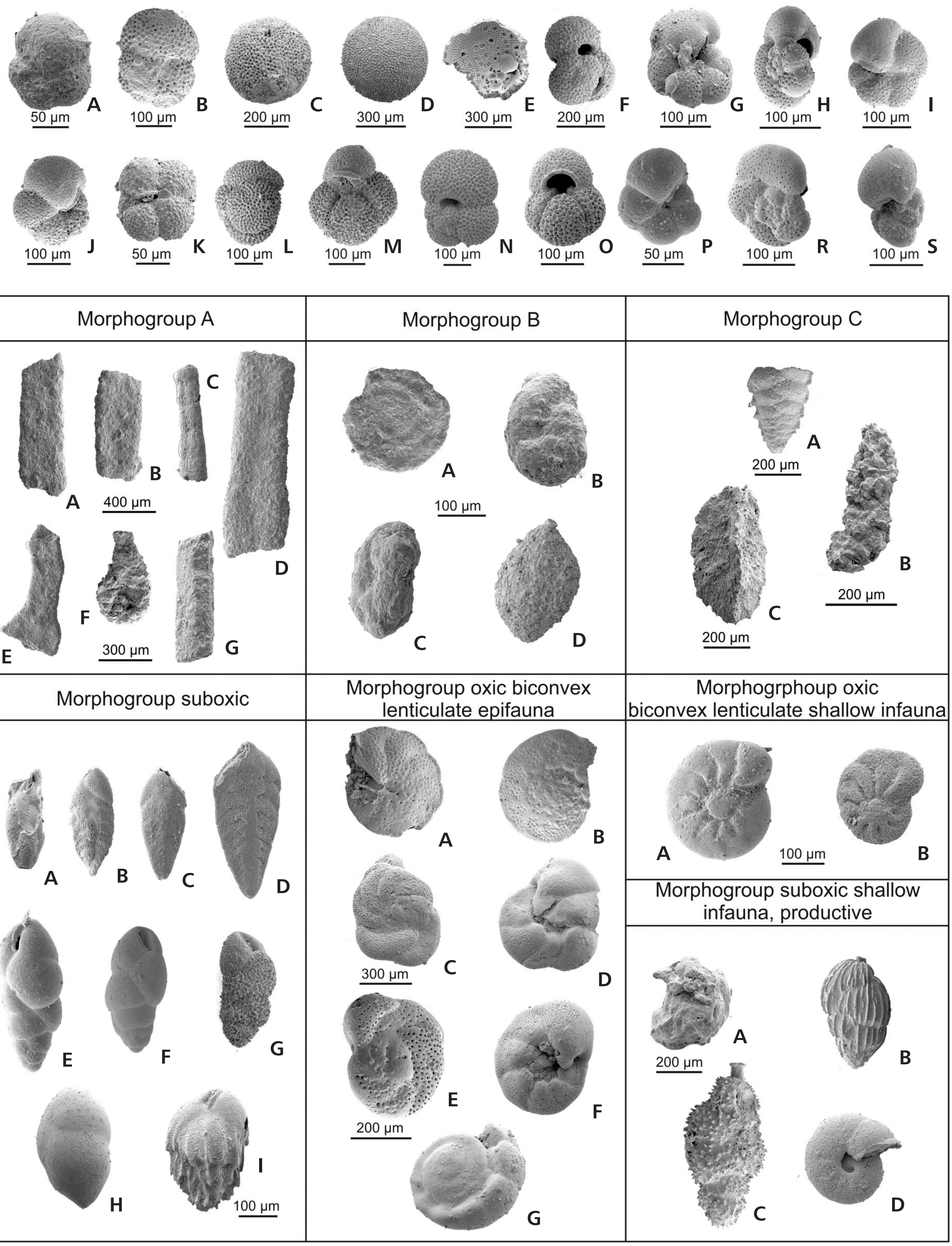
The results include data obtained from core material, calcareous nannoplankton (Fig. 2), planktonic and benthic foraminifera (Fig. 3), pollen distribution and heavy mineral analysis of the Trakovice-1 and Trakovice-4. For detailed core description of the mentioned Ratkovce-1 well see Rybár *et al.* (2015). Additionally, this study is supplemented with biostigraphical data obtained from the Krupá-5 and Špačince-5 wells.

Core description – sedimentary textures and structures

The Trakovice-1 well is located on bedrock elevation, which caused the insignificant thickness of the basal conglomerates. The dolomite breccia passes into dolomite conglomerate (1550–1500 m) followed by poorly sorted sandstones with volcanic material (Fig. 4F). Its dark brownish colour is caused by abundant, relatively large idiomorphic biotite (up to 1 cm in diameter). The marine conditions are indicated by glauconite. At the depth of 1500 m a rapid transition to mudstones occurs (Fig. 5). At the depth of 1420–1060 m, heterolithic sediment is present and is composed of alternating sandstone and mudstone. Ripple cross lamination, carbonized plant fragments and bioturbation are abundant (Fig. 4H). Occasional intercalations of pebble layers occur. High input of reworked volcanic material was observed (1240–1060 m). Mudstones are characterized by abundant bioturbation and sporadic sandy ripples (Fig. 4I, J). Post oxidation anoxia (post-depositional) is confirmed by finds of framboidal pyrite and various pyritized fossil fragments. The overlying part (1060–750 m) is represented by mudstones with rare volcanic particles of granule size, which have a fining upwards trend. No bioturbation was found at this level. In heavy fraction, bacterial pyrite dominates. At the depth of 650 m a mass occurrence of fossil fish scales and pteropods was documented (Fig. 4O, P, P').

The pre-Neogene basement of the Trakovice-4 well (1688–1674 m) is composed of limestones. Above, in the interval between 1620–1595 m, grey carbonate conglomerate occurs. It contains mainly micritic (mudstone) and sparitic carbonates. Fragments of oolitic (grainstone) and biodetritic carbonates (wackestone to grainstone) with common microstylolites, calcite and pyrite veins are also included. Bioclasts are derived from echinodermata,

Figure 3. Foraminifera found in the Trakovice-1 and Špačince-5 well cores. Stratigraphically important species: • A – *Globorotalia praescitula* Blow; Trakovice-1, core 17, box 3, 0–10 cm. • B – *Globigerinoides trilobus* (Reuss); Trakovice-1, core 17, box 2, 30 cm. • C – *Orbulina suturalis* (Brönnimann); Trakovice-1, core 15, box 1, 50 cm. • D. *Orbulina universa* d'Orbigny; Trakovice-1, core 7, box 2, 35 cm. • E – *Orbulina universa* d'Orbigny; Trakovice-1, core 7, box 2, 35 cm. • F – *Globigerinoides altiaperturus* Bollii; Trakovice-1, core 2, box 4, 20 cm. • G. *Fohsella peripheroronda* (Blow & Banner); Trakovice-1, core 2, box 4, 20 cm. • H – *Fohsella peripheroronda* (Blow & Banner); Trakovice-1, core 2, box 4, 20 cm. • I – *Globorotalia scitula* Brady; Trakovice-1, core 2, box 4, 20 cm. • J – *Globoconella* cf. *minoritesta* (Papp); Trakovice-1, core 2, box 4, 20 cm. • K – *Turborotalita* cf. *quinqueloba* (Natland); Trakovice-1, core 2, box 4, 20 cm. • L – *Globoquadrina dehiscen*s Chapman Parr & Collins; Trakovice-1, core 3, box 1, 50 cm. • M – *Globigerina druryi* Akers; Špačince-5, core 7, box 2, 30 cm. • N – *Globigerinoides trilobus* (Reuss); Špačince-5, core 7, box 1, 50 cm. • O – *Globigerina woodi decoraperta* (Takayanagi & Saito); Špačince-5, core 7, box 1, 70 cm. • P – *Globorotalia bykovae* Aisenstat; Špačince-5, core 7, box 2, 30 cm. • R – *Globorotalia bykovae* Aisenstat; Špačince-5, core 7, box 2, 30 cm. • S – *Globorotalia bykovae* Aisenstat; Špačince-5, core 7, box 2, 30 cm.
Morphogroup A (Jones & Charnock 1985). • A, B – *Bathysiphon filiformis* (Sars); Trakovice-1, core 16, box 2, 20 cm. • C. *Bathysiphon pocutica* (Pishvanova); Trakovice-1, core 5, box 3, 20 cm. • D – *Bathysiphon* cf. *major* de Folin; Trakovice-1, core 17, box 3, 0–10 cm. • E – *Hyperammina elongata* Brady; Trakovice-1, core 16, box 2, 20 cm. • F – *Lagenammina grzybowski* (Schubert); Trakovice-1, core 17, box 3, 0–10 cm. • G – *Rhizammina* sp.; Trakovice-1, core 17, box 3, 0–10 cm.
Morphogroup B (Jones & Charnock 1985). • A – *Ammodiscus* cf. *pennyi* Cushman & Jarvis; Trakovice-1, core 12, box 1, 50 cm. • B – *Cyclammina* sp.; Trakovice-1, core 12, box 1, 50 cm. • C – *Cyclammina carpathica* Cicha & Zapletalová; Trakovice-1, core 12, box 1, 50 cm. • D – *Sigmoilopsis schlumbergeri* (Silvestri, 1904); Trakovice-1, core 3, box 1, 50 cm.
Morphogroup C (Jones & Charnock 1985). • A – *Spiroplectammina deperdita* (d'Orbigny, 1846); Trakovice-1, core, box 1, 50 cm. • B – *Ammobaculites agglutinans* (d'Orbigny, 1846); Trakovice-1, core 11, box 2, 35 cm. • C – *Pseudoclavulina* sp.; Trakovice-1, core 6, box 5, 50 cm.
Morphogroup suboxic (Kaiho 1994). • A – *Fursenkoina schreibersiana* (Czjzek); Trakovice-1, core 17, box 3, 50 cm. • B – *Bolivina pokornyi* Cicha & Zapletalová; Trakovice-1, core 9, box 3, 50 cm. • C, D – *Bolivina dilatata maxima* Cicha & Zapletalová; Trakovice-1, core 8, box 3, 50 cm. • E – *Bulimina elongata* d'Orbigny; Špačince-5, core 7, box 1, 50 cm. • F – *Bulimina elongata* d'Orbigny; Trakovice-1, core 3, box 1, 50 cm. • G – *Bulimina elongata* d'Orbigny (conf. Rupp 1986); Špačince-5, core 7, box 2, 50 cm. • H. *Protoglobobulimina pupoides* (d'Orbigny); Špačince-5, core 7, box 1, 50 cm. • I – *Bulimina striata* d'Orbigny *in* Guérin-Méneville; Špačince-5, core 7, box 2, 50 cm.
Morphogroup oxic (Kaiho 1994), biconvex lenticulate epifauna (Murray 2006). • A, B – *Cibicides ornatus* (Cushman); Trakovice-1, core 11, box 2, 50 cm. • C–F – *Valvulineria complanata* (d'Orbigny); C, D – Trakovice-1, core 9, box 3, 50 cm; E, F – Trakovice-1, core 9, box 5, 50 cm. • G – *Hansenisca soldanyi* (d'Orbigny); Špačince-5, core 7, box 1, 50 cm.
Morphogroup oxic (Kaiho 1994), biconvex lenticulate shallow infauna (Murray 2006): A – *Ammonia parkinsoniana* (d'Orbigny); Špačince-5, core 7, box 1, 50 cm. • B – *Elphidium* sp.; Špačince-5, core 7, box 1, 50 cm.
Morphogroup suboxic (Kaiho 1994), shallow infauna, productive (Murray 2006). • A – *Uvigerina macrocarinata* Papp & Turnovsky; Trakovice-1, core 17, box 2, 50 cm. • B – *Uvigerina pygmoides* Papp & Turnovsky; Špačince-5, core 7, box 1, 50 cm. • C. *Uvigerina aculeata* d'Orbigny; Špačince-5, core 7, box 1, 50 cm. • D – *Melonis pompilioides* (Fichtel & Moll.); Trakovice-1, core 4, box 3, 50 cm.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Morphogroup A
A B C D E F G
400 µm
300 µm
Morphogroup B
A B C D
100 µm
Morphogroup C
A B C
200 µm
200 µm
200 µm
Morphogroup suboxic
A B C D E F G H I
100 µm
Morphogroup oxic biconvex lenticulate epifauna
A B C D E F G
300 µm
200 µm
Morphogrphoup oxic biconvex lenticulate shallow infauna
A B
100 µm
Morphogroup suboxic shallow infauna, productive
A B C D
200 µm

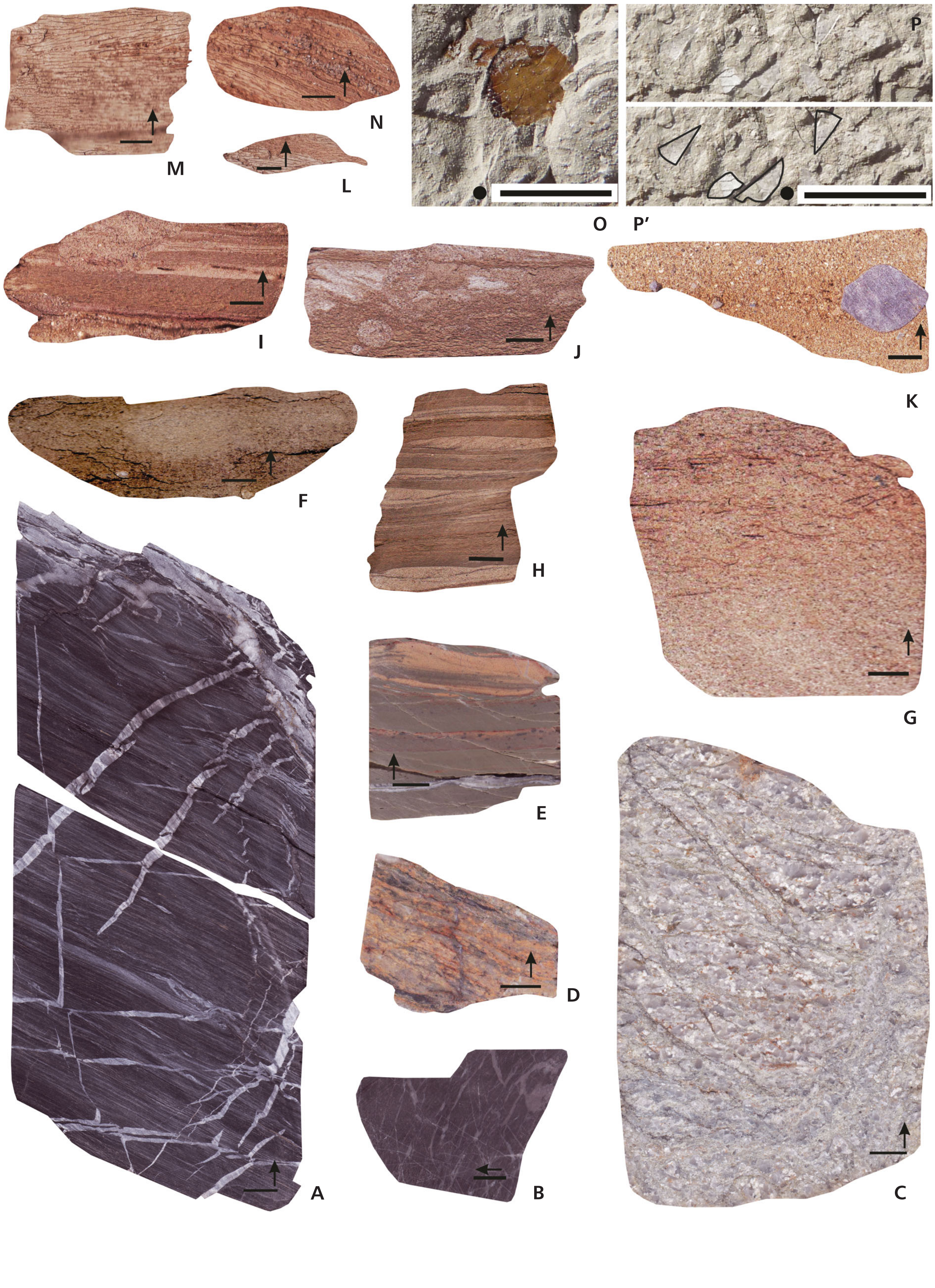
ostracoda, bivalvia, foraminifera and porifera spicules. The overlying conglomerates (1598–1594 m) differ by presence of numerous red fissures and clast composition (Fig. 6D). The clasts are composed of calcareous siltstones with detrital quartz, cherts, spongolites and quartz sandstone. These conglomerates are composed of carbonate clasts with micritic matrix. Interval between 1556–1555 m is occupied by well sorted and clast supported conglomerates (clasts up to 1 cm in diameter; Fig. 6E). In the depths of 1555–1503 m alternations of mudstone and sandstone yielded a convolute bedding (1506–1503 m; Fig. 6F). Glauconite and marine microfossils are present. In the depth of 1500–1300 m heterolithic sediment prevails. The sandy fraction occasionally forms ripple cross-lamination. At around 1400 m a 3.6+ m thick layer of fine-grained tuffite composed of vitroclasts appears (Figs 6G, 7A). At the depth of 1300–950 m, conglomerates and sandstones start to dominate again, with two different sediment types. The first type is represented by sandstone and well-sorted conglomerates with normal gradation. The bioturbated sandstones contain abundant carbonized plant fragments (Fig. 6J). Rarely, clasts with carbonate growth rings and fossil algae growth with a stromatolithic structure are present (Fig. 8G, H). The second type is characterized by sandstone passing into diamictite layers with both intra and extra clasts. The clay intraclasts are plastically deformed and often coated in pebbles (Fig. 6J, K).

Calcareous nannoplankton, foraminifera and pollen record

Biostratigraphy of the sedimentary record of the Trakovice-1, Trakovice-4, Špačince-5 and Krupá-5 wells was implemented by using calcareous nannoplankton (Fig. 2) and foraminiferal associations (Fig. 3). A very poorly diversified association dominated by *Coccolithus pelagicus* (95%) contains an Upper Cretaceous reworked species, indicates the NN4 Zone, which was previously associated with the Karpatian stage (Lehotayová 1975, 1982; Spezzaferri & Ćorić 2001; Ćorić & Rögl 2004) was identified in the Krupá-5 well (745–650 m) and Špačince-5 well (3105–2652 m). Samples from the base of the Trakovice-1 well (1691–1690 m) consist of fine-grained material. In smear slides full of carbonized plant fragments, calcareous nannofossils were missing, which does not allow age determination. In the overlying samples (1410–1405 m) reworked Paleogene nannofossils were determined.

In the Trakovice-1 well (1360–1355 m) nannofossils may indicate the Lower Badenian NN5a, b Zone (*sensu* Andrejeva-Grigorovič *et al.* 2001) based on the occurrence of *Sphenolithus heteromorphus*, *Helicosphaera waltrans* and *H. ampliaperta*, *H. carteri*, *H. mediterranea*, *H. walbersdorfensis*, *Coronocyclus nitescens* and abundant *Coccolithus pelagicus*, *Discoaster deflandrei*, *Reticulofenestra haqii*, *R. minuta*, *Umbilicosphaera rotula.* In the Špačince-5 well (2692–2195 m) and in the Trakovice-4 well (1456–1452 m; Figs 9, 10) based on the occurrence of *S. heteromorphus* together with the absence of *H. ampliaperta*, the base of the NN5 Zone containing high number of reworked species from the Eocene and Upper Cretaceous was detected. An equivalent of the NN5a Zone was identified in the Krupá-5 well (650–645 m) by co-occurrence of *Sphenolithus heteromorphus* and *Helicosphaera waltrans*. The NN5b Zone occurs in the Trakovice-1 well (1155–1150 m) which is indicated by the acme of *H. walbersdorfensis*, while at the depth of 1106–1101 m in the Trakovice-1 well the C+P (Cretaceous+Paleogene) nannofossils species are replaced with a marine assemblage with discoasters (*e.g. D. variabilis*, *D. exilis*), *U. rotula*, *R. pseudoumbilicus* and *R. haqii*. These species are correlated with the NN5c Zone (*sensu* Andrejeva-Grigorovič *et al.* 2001). In the intervals 1061–1056 m and 1007–1002 m age determination was not possible, but the reworked specimens are abundant. The last occurrence of *Sphenolithus heteromorphus* in the overlying strata of the Trakovice-1 well (960–955 m) was documented, therefore this interval is correlated with the NN5/NN6 zones boundary (the NN6 Zone was also identified in the Trakovice-4 well in the depth of 750 m, in the

Figure 4. Well core samples from the Trakovice-1. Explanatory notes: arrow – pointing towards the top; dot – bedding plane; scale bar = 1 cm. • A – dark blue shale (mudstone), cut by numerous veins filled with calcite and bacterial pyrite; Trakovice-1, core 39, 2134–2135.5 m, box 1, 20–35 cm. • B – dark blue limestone cut by numerous calcite veins; Trakovice-1 core 29, 1821–1822 m, box 1, 25–30 cm. • C – light grey quartzite; Trakovice-1 core 26, 1761–1763 m, box 1, 0–15 cm. • D – grey to pale green carbonate with yellow sandy interactions, occasionally cut by calcite veins; Trakovice-1, core 25, 1719–1720 m, box 1, 70–88 cm. • E – grey to pale green carbonate with yellow sandy interactions, occasionally cut by calcite veins; Trakovice-1, core 22, 1643–1645 m, box 1, 0–15 cm. • F – brown, coarse grained sandstone with abundant biotite; Trakovice-1, core 19, 1505–1507 m, box 1. • G – pale brown sandstone with abundant carbonized plat fragments; Trakovice-1, core 15, 1305–1310 m, box 5, 50–56 cm. • H – mudstone with lenticular sandstone intercalation yielding ripple cross bedding; Trakovice-1, core 14, 1255–1260 m, box 1, 15–20 cm. • I – bioturbated mudstone with abundant sandstone layers; Trakovice-1, core 13, 1201–1206 m, box 3, 50–53 cm. • J – bioturbated mudstone with abundant sandstone layers; Trakovice-1, core 12, 1150–1155 m, box 2, 50–53 cm. • K – pale brown conglomerate; Trakovice-1, core 11, 1101–1106 m, box 5, 0–20 cm. • L – brown mudstone; Trakovice-1, core 6, 851–856 m, box 4, 0–10 cm. • M – brown mudstone; Trakovice-1, core 4, 750–755 m, box 3, 50–56 cm. • N – brown pebbly mudstone; Trakovice-1, core 5, 800–804 m, box 1, 50–55 cm. • O – fish scale; Trakovice-1, core 2, 650–655 m, box 2, 30 cm. • P – pteropods; Trakovice-1, core 2, 650–655 m, box 2, 30 cm.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Krupá-5 well at 250 m and in the Špačince-5 well at 1396 m; Fig. 10). In the same samples from the Trakovice-1 well (960–955 m) a foraminiferal assemblage of CPN8 Zone with *Globigerina druryi* was recognized. The discoasters, *Triquetrorhabdulus rugosus* and *Sphenolithus abies* were present and indicate the NN6 Zone. Reworked C+P taxa dominated in the depth of 910–905 m. Significant environmental change in the Trakovice-1 well core material is observed in the depth of 856–851 m where the acme zone of *S. abies* associates with *U. rotula* and reworked Cretaceous nannofossils (observed in the Trakovice-4 well at 755–700 m; in the Špačince-5 well at 702–600 m and in the Krupá-5 well at 250 m) correlated with the NN6 Zone. In the overlying sediments of the Trakovice-1 well (755–750 m and 655–650 m), the acme zone of S. *abies* together with *Calcidiscus premacintyrei* and reworked C+P taxa follows. The above-mentioned assemblage was correlated with the associations of the Trakovice-4 well (652 m) and with the Ratkovce-1 well in the depth of 1055–1052 m (Rybár *et al.* 2015). In the Trakovice-1 well (710–705 m) occurrence of *S. abies*, discoasters and reworked C+P material indicated the NN6 Zone.

Foraminiferal assemblages correlate with the results of calcareous nannoplankton study (Figs 5, 9, 10). In the lowermost portion of all studied wells, foraminifers do not outline the precise age. Rare Karpatian (latest Burdigalian) *Uvigerina graciliformis* in the Krupá-5 (655 m) and Špačince-5 (3105 m) wells were found. In the Trakovice-1 well (1454–1450 m) presence of a benthic offshore Badenian (Langhian) agglutinated assemblage of morphogroup A (pioneer settlement) composed of *Bathysiphon pokutica*, *Bathysiphon* sp. and *Lagenammina* sp. is typical (Gradstein & Berggren 1981, Jones & Charnock 1985, Cicha *et al.* 1998, Jones 2011, Murray *et al.* 2011). A similar benthic association was displayed in the Špačince-5 well at the depth of 2649–2402 m (Fig. 3F). In the same well at the depth of 2200 m a diverse planktonic association with goloborotaliids (*e.g. Globorotalia bykovae*) and *Orbulina suturalis* was abundant. Benthic assemblage characterizes the dominance of *Valvulineria* and agglutinated species of *Haplophragmoides, Bathysiphon* and *Reticulophragmium* genera. In the next interval of the Trakovice-1 well (1007–1002 m) *Bathysiphon* sp. dominated, but planktonic foraminifera became much more abundant. Abundant globigerinoideses are present here and occurrence of *Globigerinoides sicanus* indicates an age older than 14.4 Ma (Iaccarino *et al.* 2011). In the Trakovice-1 well (960–955 m and 910–905 m) globigerinids prevail (*e.g. Globigerina druryi*, *G. bulloides*; Spezzaferri & Premoli Silva 1991; Spezzaferri 1995, 1996; Gallagher *et al.* 2001; Bicchi *et al.* 2003; Kováčová & Hudáčková 2009). Reworked Cretaceous (*Globotruncana*) and Paleogene (*Cassigerinella*) taxa are present as well. According to Cicha *et al.* (1975), this association (Fig. 3) is ranked into the CPN8 Zone and was found in the Ratkovce-1 well (1055 m; Rybár *et al.* 2015), in the Špačince-5 well (1402 m) and in the Trakovice-4 well (750 m). Dominance of benthic foraminifera *Bolivina tortuosa*, *B. pokornyi*, *Bulimina elongata* and acme of the *Cassidulina laevigata* was documented here. Absence of bioturbation, large amount of bacterial pyrite, pyritized foraminifera confirm was also documented. The assemblages with dominant *Globigerina quinqeloba* and *G. bulloides* in the Trakovice-1 (856–851 m), Trakovice-4 (655 m) and Špačince-5 (1099 m) wells were present. In the Trakovice-1 in the depth of 705 m low diversified assemblage of benthic foraminifera composed by *Bulimina* and *Uvigerina* and planktonic *Globorotalia* and *Globigerina* was documented. In the last sampled cores of the Trakovice-1 (655–650 m), Trakovice-4 (657 m) and the Ratkovce-1 (855 m) well planktonic foraminifers are absent and benthic assemblage is dominated by *Ammonia* and *Porosonion*.

Pollen assemblages from Trakovice-1 well (1360–1355 m) contained rich palynomorphs including dinoflagellates, phytoclasts, fungi spores and reworked sporomorphs. Pollen are represented by 4 and 5 porate *Alnus*, *Sparganium*, *Carya*, *Engelhardia*, Taxodioidae, *Potamogeton*, *Zelkova*, *Fraxinus*, *Zelkova*, *Quercoidites*, *Tricolporopollenites edmundi* type, Sapotaceae, *Cathaya*, *Picea*, *Tsuga*, *Abies*, Cupressaceae, Theaceae, Fagaceae, Caprifoliipites (Adoxaceae), *Oleaceae*, *Myrica*, *Quercus ilex* type, *Quercus robur* type. Additionally, at the depth of 910–905 m, *Laevigatosporites*, *Castanea*, *Ulmus*, *Pterocarya* and *Platycarya* occur along with the rapid decrease in diversity of Pinaceae while at the depth of 755–750 m, the abundance of *Pinus* increased accompanied by taxa mentioned above with high Sapotaceae abundance.

Heavy mineral composition

The association of heavy minerals in the Trakovice-1 and Trakovice-4 wells is relatively monotonous and agrees with the composition of material identified from gravel-sized samples. Heavy fraction consists of garnet, tourmaline, apatite, staurolite, zircone, epidote, biotite, bacterial pyrite, ilmenite and minerals of limonite group. Transparent heavy minerals are dominated by garnets and form 21.50–72.82% of the sandy samples. They can be divided into pink and deep orange-pink colour types. Nevertheless, the microprobe study did not show any significant chemical differentiation. Their chemical composition corresponds to almandine garnet (Fig. 11) and they are free from visible zonation. Some garnets are free of inclusions while others contain inclusions of quartz, mica, epidote, ilmenite and apatite. Increasing content of the deep-coloured

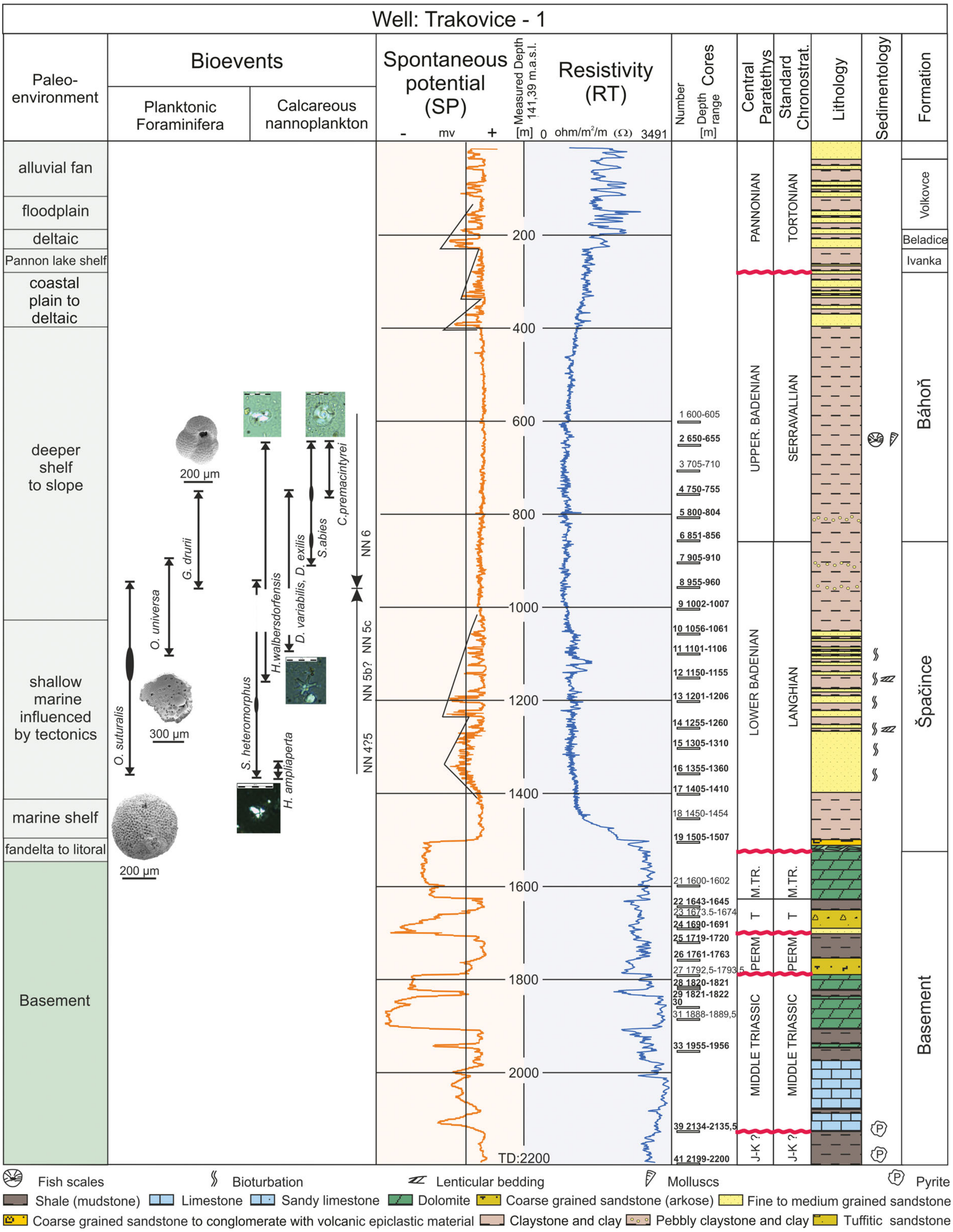


Figure 5. Trakovice-1 well: sedimentary formations, lithology, SP & RT logs, stratigraphy, bioevents and palaeoenvironment of deposition.

garnets in the volcanic material rich sediment derived from the Miocene volcanism and volcanic clasts with garnets (Fig. 7G, H) in the Trakovice-1 well are present. One single garnet of andradite composition was also identified. Andradite garnets are typical for contact metamorphic rocks – skarns. The volcanic epiclastic material includes traces of a hydrothermal mineralization confirmed by sphalerite and mineralized Fe-Mg carbonate fragment identified by EDAX analysis. In samples without volcanic admixtures, brown tourmaline (Srl-Drv series) forms 4.0–8.9% and in samples with volcanic admixture, the relative amount is reduced to 1%. The amount of apatite is 2–7%. Zircon, staurolite, rutile and epidote form less than 1%. EDAX analysis revealed an increased content of Rare Element Resources (REE) in epidote – allanite. Biotite and chlorite co-occurred in the transparent minerals of the heavy fraction. Idiomorphic biotites constitute 40% of the sand from the depth of 1500 m at the Trakovice-1 well. They occur together with volcanic debris demostrating their volcanic origin. Opaque heavy minerals are composed of ilmenite, bacterial pyrite, limonitized pyrite, limonite minerals and glauconite. Ilmenite creates 10–26% in the sandy samples and often contains inclusions of apatite and plagioclase. In the silty samples from the Trakovice-1 well (70–84% lutite fraction), the relative content of ilmenite decreases to less than 1% and is replaced by a high amount of diagenetic pyrite (90–94%). At the depth of 985–980 m in the Trakovice-4 well content of limonite minerals and oxidized pyrites increases up to 45–60%.

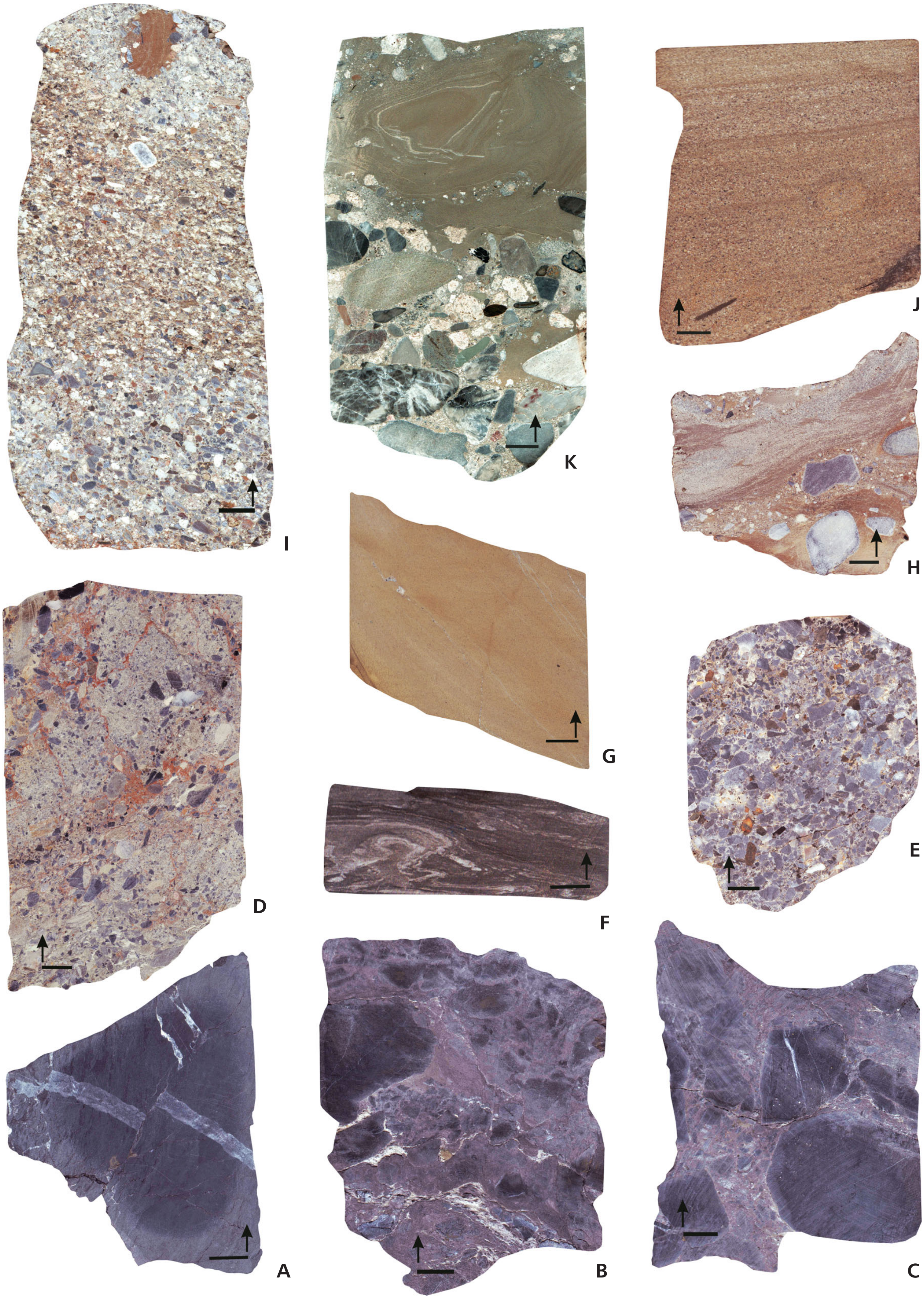
Interpretation

Interpretations of palaeoecology, paloenvironment, biostratigraphy and sediment provenance allowed us to speculate abouth the Neogene evolutions of the northern Danube Basin.

Palaeoecology, palaeoenvironment and biostratigraphy

In all studied wells the Cenozoic sedimentation starts with conglomerates. In the Trakovice-4 well (1598–1594 m) the fissures occurring in these conglomerates were probably caused by gravity rock falls. The red colour of the fissure infill was caused by iron-oxides occurring in the microstructure as pseudomorphs of rhombic shape. Therefore we believe that the rocks were exposed to the subaerial conditions and oxidised before their lithification. This could imply a deposition at the water-land interface. The overlying well-sorted conglomerates may have been deposited in an alluvial fan or fan-delta channels. Mudstones and sandstone of the overlying sequence (1555–1503 m) indicate a deposition in a sublittoral marine environment documented by glauconatie and microfossils. The convolute bedding recognized at the top of this interval is interpreted as a result of gravity slumping. In the Trakovice-1 well at the depth of 1500 m presence of an agglutinated foraminifera association allow us to speculate about an extremely rapid deepening of the sedimentary environment due to pronounced fault activity (Fig. 12). In the Trakovice-4 well (1400 m) a 3.6 m thick tuffite layer indicates onset of volcanism in the vicinity. The described fossil algae growth rings (stromatolitic structure) found in overlying strata (1300–950 m) and abundant carbonized plant fragments indicate short transportation from the littoral zone. Marine conditions are documented by foraminifera in the carbonate matrix. In the last sampled interval, deformed clay intraclast point to gravity transport. Warm water conditions in the Trakovice-1 (1007–1002 m) are indicated by abundant globigerinoideses (*e.g. Globigerinoides quadrilobatus*; Spezzaferri & Premoli Silva 1991; Spezzaferri 1995, 1996; Gallagher *et al.* 2001; Bicchi *et al.* 2003) and oxygen deficiency at the bottom, rich in organic matter, is documented by strongly dominated *Valvulineria* (Murray 2006). Nannofossil assemblage in the depth of 960–955 m indicate open marine conditions. Sublittoral environment (seabed ~150–200 m) and a gradual water cooling is documented in intervals between 960–955 m and 910–905 m by an overall faunal composition and also by prevailing globigerinids (*e.g. Globigerina druryi*, *G. bulloides*; Spezzaferri & Premoli Silva 1991; Spezzaferri 1995, 1996; Gallagher *et al.* 2001; Bicchi *et al.* 2003; Kováčová & Hudáčková 2009). Foraminiferal associations found in the samples from the Trakovice-1 (960–955 m, 910–905 m), Ratkovce-1 (1055 m; Rybár *et al.* 2015), Špačince-5 (1402 m)

Figure 6. Well core samples from the Trakovice-4. Explanatory notes: arrow – pointing towards the top; dot – bedding plane; scale bar = 1 cm. • A – grey to blue limestone, cut by numerous veins filled by calcite and bacterial pyrite; Trakovice-4, core 17, 1674–1677 m, box 2, 23–27 cm. • B, C – grey to blue, poorly sorted and poorly rounded carbonate conglomerate with rare bacterial pyrite inclusions; Trakovice-4, core 15, 1627–1631 m, box 2. • D – grey to blue poorly sorted conglomerate, cut by numerous red fissures; Trakovice-4, core 14, 1594–1598 m, box 1, 50–65 cm. • E – blue to grey, well sorted carbonate conglomerate; Trakovice-4, core 12, 1552–1556 m, box 1, 90–85cm. • F – dark brown mudstone with convolute bedding; Trakovice-4, core 11, 1503–1506 m, box 3. • G – yellow tuffite, cut by calcite veins; Trakovice-4, core 9, 1401–1406 m, box 3, 10–15 cm. • H – grey to brown diamictite (paraconglomerate); Trakovice-4, core 6, 1078–1084 m, box 3, 60–65 cm. • I – grey, clinostratified, well sorted and rounded conglomerate with armoured clay intraclats; Trakovice-4, core 6, 1078–1084 m, box 4, 70–90 cm. • J – yellow to brown layered sandstone with bioturbations and carbonized plat fragments; Trakovice-4, core 3, 948–953 m, box 5, 60–70 cm. • K – conglomerates with armoured clay intraclasts; Trakovice-4, core 3, 948–953 m, box 5, 70–85 cm.



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and Trakovice-4 (750 m) wells indicate stratification of the water column with dysoxic condition near the seabed. This was documented by high dominance of benthic foraminifera *Bolivina tortuosa*, *B. pokornyi* and *Bulimina elongata* that are typical for the late Badenian (early Serravallian) *Bulimina-Bolivina* Zone (Hudáčková & Spezzaferri 2002, Holcová 2008, Kováčová & Hudáčková 2009). Moreover, the cold-water environment is demonstrated by planktonic forms (Kováčová & Hudáčková 2009) and by acme of the benthic species *Cassidulina laevigata* (Kaiho 1994, Murray 2006). Absence of bioturbation together with a large amount of bacterial pyrite and pyritised foraminifera confirm low oxic conditions.

In the Trakovice-1 (856–851 m), Trakovice-4 (655 m) and Špačince-5 (1099 m) wells the nutrient rich upwelling environment is assumed according to the dominance of *Globigerina quinqeloba* and *G. bulloides* in the foraminiferal associations. Water depth was about 150 m implied from the bentic association (*Bulimina elongata gr.*, *Hoeglundina elegans*, *Budashewaella willsoni*). In the Trakovice-1 well (705 m) pronouncing water column stratification documented by a poorly diversified assemblage of benthic foraminifera composed by *Bulimina* and *Uvigerina* and further decrease in temperature is implied by temperate–cold water *Globigerina* assemblage was observed. Mass occurrence of fossil fish scales, pteropods (Fig. 4O, P, P'), and globigerinids, like the opportunistic *Turborotalita quinqueloba* represents the last documented evidence of upwelling (Trakovice-1 well, 655–650 m). The absence of planktonic foraminifers and increasing abundance of benthic genera *Ammonia* and *Porosonion* in the uppermost part of the well core samples points to a gradual shift to a shallow water environment which can be correlated with the Trakovice-4 (657–652 m) and the Ratkovce-1 (855 m) wells (Rybár *et al.* 2015).

The vegetation during the Lower Badenian was dominated by thermophilous elements such as evergreen trees and shrubs (*e.g.* Sapotaceae, *Engelhardia*, *Platycarya*) corresponding with subtropical climate conditions. In the hinterland, the lowlands were populated by a dominantly broadleaved evergreen forests. Humid like conditions most likely favoured the wide distribution of swamp forests and ecologically related riparian forests with *Alnus* (div. sp.) dominancy. Mixed evergreen-deciduous forest composed mainly of taxa such as Sapotaceae, *Quercus deciduous* type and *Q. ilex* type, *Carya*, *Fagus*, *Ilex*, *Carpinus*, *Engelhardia*, *Platycarya* and Caprifoliaceae. From the altitudinal distribution point of view, the extrazonal vegetation elements such as *Tsuga*, *Abies*, *Picea* and *Cathaya* reflect mid- and high-altitudes in the Danube Basin vicinity.

Sediment provenance

In the Trakovice-4 well Miocene sedimentation started with basal carbonate breccia. The structure and composition of the carbonate debris is derived from Triassic and Jurassic rocks. On the other hand, a small amount of polycrystalline quartz, K-feldspar and plagioclase in the basal conglomerate points to a source in the granitoides and gneisses. In the overburden content of carbonate, debris decreases upwards and is gradually replaced by fragments of granitoids (Qz + K-fsp ± mica), quartzites-gneisses (Qz + mica) and mica or chlorite schist (Fig. 8E, F). This composition indicates a common provenance in the Central Western Carpathians. The upwards increasing amount of crystalline fragments points to a continuous erosion of the source area, which is assumed to be in the pre-Neogene basement of the Danube Basin (central part). At present, it is built up only by crystalline complexes (Fusán *et al.* 1987).

Provenance of the clastic material from Neogene stratovolcanos is indicated by the presence of various volcanic material (Figs 7B–H, 11, 13). Some lithoclasts of gravel size are rounded but their surface is irregular. This is caused by the leaching of plagioclase phenocrysts. Associated recrystallized vitroclasts are less abundant. Some debris with diorite structure (Fig. 7B) probably originated from a deeper section of the volcano (volcanic chimney). In the sandy fraction, volcanic lithoclasts and vitroclasts are accompanied by zonal plagioclase. The variable structure, degree of recrystallization and alteration of volcanic debris points to the epiclastic origin. Reworked volcanic debris was first recorded at a depth of 1507 m in the Trakovice-1 well. In the Trakovice-4 well the first occurrence of the fine-grained tuffites with few voids and chlorite vein is at the depth of 1406 m (Fig. 7A) and reworked volcanic debris is present at the depth of 1205 m. They are vitroclastic with admixture of detritic quartz. Reworked volcanic lithoclasts are composed of recrystallized glass with plagioclase phenocrysts. Decomposition of plagioclase to kaolinite or carbonitization often occurs. Dark minerals are preserved only as pseudomorphs, mainly of an amphibole shape (Fig. 7F). Px pseudomorphs and Bt are less abundant. Glassy material was recrystallized to a mixture of Qz, Pl and K-Fsp (Fig. 7D). Composition of volcanic lithoclasts points to a trachyte to andesite

Figure 7. Microphoto of volcanic rock types. • A – tuffite layer; plane polarized light; Trakovice-4, core 9. • B – debris with diorite structure; crossed polars; Trakovice-4, core 6. • C – reworked volcanic debris; crossed polars; Trakovice-4, core 3. • D – grain of recrystallized volcanic glass; BSE; Trakovice-1. • E – plagioclase phenocryst in volcanic debris; BSE. • F – pseudomorphose after amphibole in volcanic debris; BSE. • G, H – garnet in reworked volcanic debris.

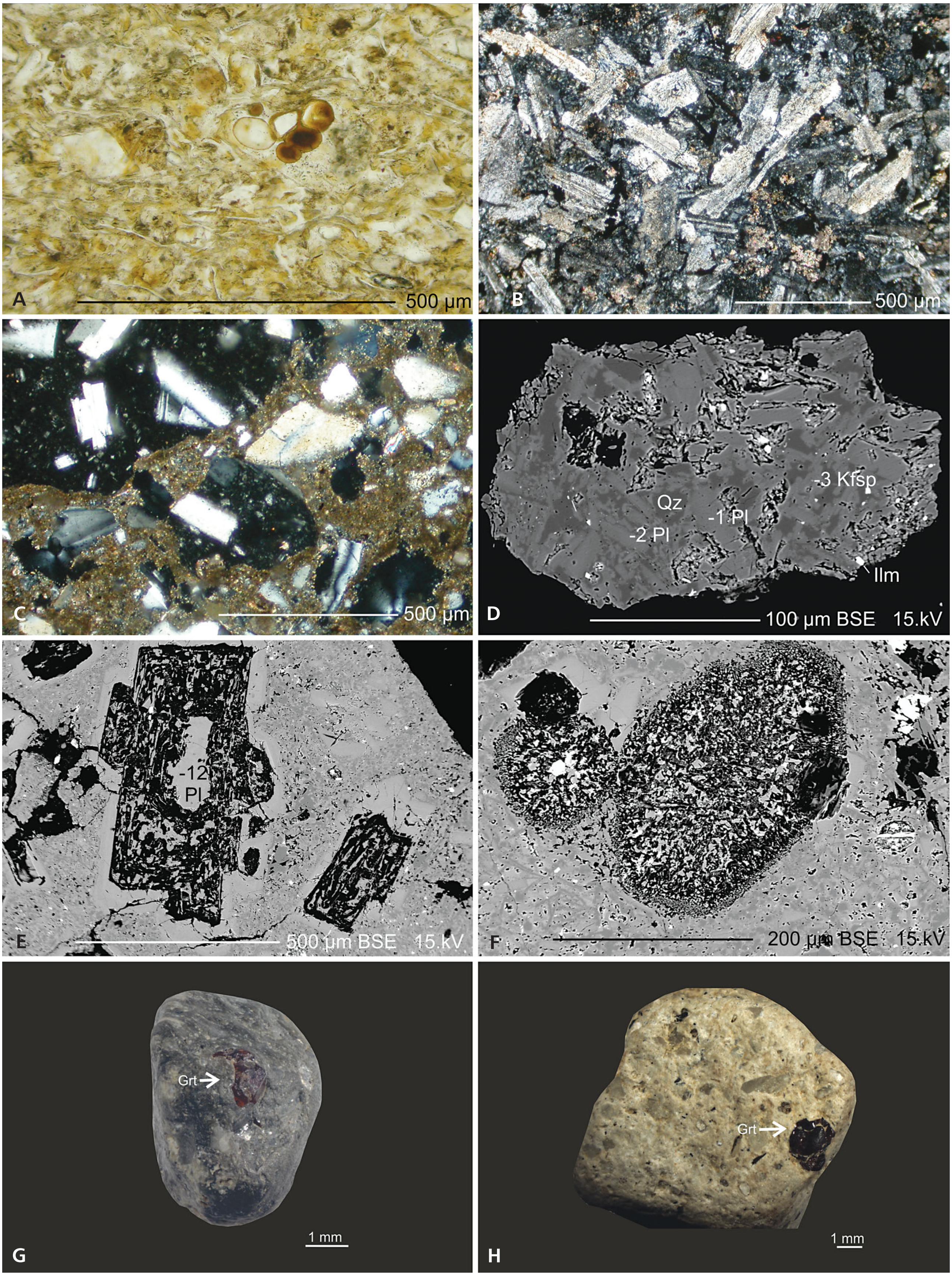

A
500 µm
B
500 µm
C
500 µm
D
Qz
-3 Kfsp
-1 Pl
-2 Pl
Ilm
100 µm BSE 15.kV
E
-12
Pl
500 µm BSE 15.kV
F
200 µm BSE 15.kV
G
Grt
1 mm
H
Grt
1 mm

Table 1. Selected analyses of feldspars from volcanic debris calculated on the basis of 8 anions.

	Trakovice-1			Trakovice – separated volcanic debris							Ratkovce-1			
	kfs	pl	pl	pl	pl	pl	pl	pl	pl	pl	pl	pl	pl	pl
Analyse	9	7	8	2	3	4	6	7	11	12	1	3	4	5
SiO_2	67.34	55.01	56.14	55.77	55.54	56.46	56.29	56.40	56.43	51.29	53.59	54.01	53.22	55.34
Al_2O_3	17.70	28.25	27.60	26.94	27.55	26.54	26.51	26.40	26.07	29.22	29.51	28.61	29.11	27.79
SrO	n.d.	0.07	0.07	0.07	0.14	0.10	0.08	0.09	0.08	0.11	0.12	0.05	0.08	0.09
FeO	0.33	0.66	0.48	0.44	0.38	0.38	0.32	0.30	0.24	0.26	0.46	0.43	0.70	0.68
MgO	0.02	0.03	0.03	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.03	0.04	0.05	0.07
BaO	0.03	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
CaO	0.70	10.75	10.22	9.93	10.21	9.24	9.70	9.38	9.46	13.38	12.83	11.93	12.99	11.33
Na_2O	3.25	4.90	5.36	5.45	4.95	6.25	5.51	5.85	5.79	3.73	3.96	4.05	3.99	4.52
K_2O	9.94	0.77	0.43	0.39	0.38	0.42	0.35	0.36	0.49	0.18	0.24	0.25	0.17	0.64
Total	*99.31*	*100.45*	*100.33*	*98.98*	*99.15*	*99.40*	*98.76*	*98.77*	*98.56*	*98.18*	*100.73*	*99.37*	*100.30*	*100.45*
Si	3.052	2.481	2.523	2.539	2.522	2.560	2.562	2.568	2.576	2.377	2.414	2.456	2.412	2.495
Al	0.945	1.502	1.462	1.446	1.475	1.418	1.423	1.416	1.402	1.596	1.567	1.533	1.555	1.477
Sr		0.002	0.002	0.002	0.004	0.003	0.002	0.002	0.002	0.003	0.003	0.001	0.002	0.002
Fe	0.013	0.025	0.018	0.017	0.014	0.014	0.012	0.012	0.009	0.010	0.017	0.016	0.027	0.026
Mg	0.001	0.002	0.002	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.002	0.003	0.004	0.004
Ba	0.001													
Ca	0.034	0.520	0.492	0.484	0.497	0.449	0.473	0.458	0.463	0.665	0.619	0.581	0.631	0.547
Na	0.285	0.428	0.467	0.481	0.436	0.550	0.487	0.516	0.513	0.335	0.346	0.357	0.351	0.395
K	0.574	0.044	0.025	0.023	0.022	0.024	0.020	0.021	0.028	0.011	0.014	0.014	0.010	0.037
cat. sum	4.905	5.004	4.991	4.991	4.970	5.018	4.980	4.993	4.993	4.997	4.982	4.963	4.991	4.983
Or %	64.28	4.44	2.50	2.31	2.29	2.38	2.07	2.09	2.82	1.07	1.44	1.50	0.98	3.76
Ab %	31.94	43.17	47.49	48.69	45.70	53.75	49.64	51.89	51.06	33.15	35.34	37.51	35.38	40.33
An %	3.78	52.39	50.01	49.00	52.02	43.87	48.28	46.02	46.12	65.79	63.22	61.00	63.64	55.90

character of volcanism. Plagioclase phenocryst contains 68% (core) to 46% (rim) anorthite molecules (labradorite to andesine) and plagioclase in a glassy matrix has 40–53% anorthite molecules (Fig. 14, Table 1). This was compared to volcanic lithoclast from the Ratkovce-1 well and a similar composition of the plagioclase phenocryst was observed (55–63% anorthite molecule). Chemical analysis of separated volcanic debris from Trakovice-4 and Ratkovce-1 fluctuates between trachyandesite and andesite (Fig. 13, Table 2) supported also by the occurrence of plagioclase.

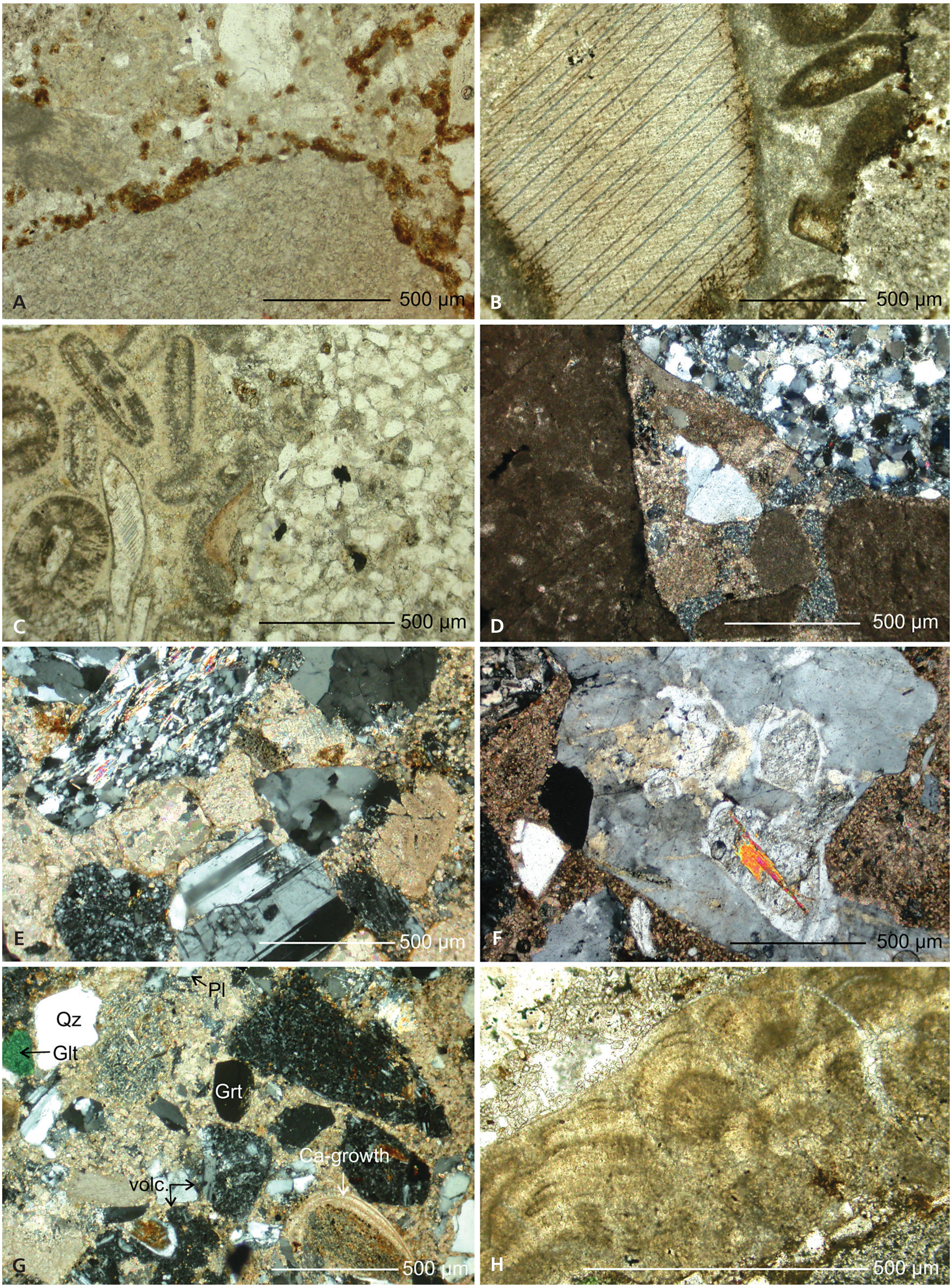
Discussion

The form and shape of the northern Danube Basin is the result of complex tectono-sedimentary processes, which took place during the Neogene (Fig. 1). Biostratigraphy, sedimentary record, structural data, but mainly provenance of the Miocene sediments shows a completely different palaeogeographic configuration than today.

Discussion: Middle Miocene biostratigraphy, palaeogeography, depositional environment and sediment provenance in the north-western Danube Basin

Based on the depositional environment, basal parts of the Cenozoic fill of the studied wells can be assigned to carbonate breccias and rubble (Trakovice-4, Trakovice-1), basal

Figure 8. Microphoto of the key rock types. • A – basal carbonate conglomerate (Jablonica Fm.) with iron oxides in matrix; plane polarized light; Trakovice-4, core 14. • B – debris of the crinoidal limestone in basal conglomerate; plane polarized light; Trakovice-4, core 14. • C – volcanic; plane polarized light; Trakovice-4, core 14. • D – debris of the mikritic carbonate and quartz arenite in poikilitic cement; crossed polars; Trakovice-4, core 12. • E – schist, volcanic clasts, carbonate grain, polycrystalline quartz and pladioclase in sandstone; crossed polars; Trakovice-4, core 4. • F – granitoide debris; crossed polars; Trakovice-4, core 6. • G – Ca-growth on coarse grain, sandstone with high amount of reworked volcanic clasts; crossed polars; Trakovice-4, core 3. • H – fragment of algal growth; plane polarized light; Trakovice-4, core 6.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G
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H
500 µm

Table 2. Chemical composition handpicking volcanic debris.

		Ratkovce-1	Trakovice-4
SiO_2		53.87	61.1
TiO_2		0.64	0.55
Al_2O_3		19.57	20.14
Fe_2O_3*		7.24	2.09
Cr_2O_3		< 0.002	0.002
MgO	%	1.42	0.23
MnO		0.1	0.01
CaO		6.38	4.83
Na_2O		3.13	3.83
K_2O		2.97	3.65
P_2O_5		0.21	0.19
Ni		< 20	< 20
Sc		6	2
Ba		496	529
Nb	ppm	10	10
Sr		320	316
Zr		138	170
Y		18	13
Tot C	%	0.44	0.14
Tot S	%	0.33	0.68

conglomerates without volcanic material of the Jablonica Formation (Ratkovce-1; Rybár *et al.* 2015), and basal conglomerates with volcanic material of the Špačince Formation (Trakovice-4, Trakovice-1, Ratkovce-1).

The carbonate rubble of the Trakovice-1 and Trakovice-4 wells, composed mainly of the carbonate conglomerates, originally assigned by Biela (1978) to the pre-Neogene basement, is assumed to be a product of continental weathering. In the Trakovice-4 well conglomerates filled by red matrix were deposited before the onset of a marine transgression at the water-land interface (Figs 6B, C, 10). In the late Burdigalian–earliest Langhian (late Karpatian–earliest Badenian) the Jablonica and the Aderklaa conglomerates were divided by the transform Leitha fault system today located at the eastern margin of the Vienna Basin. The alluvial to deltaic conglomerate and sandstone seems to be fed from the south-west by similar sources belonging to the tectonic units of the Eastern Alps and Central Western Carpathians (see *e.g.* Kováč 1985, Rybár *et al.* 2015). This led us to believe that they once formed a single unit (Fig. 15A). Their sedimentation took place before the opening of the Vienna Basin pull-apart depocentres and before rifting of the Danube Basin associated with strong volcanic activity (*e.g.* Kováč *et al.* 1989). This assumption is confirmed by the current position of the Jablonica and Aderklaa conglomerates scattered in the southern Vienna Basin, within the horst structure of the Malé Karpaty Mts, and at the base of the north-western Blatné depression sedimentary fill.

Emersion and exposure of the Danube Basin pre-Neogene basement (in its western sector) is additionally reflected in conglomerates with volcanic material present in the lowermost part of the overlying Špačince Formation (Figs 5, 6E, 9, 10). Besides the volcanic epiclasts, they are composed of Mesozoic carbonate, Paleozoic granitoide and gneiss. This indicates provenance in the Tatric crystalline basement together with the cover and nappe units of the Central Western Carpathians. We speculate that the Mesozoic rocks formed the basin margin during the Langhian (Lower Badenian) transgression. The sea probably entered the basin across an archipelago situated in the Danube Basin central-eastern part (Fig. 15B–D). Gradual increase of the crystalline debris at the expense of carbonate clasts in conglomerates indicates continual denudation of the provenance area (Danube Basin basement). Therefore, we assume that the provenance of clasts was in an elevated zone extended from the present Považský Inovec Mts in the north towards the Mihály ridge buried under the Upper Miocene basin fill in the south (in Hungary). Evidence for such elevated structure can be found also in the deep wells Bernolákovo-1, Senec-1, Abrahám-1 and Sereď-8 (Biela 1978), where crystalline rocks of the pre-Neogene basement are directly overlain by Serravallian mudstones. Mesozoic cover and nappe units are absent and minor Langhian sediments are found in the Sereď-8 and Abrahám-1 wells and completely disappear at the Bernolákovo-1 and Senec-1 wells (Biela 1978). Therefore, the transgression did not reach most of the area before the late Langhian–Serravallian.

Based on the above mentioned sedimentary structures and textures in the Trakovice-4 well, sediments belong to a fan-delta depositional system. Moreover, the fan-delta channel sediments can by recognized on the SP log (high negative excursion) between two funnel-shape trends indicating coarsening upwards cycles (1510–1430 m; Fig. 9). In the Trakovice-1 well, a gradual transition from the terrestrial into shallow shelf conditions was observed (Fig. 5). The earliest Langhian (earliest Badenian) juvenile depocentre of the Blatné depression was fed with sediments from the south-west (Kováč 1985), later the source changed and the material was transported from the south-east documented by composition of conglomerates at the Špačince Formation base (Fig. 10).

An offshore sedimentary environment was displayed in the Špačince-5 well at the depth of 2649–2402 m and in Trakovice-1 in the depth of 1454–1450 m (Fig. 3F). In the Trakovice-1 well (1420–1060 m) the SP log shows one symmetrical serrated trend, not visible on the RT log, followed by a belt shape trend visible on both SP and RT logs (Fig. 5). Based on the composition, age classification and alteration similarities, we can speculate about the same provenance of volcanic material in the Trakovice-1,

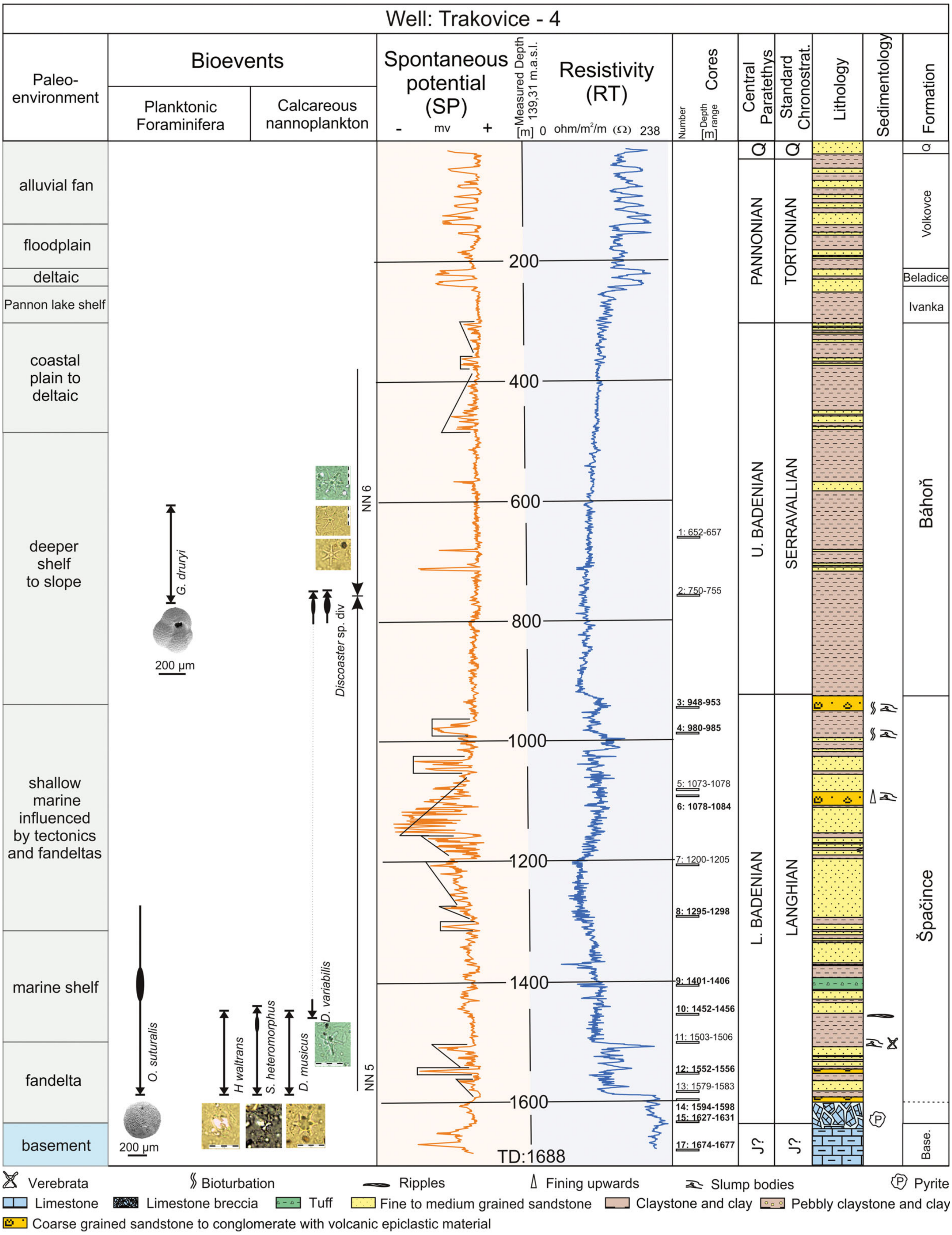

Figure 9. Trakovice-4 well: sedimentary formations, lithology, SP & RT logs, stratigraphy, bioevents and palaeoenvironment of deposition.

Table 3. Selected analyses of garnet calculated on the basis of 8 cations.

Well	Trakovice-1								Trakovice-4					
SiO_2	37.99	37.78	37.67	37.71	36.98	36.69	37.40	36.96	37.82	37.69	38.48	37.99	38.45	35.37
TiO_2	0.13	0.22	0.06	0.31	0.34	0.28	0.00	0.33	0.14	0.37	0.05	0.35	0.02	0.02
Al_2O_3	21.00	21.00	21.30	20.90	21.04	20.89	21.63	20.88	21.46	20.72	21.87	20.82	21.98	0.36
Cr_2O_3	0.00	0.00	0.00	0.00	0.00	0.02	0.07	0.00	0.00	0.01	0.02	0.00	0.02	0.21
Fe_2O_3	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	29.94
FeO	29.44	28.95	31.24	30.73	31.00	30.62	34.66	31.01	28.46	31.22	29.37	31.24	28.13	n.d.
MgO	4.55	4.40	2.75	3.13	3.40	3.21	4.13	3.38	1.32	3.35	7.12	3.27	4.19	0.13
MnO	2.68	3.11	0.09	2.44	2.04	2.56	2.35	2.04	3.24	2.15	1.55	2.19	0.85	0.03
CaO	4.88	5.03	7.38	5.50	5.75	5.58	1.11	5.71	9.04	5.21	2.88	5.46	7.73	33.45
Total	*100.66*	*100.50*	*100.49*	*100.73*	*100.57*	*99.85*	*101.35*	*100.31*	*101.49*	*100.72*	*101.33*	*101.31*	*101.36*	*99.51*
Si	2.987	2.978	2.983	2.990	2.931	2.933	2.955	2.938	2.983	2.988	2.963	2.994	2.982	2.993
Al^T	0.013	0.022	0.017	0.010	0.069	0.067	0.045	0.062	0.017	0.012	0.037	0.006	0.018	0.007
Al	1.934	1.929	1.971	1.943	1.897	1.901	1.969	1.894	1.979	1.924	1.948	1.928	1.991	0.029
Ti	0.007	0.013	0.004	0.018	0.020	0.017	0.000	0.020	0.008	0.022	0.003	0.021	0.001	0.001
Cr	0.000	0.000	0.000	0.000	0.000	0.001	0.004	0.000	0.000	0.001	0.001	0.000	0.001	0.014
Fe^{3+}	0.059	0.058	0.026	0.039	0.083	0.080	0.027	0.086	0.013	0.053	0.048	0.051	0.007	1.906
Fe^{2+}	1.877	1.851	2.044	1.999	1.973	1.967	2.262	1.976	1.865	2.017	1.844	2.009	1.817	0.000
Mg	0.533	0.517	0.324	0.370	0.402	0.382	0.487	0.401	0.155	0.396	0.818	0.384	0.485	0.016
Mn	0.178	0.208	0.006	0.164	0.137	0.173	0.157	0.137	0.216	0.144	0.101	0.146	0.056	0.002
Ca	0.412	0.425	0.626	0.467	0.488	0.478	0.094	0.486	0.764	0.443	0.238	0.461	0.643	3.032
Prp %	17.77	17.23	10.82	12.32	13.41	12.73	16.23	13.36	5.17	13.19	27.26	12.80	16.15	0.54
Sps %	5.94	6.92	0.20	5.46	4.57	5.78	5.24	4.57	7.22	4.82	3.36	4.87	1.86	0.06
Alm %	62.57	61.69	68.12	66.64	65.75	65.56	75.42	65.86	62.15	67.23	61.46	66.95	60.57	0.00
Adr %	2.94	2.88	1.28	1.94	4.13	4.02	1.36	4.30	0.64	2.67	2.39	2.55	0.36	93.74
Grs %	10.78	11.27	19.58	13.64	12.15	11.91	1.76	11.92	24.82	12.09	5.53	12.83	21.06	5.66

Trakovice-4 and Ratkovce-1 wells. Documented volcanic activity is in accordance with assumed Middle Miocene rifting of the Danube Basin during the lateral escape and stretching of ALCAPA microplate from the Alpine domain (*e.g.* Ratschbacher *et al.* 1991; Kováč *et al.* 1994, 1998) associated with the asthenospheric mantle uplift in the Pannonian domain (Konečný *et al.* 2002). The quantity of volcanic material found in all wells led us to believe that volcanoes reached above sea level. The nearest documented volcano (Kráľová) is buried below the basin sedimentary fill. It is identified on seismic lines and in the well core material (Biela 1978, Hrušecký 1999). The volcanic centre is more than 30 km away from the Trakovice wells (near the Šaľa town, Slovakia) and is covered only by Serravallian sediments. Towards the overlying strata in all studied wells the sediments show a quick transition from shallow to deeper marine environment. Deep water conditions are indicated by serrated trends displayed on the SP and RT logs (Figs 5, 9, 10), and the Langhian (Lower Badenian) age of the Špačince Formation is confirmed by a calcareous nannoplankton assemblage of the NN5a, b Zone. The sediment is mostly composed of mudstones with sporadic sandstone intercalations. Observed slump structures in the Špačince Formation (Trakovice-1 and Trakovice-4 wells) triggered by pronounced tectonic activity, which indicate gravity transport could be interpreted as retrogradation of the shoreline (Figs 10, 15B–D). Syn-sedimentary volcanic activity is clearly demonstrated by the presence of volcanic extraclasts in all wells and by a 3.6 m thick tuffite layer in the Trakovice-4 well. This points to the possible presence of a volcano in the vicinity, indirectly proven by a continuous, high amplitude, concave reflector on the reflection seismic line 558-86 (Figs 1, 12). This assumption is additionally supported by preserved sphalerite, andradite and mineralized carbonate grains in the heavy fraction of the Trakovice-1 and Trakovice-4 wells (Fig. 7, Table 3). The volcanic activity in the Danube Basin area must have lasted up to the early Serravallian (Upper Badenian), confirmed by the occurrence of volcanic Pele's hair found in the rinsed residue.

Nannofosils found in the Trakovice-1 well (1310–1255 m) can be compared with the assemblage described by Švábenická (2002) in horizon with *Sphenolithus heteromorphus* in the Lower Badenian mudstones (tegel) of the Carpathian foredeep western part in Moravia. In the

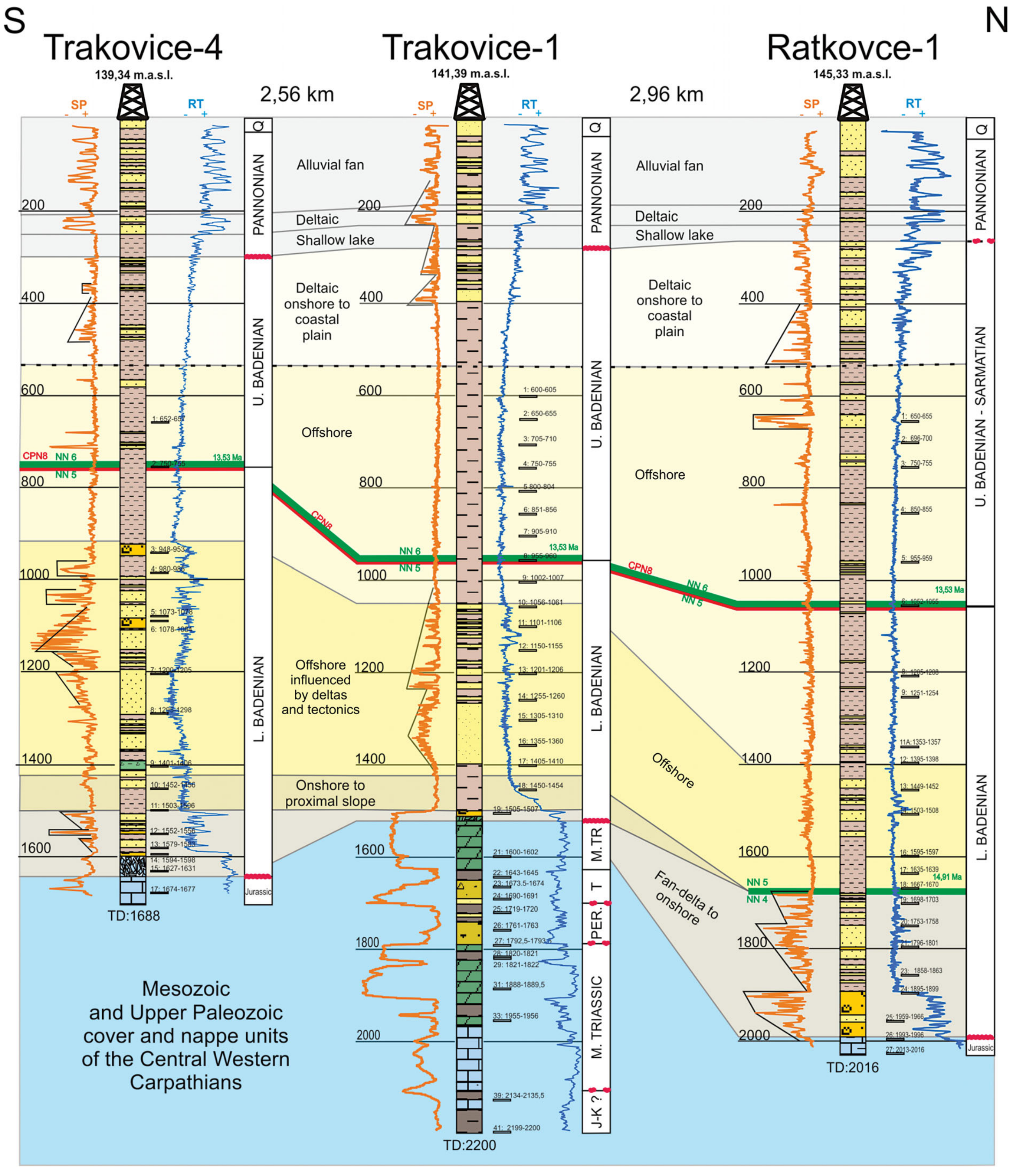

Figure 10. Correlation between the Trakovice-4, Trakovice-1 and Ratkovce-1 wells.

Trakovice-4 well (1390–950 m), the SP and RT logs display two funnel and one bell trend, succeeded by two cylindrical trends documenting progradation and subsequent retrogradation (Fig. 9). At this level, the amount of the reworked volcanic material increases which could imply that the material was deposited by fan-deltas (Fig. 15D). Associated sediments in the Ratkovce-1 well are composed of fine-grained sandstone and mudstone containing debris

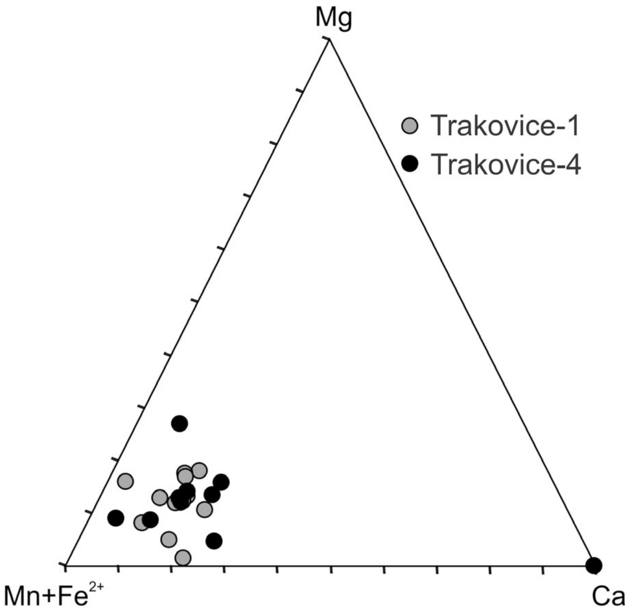

Figure 11. Garnet composition in the Trakovice-1 and Trakovice-4 wells. Andradite garnet is projected to Ca peak.

flow structures linked to slope environment (Rybár *et al.* 2015). Pisoids, fragments of algae and foraminiferal assemblages associated with seaweed growth (*Ammonia parkinsoniana* and *Asterigerinata planorbis*; Trakovice-4, 1205–1200 m) demonstrate that the sediment was derived from the sublittoral zone. Similarly, reworked Burdigalian (Karpatian) microfossils indicate erosion and reworking of older strata along the coastal line. The Langhian (Lower Badenian) age of sedimentary record is demonstrated by the occurrence of *Orbulina suturalis* together with globorotaliids and calcareous nannoplankton of the NN5 Zone. Towards the overlying strata, the diverse and abundant foraminiferal assemblage yielded deep water planktonic foraminifers (Fig. 3; *Orbulina* acme zone, *Globorotalia* sp.; Trakovice-1, 1106–1101 m) similar to the assemblage of "Group II" in the Baden Soos well (Rupp & Hohenegger 2008, Hohenegger *et al.* 2008) and calcareous nannoplankton of the NN5c Zone (Fig. 2) that show deepening of the seabed to 150–200 m (after Ozdínová 2008, Gonera 2013). Gradual flooding of the provenance area followed and was controlled by extensional tectonics, which opened the Danube Basin as a whole. The widening of the sea realm led to retrogradation (Fig. 15D, E). Above the boundary of the NN5 and NN6 zones (Langian–Serravallian) a gradual cessation of fault activity is documented on reflection seismic sections in the Blatné depression (Fig. 12). The early Serravallian (late Badenian) strata were deposited in the neritic offshore zone (Fig. 10). Foraminiferal association and sedimentary structures indicate eutrophic condition and stratification of the water column with dysoxia on the seabed. A mudstone-dominated sequence is confirmed by the shape of the SP and RT logs which hold a serrated trend (Figs 5, 9). This environment is documented also by a rich foraminiferal assemblage (*e.g. Globigerina nepenthes*). Moreover, open marine conditions are supported by the presence of calcareous nannoplankton (bloom of discoasters) and planktonic foraminifera *Globigerina druryi* and *G. decoraperta.* In the Špačince-5 well (2200 m) an association of planktonic and benthic foraminifera indicates sublittoral environment (~ seabed around 200 m). Foraminiferal association (Fig. 3) found in the depth of 960–955 m of the Trakovice-1 well is ranked into the CPN8 Zone (according to Cicha *et al.* 1975). Similar association was also found in the Ratkovce-1 well (1055 m; Rybár *et al.* 2015), in the Špačince-5 well (1402 m) and in the Trakovice-4 well (750 m). The assemblage with dominance of *Globigerina quinqeloba* and *G. bulloides* in the Trakovice-1 well (856–851 m) confirms a nutrient-rich environment in the water column, indicating coastal upwelling conditions (Levitus & Boyer 1994) documented also in the Trakovice-4 well (655 m) and Špačince-5 well (1099 m). Similar foraminiferal association (*Bulimina elongata gr.*, *Hoeglundina elegans*, *Budashewaella willsoni*) studied in the Vienna Basin by Bartakovics & Hudáčková (2004) led us to assume that the water depth was about 150 m during deposition. These environmental conditions were also observed at 705 m of the Trakovice-1 well (*Globorotalia*, *Globigerina*) with more pronounced stratification of the water column (documented by a low diversified assemblage of benthic foraminifera composed by *Bulimina* and *Uvigerina*). A further decrease in temperature is implied by temperate-cold water *Globigerina* assemblage comparable to the Vienna Basin (Hudáčková *et al.* 2002, Báldi 2006, Kováčová & Hudáčková 2009).

In the latest Langian–early Serravallian palaeogeography of the northern Danube Basin gained a similar character as it has today (Fig. 15E). The horst structure of the Malé Karpaty Mts appeared on the surface, at least in the form of an archipelago and supplied pebble material for conglomerates on the Blatné depression western margin (Doľany conglomerate Member; Vass 2002). The eastern margin of the Blatné depression was still not elevated.

In the uppermost part of the studied wells, the absence of planktonic foraminifera and the presence of benthic *Bulimina elongata* and *Ammonia* sp. confirm further restriction of water circulation, shallowing and gradual basin fill up (Trakovice-1, 650 m; Fig. 5). The occurrence of volcanic Pele's hair refers to continuous volcanic activity. Towards the top of the Middle Miocene, the SP and RT logs display an increase in the amount of sandy layers (Figs 5, 9, 10). This can be connected with the Serravallian (late Badenian–Sarmatian) deltaic system described in the neighbouring Rišňovce depression (Fordinál & Elečko 2000, Kováč *et al.* 2006). After the late Serravallian regres-

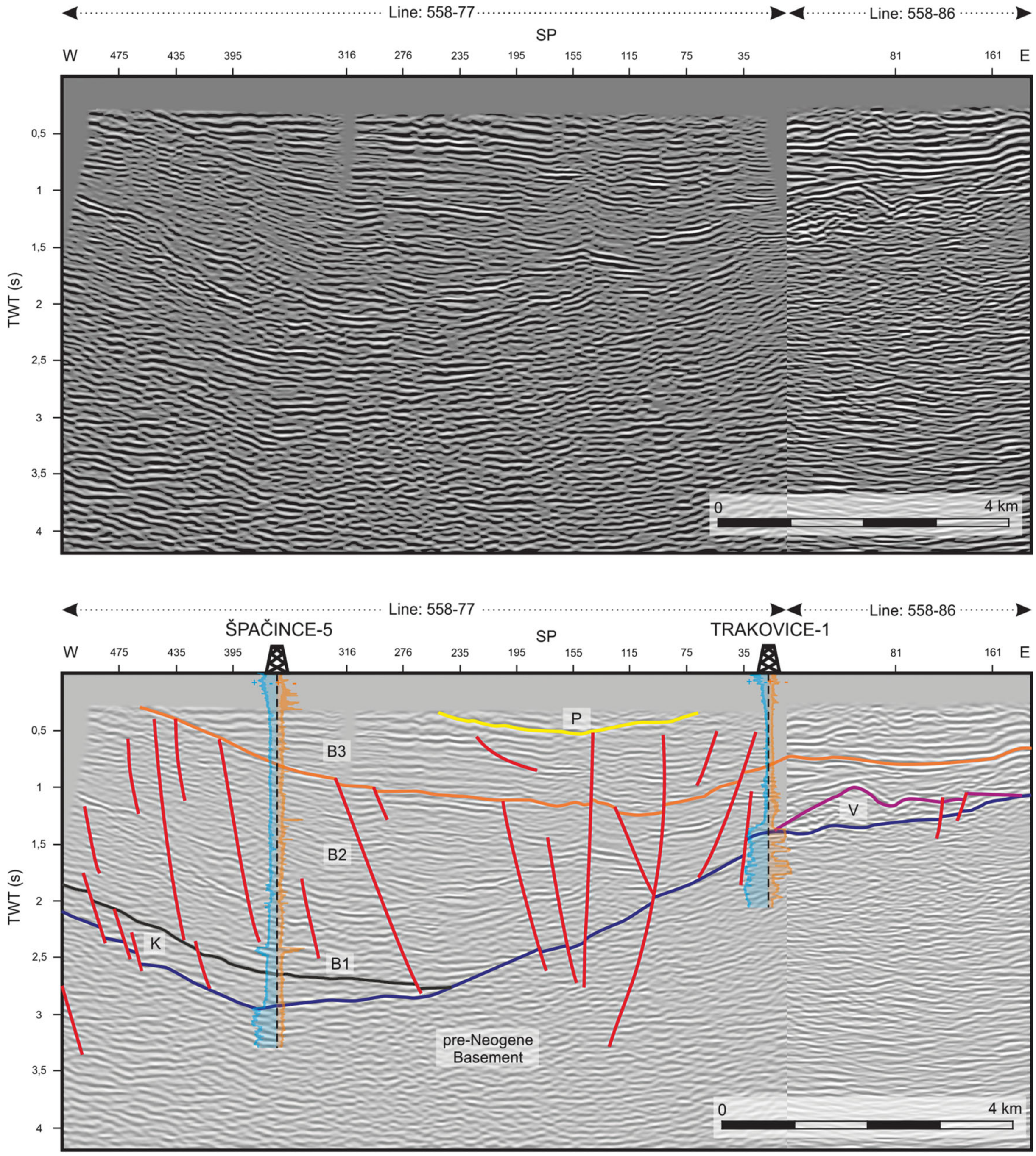

Figure 12. Interpretation of reflection seismic lines 558-77 and 558-86: A – clean line, B – interpreted line. Explanatory notes: K – Karpatian (NN4); B1 – Lower Badenian (NN4); B2 – Lower Badenian (NN5); B3 – Upper Badenian (NN6); P – Pannonian; V – volcanics.

sion, an overall decrease in salinity in the Central Paratethys is observed. Gradual uplift of surrounding mountain ranges during the late Serravallian (Sarmatian) is recorded in the pollen spectra containing mountain vegetation (Kvaček *et al.* 2006).

Finally lacustrine conditions of Lake Pannon are documented in the Danube Basin (Kováč 2000) and indicate transition to the Late Miocene.

Discussion: Late Miocene to Quaternary biostratigraphy, palaeogeography, depositional environment and sediment provenance in the north-western Danube Basin

Compared to the previous Middle Miocene synrift development, the Late Miocene sedimentation in the Blatné

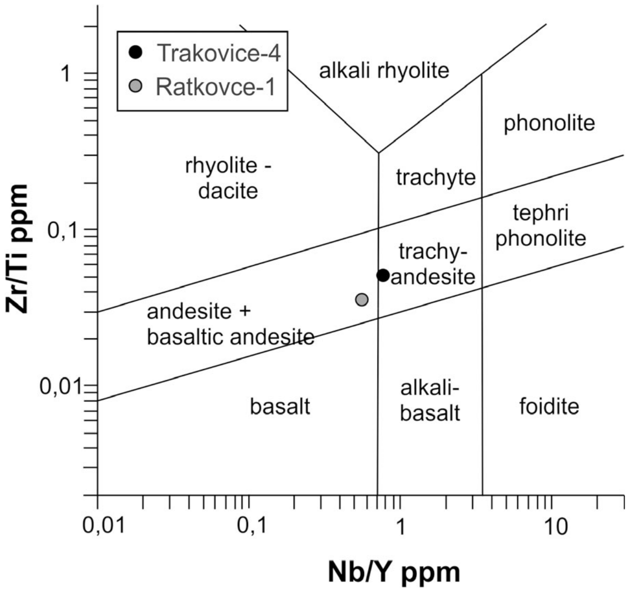

Figure 13. Chemical composition of separated volcanic fragments in discrimination diagram (after Pearce 1996).

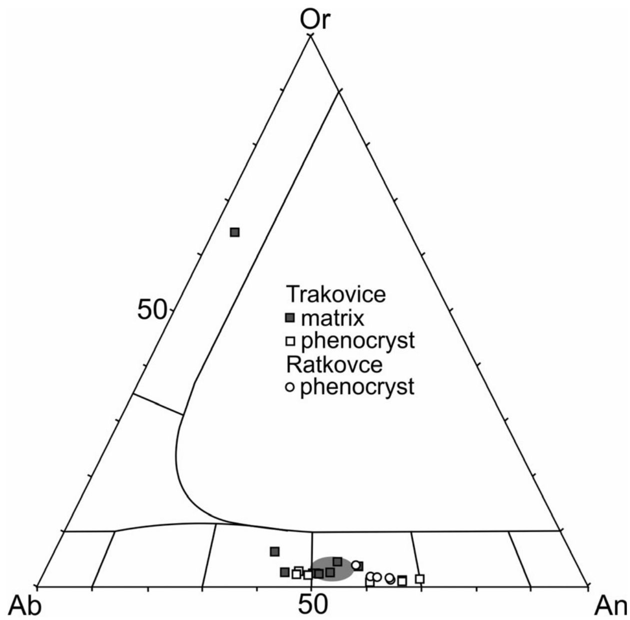

Figure 14. Feldspar composition from reworked volcanic clasts. Grey field – no published data from the Kráľová stratovolcano (Kráľová-1 well).

depression is only marginal, unlike in the centre of the Danube Basin (Tari *et al.* 1992; Magyar *et al.* 1999, 2013; Kováč *et al.* 2011). The Malé Karpaty Mts and Považský Inovec Mts rimmed the depression only in its northern part, in the southern part a significant uplift of these mountains is documented.

The beginning of the Late Miocene epoch in the Blatné depression was related to the water level rise of Lake Pannon, which reached its maximum extent at *ca* 10.5 Ma (Magyar *et al.* 1999, Harzhauser *et al.* 2008, Harzhauser & Mandic 2008, Ter Borg *et al.* 2013). Transgressive facies mostly overlie an erosive surface, that may be related to a basin inversion phase at the Middle-Late Miocene boundary (could be correlated with the Sarmatian unconformity), documented in the central part of the Pannonian Basin System (Horváth *et al.* 2006). The Late Miocene sequence represents a continual record of sedimentation. Basal clastics are usually absent, with an exception observed in the south-western part (gravels in the Bučany-29 and Bučany-24 wells; Fig. 16). Lacustrine sediments are mostly composed of grey and green calcareous mudstone. Well-log trends are serrated with low amplitude. In the basal part of the lacustrine sequence in the Trakovice-2 and Trakovice-8 wells a thick blocky pattern (up to 10 m) was observed. This indicates an input of coarse-grained material into the shallow lacustrine environment. The funnel shaped trend in the Ratkovce-1 well (280–260 m) might indicate a prograding fan-delta lobe. The earliest Tortonian (earliest Pannonian) lacustrine sequence was linked by Lunga (1964a, b, 1968) to the mollusc zones B and C (*sensu* Papp 1951). It contains sublittoral *Congeria czjzeki* (Lunga 1965, Maglay *et al.* 2011) and littoral, brackish molluscs of the *Limnocardium conjugens* Zone (Magyar *et al.* 2007). Deposits, with a stable thickness of 80–100 m, accumulated in shallow shelfal environment were assigned to the Ivanka Formation. The Tortonian evolution of the Blatné depression is similar to the development in the Vienna Basin (Kováč *et al.* 1998), nevertheless it differs from the other parts of the Danube Basin, where the lacustrine sequence reaches a considerably higher thickness.

The Pannonian biozones D and E (*sensu* Papp 1951) are absent in the Blatné depression. This was probably caused by a transition from lacustrine to deltaic sedimentation between 10.5–10.0 Ma (Šujan *et al.* 2016). The above-mentioned transition was previously interpreted as a hiatus (Lunga 1965). Deltaic succession in the Blatné depression is represented by the Beladice Formation, the former equivalent of the mollusc zone F (*sensu* Papp 1951). Large amount of sandy and gravel layers with sporadic clays, occurring mainly in the northern part, indicate that the sediment source area was in close proximity (Figs 10, 16). Grey and green clays with reddish mottles and calcareous nodules of the delta plain intercalate with grey to blue calcareous clays and lignite layers of lake and pond deposits. Coarsening upward deltaic parasequences with a thickness of 10–20 m are represented by funnel-shapes on the SP and RT logs. The curves also contain blocky and symmetrical trends probably belonging to distributary channels. The freshwater to terrestrial environment is indicated by the occurrence of mollusc genera *Planorbis*, *Monacha*, *Theodoxus*, *Melanopsis* and *Mytilopsis neumayri* (Lunga 1965,

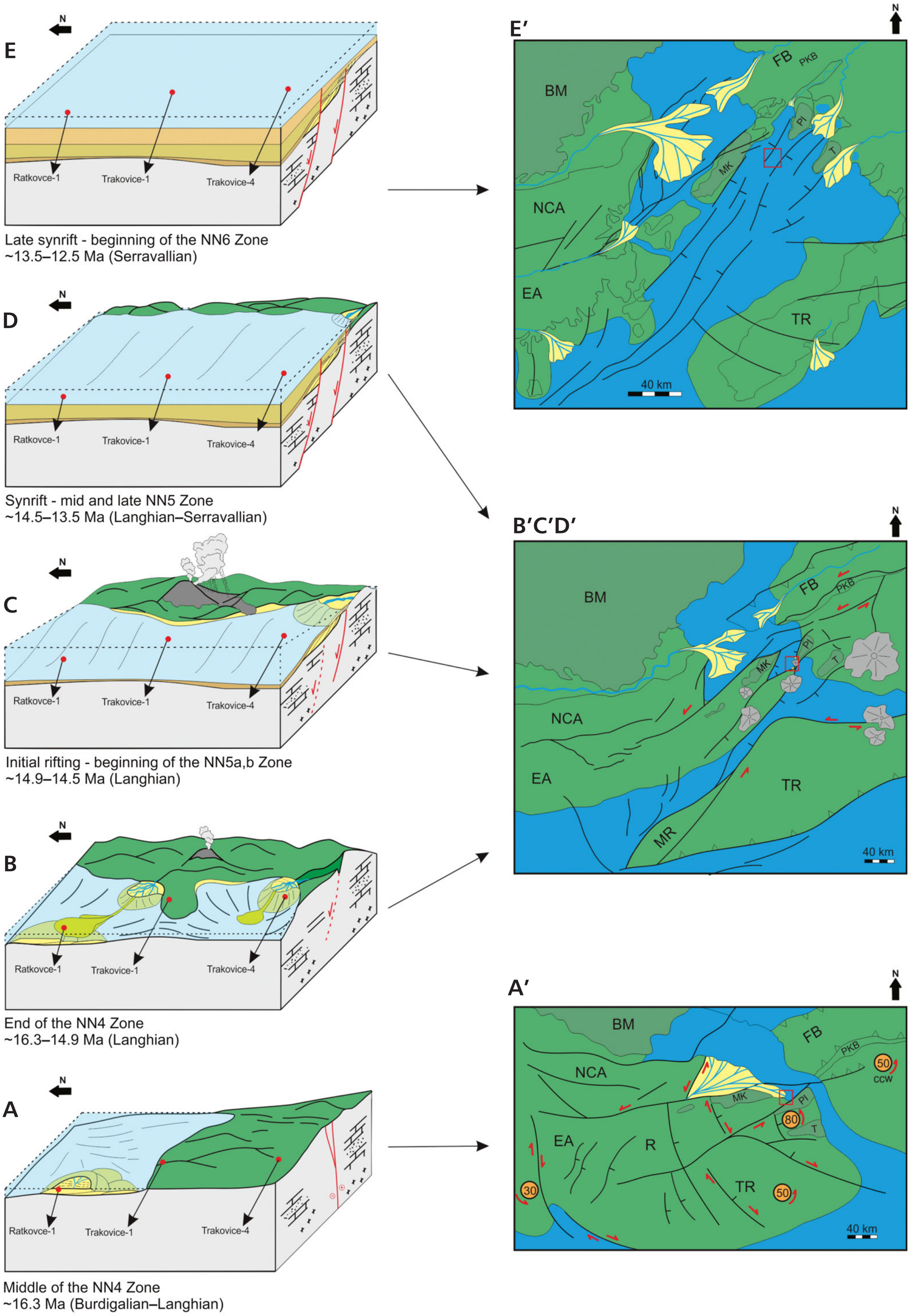

Figure 15. Block diagrams and palinspastic scheme of the northern Danube Basin evolution. Explanatory notes: BM – Bohemian Massive; CCW – counter-clockwise rotation; EA – Eastern Alps; FB – Flysh Belt; MK – Malé Karpaty Mountains; MR – Mihály ridge; NCA – Northern Calcareous Alps; PI – Považský Inovec Mountains; PKB – Pienniny Klippen Belt; R – Rechnitz window; T – Tríbeč Mountains; TR – Transdanubian range; black lines – faults; blue colour – water mass; grey colour – volcanic bodies; green colour – lad mass; red arrows – indicating fault kinematics; red square – location of block diagrams in map view; yellow circle – rotation in degrees and direction; yellow colour – deltaic deposits. Rotations after Márton *et al.* (1995).

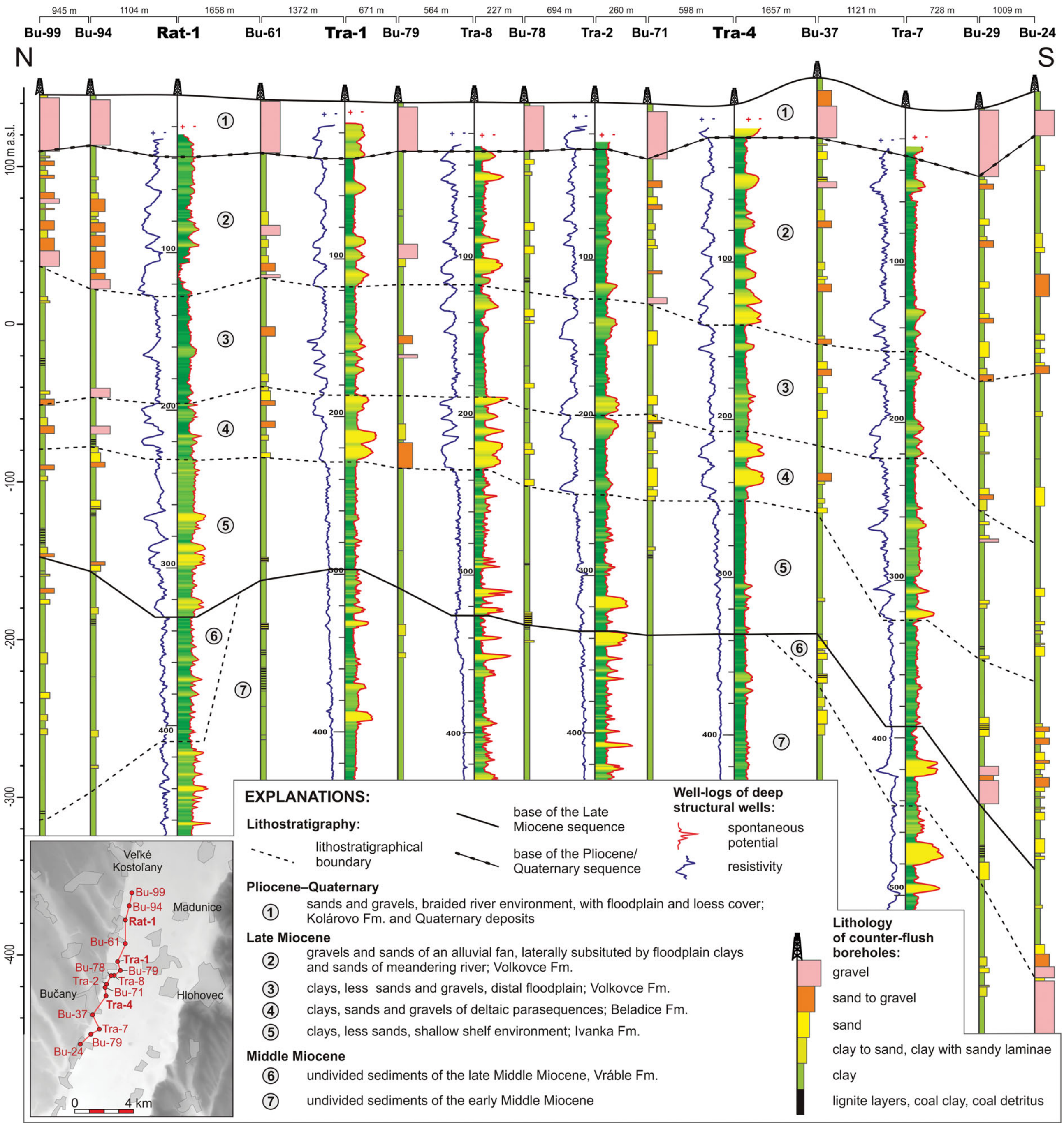

Figure 16. Late Miocene to Quaternary stratigraphic section based on the lithological logs of counter-flush wells and associated well logs. The Late Miocene sequence is assumed to be continual and bounded by two erosive surfaces: (1) Middle–Late Miocene boundary from below and (2) Late Miocene–Pliocene boundary from above, which is a result of the basin margins inversion (*sensu* Horváth 1995). Note a relatively low thickness of each stratigraphic unit, which increases gently to the south.

1966). The Beladice Formation in the northern and central part of the Blatné depression is about 30–40 m thick, in the southern part thickness increases up to 110 m. Minor thickness of this formation suggests relatively fast regression.

Sedimentation of the alluvial Volkovce Formation started at *ca* 10.0 Ma (Šujan *et al.* 2016), synchronously with culmination of the Tortonian humidity (Böhme *et al.* 2011). The Volkovce Formation could be divided into two parts with different lithofacial features (Figs 10, 16). The ~70 m thick lower part is predominantly formed by mudstones intercalated by 5–10 m thick gravel and sand layers. Clays are variegated and include plant remnants and slight reddish mottles. The low amplitudes serrated and bell shaped well logs can be interpreted as meandering channel bodies. The upper part is up to 100 m thick and is characterized by a high amount of gravel layers, representing an alluvial fan probably associated with the palaeo-Váh river. The gravels form up to 100% of the Volkovce Formation sediments near the Piešťany town (Šujan 2012). The volume of coarse-grained layers decreases towards the south, where the river reached the alluvial plain and lost its transport capacity. Negative values on the SP log in the Ratkovce-1 well (depth 125–110 m) could be caused by a high content of coal detritus in the gravel. Irregularly distributed bell shaped and cylindrical trends are common (Fig. 16). Increasing thickness of the formation towards the south points out to a still active differential subsidence. Sedimentation of the Volkovce Formation lasted to ~6–7 Ma, inferred from the occurrence of *Deinotherium proavum* (MN12 mammal biozone; Musil 1959, Tóth 2010), as well as from authigenic ^{10}Be/^{9}Be dating (Šujan *et al.* 2016).

Late Pliocene Kolárovo Formation and Quaternary deposits form the uppermost part of the studied section, with an approximately 40 m thick gravel body (Fig. 16) that is separated from the Volkovce Formation by a suggested hiatus. Low thickness and almost no vertical tectonic displacement of the coarse grained strata could be explained by sedimentation during a low subsidence regime (~4.0 Ma to recent). The sedimentary record reflects an increase of material supply from the uplifted mountains. The uplift was a result of basin inversion during the Early Pliocene (Horváth 1995). Finally the fluvial sequence was covered by floodplain deposits and by the Pleistocene loess.

Conclusions

1. Provenance of the latest Burdigalian–earliest Langhian (latest Karpatian–earliest Badenian) fan-delta conglomerates without volcanic material, deposited at the base of the northern Danube Basin (Blatné depression), indicates an emerged area to the southwest. This mountain range was built up from units of the Eastern Alps and from the pre-Neogene basement of the central Danube Basin (Fig. 15A, A'). The successive basin fill, which was originally deposited above the basal conglomerates (Jablonica Formation) at the northern foothills of the uplifted domain is composed of dark brownish mudstones with a benthic foraminiferal assemblage, consists mostly of agglutinated specimens of *Bathysiphon pokutica*, *B.* sp. and *Lagenammina* sp. ranked into the earliest Badenian (Špačince-5 well; Fig. 12). The earliest Langhian age was derived from a calcareous nannoplankton assemblage documenting the end of NN4 Zone (LO of *H. ampliaperta*; ~ older than 14.91 Ma).

2. Opening of the Langian (early Badenian) depocentre of the Blatné depression is accompanied by transition from a continental to marine environment. Onshore to proximal slope conditions coincided with the beginning of the calcareous nannoplankton NN5 Zone (~ younger than 14.91 Ma). Local fan-deltas at the base of the Špačince Formation deposited volcanoclastic conglomerates. Composition of conglomerates documents a provenance area in the south-east of the basin (Fig. 15B, B', C, C').

3. Further synrift subsidence, still associated with volcanism, resulted in deposition of mudstones and sandstones. Pronounced tectonic activity led to rapid basin deepening and development of a shelf-slope system during the calcareous nannoplankton zone NN5a, b (started with *Orbulina suturalis*; ~ younger than 15.1 Ma). During this phase, two facial types of the Špačince Formation were deposited: well-sorted conglomerates and sandstones (channel fill of fan-deltas) and diamictites with gravity transport features as slumping and armoured clay intraclasts. A basin floor environment evolved and started to dominate during the calcareous nannoplankton NN5c Zone (Fig. 15D, D').

4. Around the boundary of the NN5/NN6 zones (latest Langhian–early Serravallian; ~13.5 Ma), a calming of tectonic activity is documented which adverts the late synrift phase (Figs 10, 12). The basin was filled by offshore mudstones of the Báhoň Formation (early Serravallian; NN6 Zone), which gradually gained a dysoxic character at the basin bottom (Fig. 15E, E').

5. In the late Serravallian (~12.8 Ma) shelfal facies changed to the shallow water coastal plains of the Vráble Formation as a result of the basin fill up. The proceeding Sarmatian sedimentation is affected by regression and denudation of the area.

6. In the Late Miocene (Tortonian; ~11.6 Ma) a transgression of Lake Pannon created a shallow shelfal environment, which was subsequently replaced by a short-lived deltaic system (~10.5–10.0 Ma) and followed by deposition on an alluvial plain (~10.0–6.8 Ma). These Pannonian depositional environments are represented by the Ivánka, Beladice and Volkovce formations.

7. The Pliocene to Quaternary flood plain sedimentation is represented by alluvial and fluvial deposits (since ~5.33 Ma).

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