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Biostratigraphy, sedimentology and paleoenvironments of the northern Danube Basin: Ratkovce 1 well case study

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Abstract: The Ratkovce 1 well, drilled in the Blatné depocenter of the northern Danube Basin penetrated the Miocene sedimentary record with a total thickness of 2000 m. Biostratigraphically, the NN4, NN5 and NN6 Zones of calcareous nannoplankton were documented; CPN7 and CPN8 foraminifer Zones (N9, 10, 11 of the global foraminiferal zonation; and MMi4a; MMi5 and MMi6 of the Mediterranean foraminiferal zonation were recognized. Sedimentology was based on description of well core material, and together with SP and RT logs, used to characterize paleoenvironmental conditions of the deposition. Five sedimentary facies were reconstructed: (1) fan-delta to onshore environment which developed during the Lower Badenian; (2) followed by the Lower Badenian proximal slope gravity currents sediments; (3) distal slope turbidites were deposited in the Lower and Upper Badenian; (4) at the very end of the Upper Badenian and during the Sarmatian a coastal plain of normal marine to brackish environment developed; (5) sedimentation finished with the Pannonian–Pliocene shallow lacustrine to alluvial plain deposits. The provenance analysis records that the sediment of the well-cores was derived from crystalline basement granitoides and gneisses and from the Permian to Lower Cretaceous sedimentary cover and nappe units of the Western Carpathians and the Eastern Alps. Moreover, the Lower Badenian volcanism was an important source of sediments in the lower part of the sequence.

Key words: Danube Basin, Blatné depression, Middle and Upper Miocene, biostratigraphy, sedimentology, sedimentary petrology, depositional systems.

Introduction

The Danube Basin, located at the junction of the Eastern Alpine, Western Carpathian and Transdanubian Range, represents an important depocenter of the Pannonian Basin System on its north-western margin (Kováč 2000). The basin is divided into finger like bays situated between the Western Carpathian core mountains (Malé Karpaty, Považský Inovec, and Tríbeč Mts), and from W to E known as the Blatné, Rišňovce and Komjatice depressions (Vass 2002). In the Blatné Depression, the Ratkovce 1 well (Lat: 48° 29′ 4.2216″ Lon: 17° 55′ 48.3528″) penetrates the Middle and Upper Miocene sedimentary record (Fig. 1). The studied well, along with multiple other wells was drilled for petroleum prospecting in the late 1960s and 1970s, and was technically documented in a drilling report (Imrichová 1969). Lithostratigraphy, biostratigraphy and geophysical measurements were compiled adequate to current knowledge and methods. Isopach maps of the basin sedimentary fill were worked out by Adam & Dlabač (1969), and later the available well data were summarized by Biela (1978), without revision of sedimentology, and only with scarce refining of existing biostratigraphy. Reinterpretations of the older geophysical data in the 1990s were carried out by Hrušecký et al. (1993, 1996). Complex studies of the paleogeography, geodynamic evolution, and sequence stratigraphy of the Carpathian-Pannonian region during the Miocene were published by Kováč et al. (1999), and Kováč (2000). Paleoflora, paleoclimate and Miocene landscape was analysed in the papers of Kvaček et al. (2006), Kováč et al. (2006, 2011) and Kováčová et al. (2011). Andreyeva Grigorovich et al. (2003), Harzhauser et al. (2007), Harzhauser & Mandič (2008), and Hohenegger et al. (2014) enriched the integrated stratigraphy of the Central Paratethys, with possible implications for the Danube Basin.

Revision and re-evaluation of the well-core material from the Ratkovce 1 borehole after more than 45 years, using advanced methods of biostratigraphy, sedimentology and geophysics should contribute not only to clarify the models of basin evolution, but also the paleogeography and geodynamics of adjacent area (the works were carried out in the scope of the SRDA Project 0099-11 Danube).

Geological setting

Opening of the Danube Basin was caused by Badenian rifting over an asthenospheric upwelling, like in the whole Danube Basin area (Lankreier et al. 1995; Konečný et al. 2002). A NW-SE orientated transtensional regime was active during the entire Middle Miocene. In the latest Miocene thermal subsidence set in and subsequently deltaic and alluvial sediments filled the depocenter (Tari et al. 1992; Tari & Horváth 1995; Kováč 2000; Horváth et al. 2006).

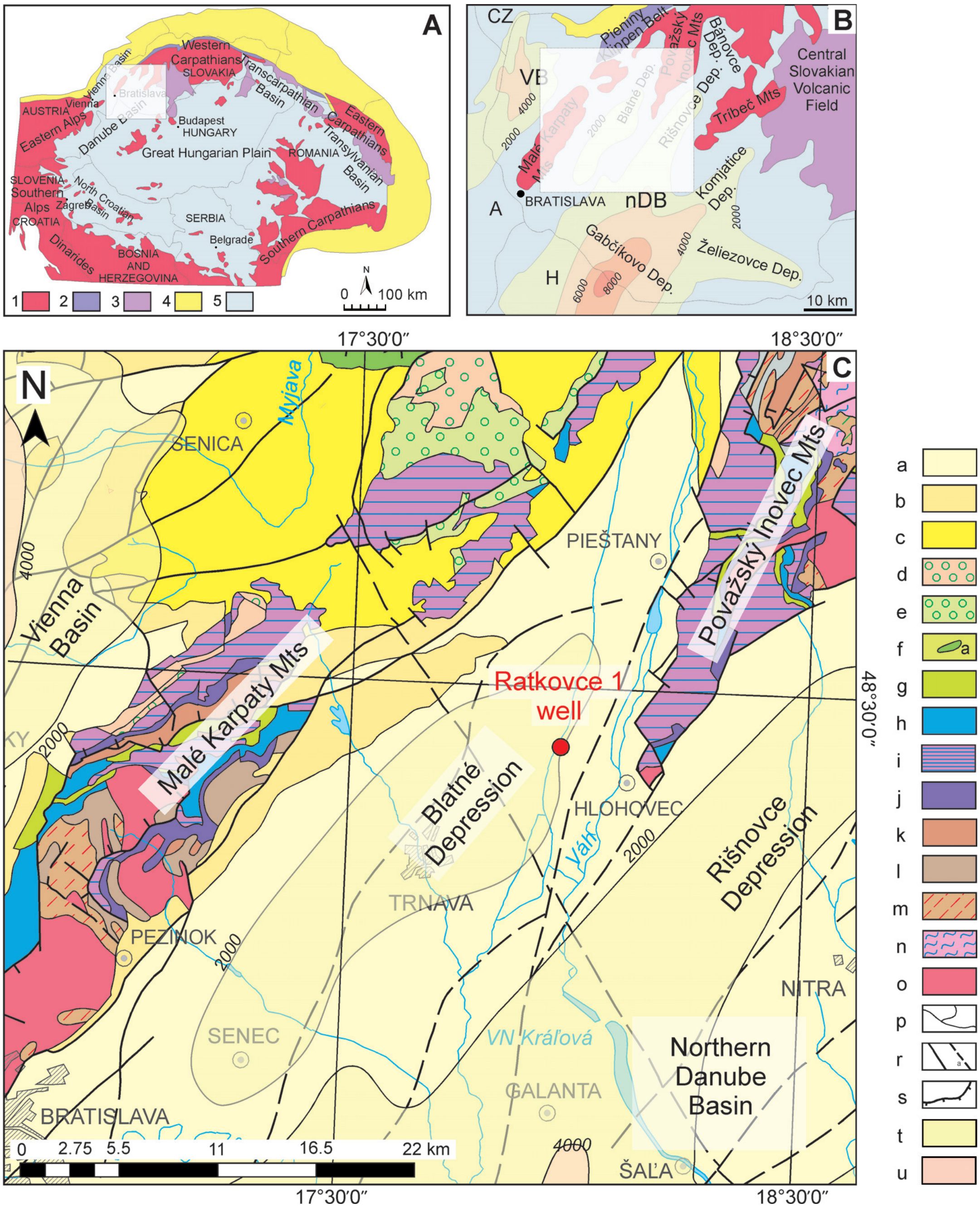


Fig. 1. Geological maps of (**A**) the Danube Basin, (**B**) Western Slovakia and (**C**) the Blatné Depression and its surroundings, with the position of the Ratkovce 1 well marked. **Explanatory notes to A and B:** 1 — Inner Alpine-Carpathian-Dinaride Units, 2 — Pieniny Klippen Belt, 3 — Neogene volcanic fields, 4 — Alpine and Outer Carpathian Flysch Belt, 5 — Neogene basins (modified from Kováč et al. 2011). **Explanatory notes to C:** a — mostly clays, silts, sands, gravels and rare lignite seams (Late Miocene–Pliocene); b — clays, claystones, siltstones, sands, sandstones, gravels, conglomerates, subordinate evaporites, algal limestones, coal seams and andesite tuffites and epiclastic volcanic rocks (Middle Miocene); c — claystones, siltstones, sands, sandstones, gravels, conglomerates, subordinate evaporites, organodetritic limestones, coal seams and rhyolite tuffs and tuffites (Early Miocene); d — conglomerates, sandstones, limestones, breccias (Paleocene–Eocene); e — marls, limestones, sandstones, conglomerates (Late Cretaceous); f — shales, marls, sandstones, conglomerates — mostly flysch (Late Cretaceous–Eocene); f-a — klippen of Jurassic–Early Cretaceous radiolarites and limestones; g — limestones, marly limestones, marlstones, shales, sandstones (Early Cretaceous); h — sandy, crinoid, mottled, radiolarian and nodular limestones, cherts, shales (Jurassic); i — limestones, dolomites, locally shales and sandstones (Middle–Upper Triassic); j — calcareous shales, shales, sandstones and quartzites (Early Triassic); k — variegated conglomerates, sandstones and shales, locally evaporites and volcanic rocks (Permian); l — phyllites and mica shists with metavolcanite horizons (Proterozoic?–Early Paleozoic); m — paragneisses, mica shists and migmatitic gneisses (Proterozoic?–Early Paleozoic); n — orthogneisses and migmatites with amphibolites and paragneiss layers (Proterozoic?–Early Paleozoic); o — granitoids, granites, granodiorites, tonalites (Late Devonian?); p — geological boundaries; r — faults: a — assumed, s — nappe and overthrust lines, t — areas where depth to basement exceeds 2000 m, u — areas where depth to basement exceeds 4000 m. Modified from Biely et al. (1996) and Kováč et al. (2011).

The sedimentary sequence of the Ratkovce 1 well in the Blatné depression begins with the earliest Badenian strata, deposited unconformably above the pre Neogene basement. After the latest Karpatian/earliest Badenian terrestrial deposition, the whole area was flooded by a transgression, which led to the shallow to deep marine environment of the Špačince and Báhoň formations, which persisted during the whole Early and Late Badenian (Vass 2002; Kováč et al. 2007). During the Sarmatian, the marine environment gradually changed to brackish and the Vráble Formation was deposited (Vass 2002; Kováč et al. 2007). The Upper Miocene succession is built up by the lacustrine Ivánka Formation, which passes into the shallow water to swamp environment of the Beladice Formation (Kováč et al. 2010). Sediments of the delta to alluvial plain are represented by the Volkovce Formation (Upper Miocene to Pliocene) and in some places are overlain by the Pliocene to Pleistocene deluvial to alluvial Kolárovo Formation (Kováč et al. 2011).

Material and methods

Well core material was obtained from the well repository of Nafta a.s. situated in the town of Gbely. For the micropaleontological analysis, 45 rock samples were collected and processed by standard preparation methods (described in Kováčová & Hudáčková 2009). Calcareous nannofossils were analysed quantitatively in smear slides prepared from all lithologies by the standard techniques (e.g. described in Švábenická 2002; Jamrich & Halásová 2011). Slides were studied under an Olympus BX 50 polarizing microscope (magnification 1250×). For biostratigraphic interpretations nannoplankton and foraminiferal associations were used, in the sense of the standard zonation of Grill (1941) and Cicha et al. (1975), the stratigraphic ranges of foraminifers follow Cicha et al. (1998), Wade (2011), Iaccarino et al. (2011), Turco et al. 2011 and Gradstein et al. (2012). Calcareous nannoplankton was compared with the standard NN zones after Martini (1971). The current status of the Miocene Central Paratethys stratigraphy 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 Ratkovce 1 well cores (Fig. 2). Paleoecological parameters were evaluated for samples containing at least 200 individuals of benthic foraminifers on the presence and dominance of taxa, exhibiting special environmental significance. Species with similar environmental importance were grouped to enable better interpretation of their distributional patterns. In order to identify and characterize changes in the assemblage structures and to relate these to changing environmental conditions for general interpretation, the data was treated statistically using the PAST software (Hammer et al. 2001). Assemblage structures and environmental stress of the foraminifers were investigated through diversity indices (Simpson, Shannon-Wiener — H' and Evenness — J'). Taphonomic analysis of the foraminiferal assemblage in the studied samples was done and evaluated according to the methods described by Holcová (1997, 1999).

The preparation of palynological samples 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 and by using $ZnCl_2$ (heavy liquid with density = 2 g/cm^3); palynomorphs were extracted in a centrifuge.

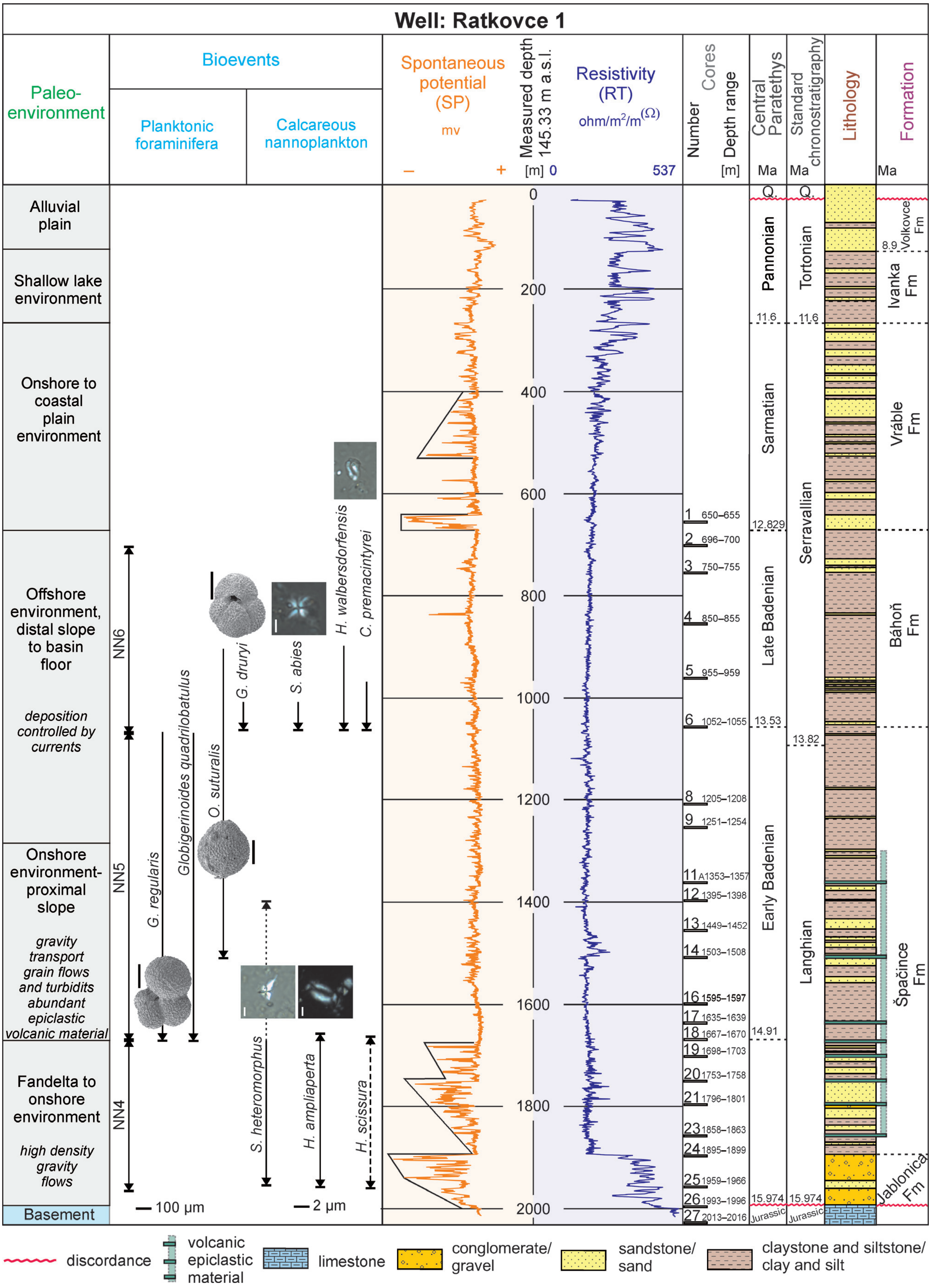
For provenance determination, coarse grained samples were selected and studied under a polarization microscope. Heavy mineral analysis was done using the 0.25–0.10 mm fraction, which was studied under a binocular microscope, and confirmed by an EDAX analysis. Garnets were analysed by a WDS quantitative analysis, with the microprobe Camera SX-100 at the Geological Institute of Dionýz Štúr, Bratislava, Slovak Republic. Measurement conditions: 15 keV 20 nA. Standards: LiF (F $K\alpha$), albite (Na $K\alpha$), orthoclase (Si $K\alpha$), Al_2O_3 (Al $K\alpha$), forsterite (Mg $K\alpha$), NaCl (Cl $K\alpha$), orthoclase (K $K\alpha$), wollastonite (Ca $K\alpha$), TiO_2 (Ti $K\alpha$), fayalite (Fe $K\alpha$), rodonite (Mn $K\alpha$), Cr (Cr $K\alpha$). Garnet analysis was calculated based on 8 cations. The Fe^{2+} and Fe^{3+} charge balance was calculated to ideal stechiometry. Photo-documentation of the separated clasts was done by a trinocular stereomicroscope (Olympus KL 1500 LCD) and the QuickPHOTO MICRO 3.0 software was used.

For the purposes of the sedimentological analysis 31 well core samples were collected, all available cores and their sampler cards were photographed. Then the samples were cut in half perpendicular to the bedding plane, washed, and treated for preservation with dispersive glue (WURSTOL and HERKULES), scanned, digitalized and finally the sedimentary textures and structures were documented, mainly in the sense of Miall (2010). Further, the evaluation of a well was based on spontaneous potential (SP) and resistivity (RT) core logs. The curves originally constructed by Moravské naftové doly, n.p. (Imrichová 1969) were interpreted based on Rider (1986), Emery & Myers (1996) and Catuneanu et al. (2011).

Biostratigraphy and paleoecology of the Ratkovce 1 well core record

The first biostratigraphical ranking of the well cores was done by Jandová (in Imrichová 1969). Thanks to a very well preserved and rich assemblage of planktonic foraminifera, yielding *Globigerina* (*Zeaglobigerina*) *decoraperta* (Takayanagi & Saito) and *Globigerina* (*Zeaglobigerina*) *druryi* (Akers) in the upper part of well core 6 — Cicha et al. (1975) established this material as the "holotype" of the Middle Badenian planktonic foraminiferal Zone CPN8 Globigerina druryi–Globigerina decoraperta. This zone was correlated by Cicha et al. (1975) with the NN5 nannoplankton Zone; although the calcareous nanoplankton assemblage was never studied in the well.

The re-evaluation of cores brought new data: the NN4 Zone of calcareous nannoplankton was detected from the base up to the well core 18 (1667–1670 m) based on the co-occurrence of the *Sphenolithus heteromorphus*, *Helicosphaera scissura* and rare *H. ampliaperta*. This zone represents the Karpatian–lowermost Badenian stage of the


Well: Ratkovce 1
Paleo-environment
Bioevents
Planktonic foraminifera
Calcareous nannoplankton
Spontaneous potential (SP)
mv
Measured depth 145.33 m a.s.l.
[m]
Resistivity (RT)
ohm/m²/m(Ω)
0
537
Cores
Number
Depth range
[m]
Central Paratethys
Ma
Standard chronostratigraphy
Ma
Lithology
Formation
Ma
Alluvial plain
Shallow lake environment
Onshore to coastal plain environment
Offshore environment, distal slope to basin floor
deposition controlled by currents
Onshore environment-proximal slope
gravity transport grain flows and turbidits abundant epiclastic volcanic material
Fandelta to onshore environment
high density gravity flows
Basement
NN6
NN5
NN4
G. regularis
Globigerinoides quadrilobatulus
O. suturalis
G. druryi
S. abies
H. walbersdorfensis
C. premacintyrei
S. heteromorphus
H. ampliaperta
H. scissura
100 µm
2 µm
0
200
400
600
800
1000
1200
1400
1600
1800
2000
1 650–655
2 696–700
3 750–755
4 850–855
5 955–959
6 1052–1055
8 1205–1208
9 1251–1254
11 A1353–1357
12 1395–1398
13 1449–1452
14 1503–1508
16 1595–1597
17 1635–1639
18 1667–1670
19 1698–1703
20 1753–1758
21 1796–1801
23 1858–1863
24 1895–1899
25 1959–1966
26 1993–1996
27 2013–2016
Q.
Pannonian
11.6
Sarmatian
12.829
Late Badenian
13.53
Early Badenian
14.91
15.974
Jurassic
Q.
Tortonian
11.6
Serravallian
13.82
Langhian
15.974
Jurassic
8.9
Volkovce Fm
Ivanka Fm
Vráble Fm
Báhoň Fm
Špačince Fm
Jablonica Fm
discordance
volcanic epiclastic material
limestone
conglomerate/gravel
sandstone/sand
claystone and siltstone/clay and silt

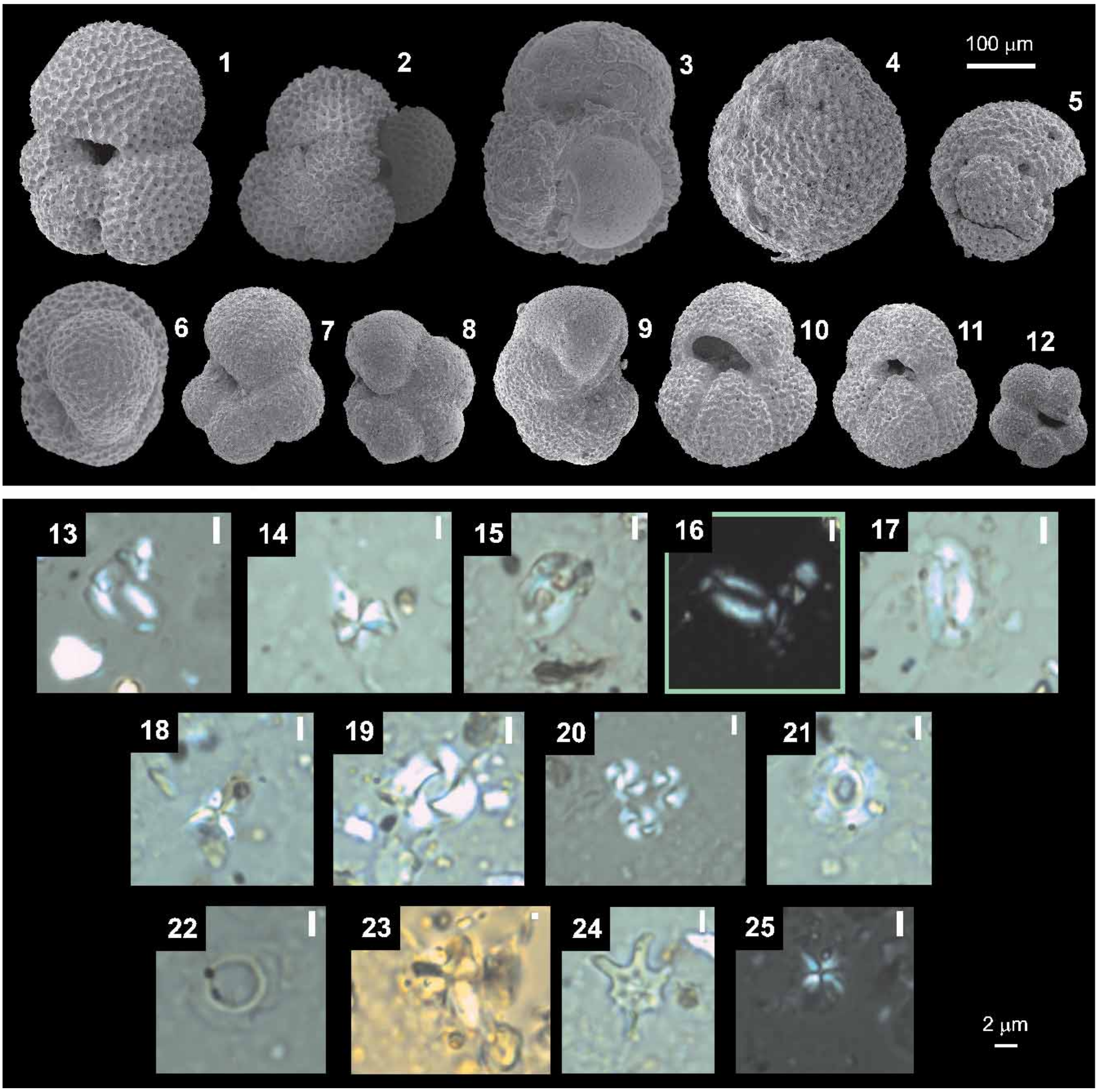


Fig. 3. **1** — *Globigerinoides quadrilobatus* (d'Orbigny), Rat1/11A/1/10; **2** — *Globigerinoides quadrilobatus* (d'Orbigny), Rat1/2/1/30; **3** — *Globigerinoides quadrilobatus* (d'Orbigny), Rat1/19/2/20; **4** — *Orbulina suturalis* Brönnimann, Rat1/12/1/10; **5** — *Globigerinoides* cf. *sicanus* De Stefani, Rat1/12/1/10; **6** — *Catapsydrax* sp. cf. *parvulus* Bolli, Loeblich & Tappan; **7** — *Globigerina regularis* d'Orbigny; **8** — *Globorotalia partimlabiata* Ruggieri & Sprovieri, Rat1/6/3/25; **9** — *Globorotalia* sp., Rat1/6/3/50 (not in WFD); **10** — *Globigerina woodi decoraperta* Takayanagi & Saito, Rat1/6/3/25; **11** — *Globigerina druyi* Akers, Rat1/6/3/25; **12** — *Turborotalita quinqueloba* (Natland), Rat1/19/2/20; **13** — *Helicosphaera ampliaperta* (Bramlette & Wilcoxon), Rat1/19/2/70; **14** — *Sphenolithus heteromorphus* (Deflandre), Rat1/19/2/70; **15** — *Helicosphaera mediterrannea* (Müller), Rat1/19/2/20; **16** — *Helicosphaera scissura* (Miller), Rat1/19/2/20; **17** — *Helicosphaera scissura* (Miller), Rat1/23/2/43; **18** — *Sphenolithus heteromorphus* (Deflandre), Rat1/23/2/43; **19** — *Reticulofenestra pseudoumbilicus* 7 μm (Gartner) Gartner, Rat1/6/3/25; **20** — *Reticulofenestra haqii* (Backman), Rat1/6/3/25; **21** — *Calcidiscus premacintyrei* (Theodoridis), Rat1/6/3/25; **22** — *Umbilicosphaera rotula* (Kamptner), Varol, Rat1/6/3/25; **23** — *Sphenolithus heteromorphus* Deflandre, Rat1/18/2/35; **24** — *Discoaster variabilis (*Martini & Bramlette), Rat1/6/3/25; **25** — *Helicosphaera walbersdorfensis* Müller, Rat1/6/6/75.

Fig. 2. Passport of the Ratkovce 1 well. Biostratigraphy column shows first occurrences (FO) and last occurrences (LO) of important index foraminifers and nannoplankton, as well as nannoplankton biozones (with black arrows) as were identified in the studied material. Correlations between Central Paratethys and standard chronostratigraphy modified from (Kováč et al. 2000, 2007, 2011; Hohenegger et al. 2014).

Central Paratethys scale (Figs. 2, 3). In the core 19 *Globigerinoides sicanus* de Stefani (3 apertures) and *Globigerina regularis* (d'Orbigny) were identified. From the well core 18 up to core 6, the NN5 Zone was identified (sensu Cicha et al. 1975), and at present is assigned to the Lower Badenian (Kováč et al. 2007; Hohenegger et al. 2014). Moreover, the NN5a Zone (sensu Andreyeva-Grigorovich et al. 2001) was identified, but the NN5b and NN5c zones of calcareous nannoplankton were not identified. The foraminiferal assemblage of the cores 18 to 6 yielded planktonic foraminifera *Globigerinoides quadrilobatulus* (d'Orbigny). The Lower Badenian biozone CPN7, based on the first occurrence (FO) of *Orbulina suturalis* (Brönnimann) was linked to core 14, where *O. suturalis* (Brönnimann) was first detected. Similar events were identified in the Badenian parastratotype of the Židlochovice site by Doláková et al. (2014). In well core 6 (1052–1055 m), the NN6 Zone documents the Upper Badenian (Fig. 2) based on the acme event of *Sphenolithus abies* (Andreyeva-Grigorovich et al. 2001) together with *H. walbersdorfensis* and absence of *S. heteromorphus* (Figs. 2, 3).

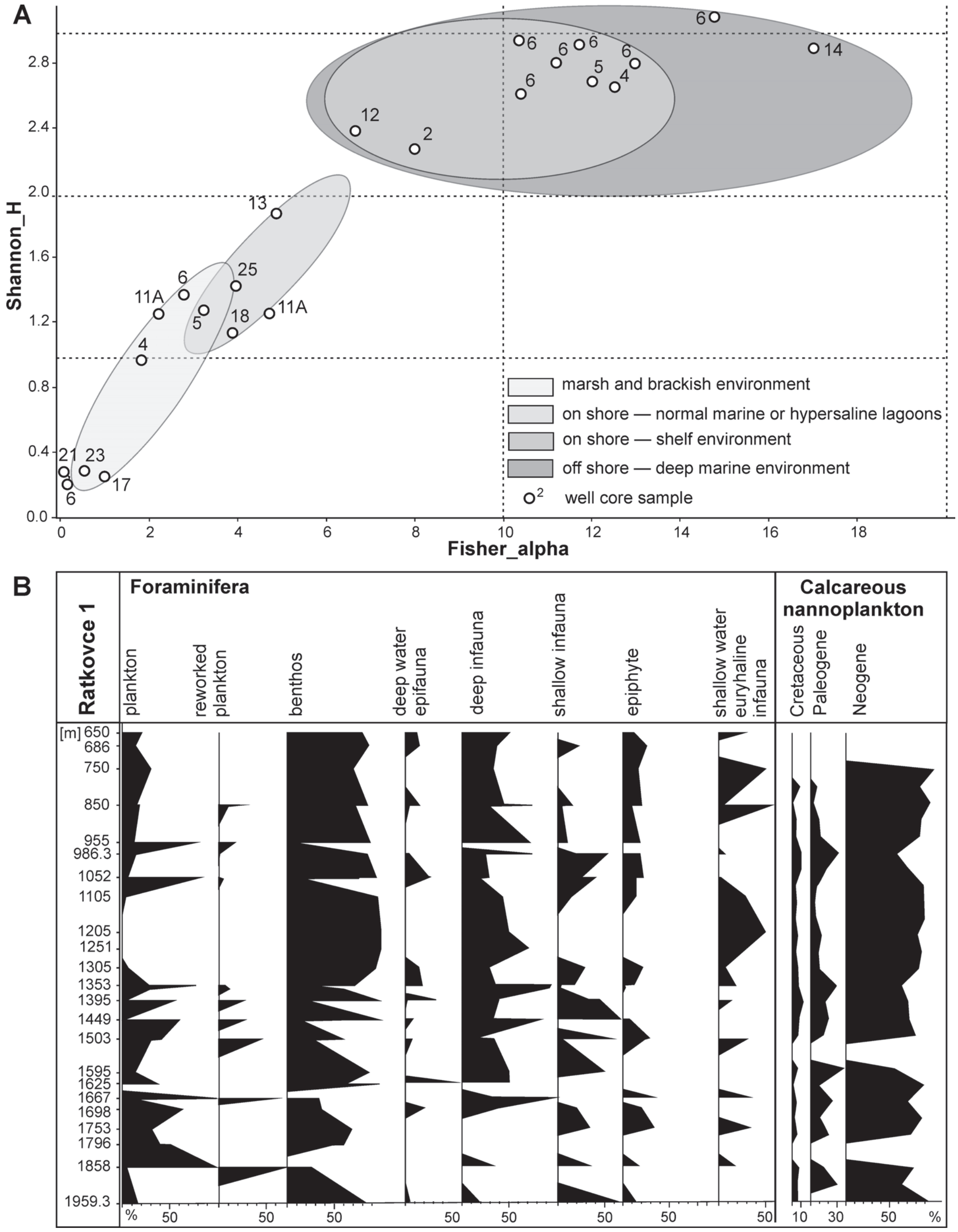


Fig. 4. Diversity and percentages of Foraminifera and calcareous nannoplankton. **A** — Diversity ratio diagram, **B** — Dominance diagram. Percentages of significant groups of Foraminifera and calcareous nannoplankton.

The foraminiferal assemblage in these sediments is typical for the CPN8 Zone, based on the FO of *Globigerina druryi* (Akers) together with *G. woodi decoraperta* (Takayanagi & Saito). In the sediments of core 5, the acme of *Paragloborotalia siakensis* LeRoy (?synonyme of *Globorotalia partimlabiata* Ruggieri & Sprovieri) was detected.

Classical "lagenide" and "agglutinated" zones of the Lower and Middle Badenian based on benthic foraminifera were not identified in the studied well profile, in contrast to the very well developed Bolivina/Bulimina Zone (sensu Grill 1941; Cicha et al. 1975). These zones were strongly linked to changes of environmental conditions and do not appear to be stratigraphically significant. In spite of the fact, that the well core6 was formerly assigned to the Middle Badenian (Wieliczkian) in the sense of our recent results these sediments represent the Upper Badenian age, associated with the NN6 Zone (sensu Kováč et al. 2007; Hohenegger et al. 2014).

For paleoecological purposes, benthic foraminifera dominance, diversity and similarity diagrams were constructed, moreover a diversity ratio graph was added (sensu Murray 2006 — Fig. 4). Samples from the well cores 25, 23, 21, 18, 17 cluster in brackish marsh to normal marine environments and confirm the deltaic to onshore position of sedimentation. Faunal associations from the well cores 12 and 14 appear in shelf to offshore deep marine environments. Nevertheless some associations are clustered in a shallow marine environment, mainly in the samples from well cores 13 and 11A, therefore this mixture of shallow and deep marine elements is interpreted as a re-deposition of foraminifera. Moreover, this statement is based on signs of size sorting and abrasion of the foraminiferal tests. The majority of associations from cores 6, 5, 4, and 2 appear to be clustered in deep marine offshore to shelf conditions with low energy environment. But on the other hand a couple of associations from these cores are scattered in-between normal marine, hypersaline lagoons and brackish march environments. This fact again confirms re-deposition from a shallow water environment, also documented by the colour and bad preservation of tests (Fig. 3).

A palynological record from the Lower Badenian sedimentary fill shows rare palynomorphs, poor in quality of preservation, probably due to the higher oxidation rates. Obtained pollen, spores and algae assemblages have been characterized by rare occurrence and a high degree of corrosion. They include: *Ulmus*, *Carya*, *Pinus*, *Pterocarya*, *Cathaya*, *Myrica*, *Castanopsis*, *Quercus*, Sapotaceae, Polypodiaceae, Dinoflagellata and Acritarcha. The samples contain a high amount of diverse palyno-debris including reworked ones, pointing to dynamic transport conditions into the accumulation space.

The Upper Badenian sediments contained very well preserved and diversified palynomorph associations. Azonal (coastal and swamp) vegetation was represented by *Myricipites bituides*, *M. myricoides Sparganium*, *Glyptostrobus*, *Nyssa*, and Cyperaceae. Zonal vegetation was documented by the fern spores Polypodiaceae, pollen *Pterocarya*, *Symplocos*, *Cercidiphyllum*, *Carya*, *Carpinus*, *Quercus*, *Engelhardia*, *Castanopsis*, Sapotaceae and a high amount of *Pinus*. Extrazonal mountain related vegetation is presented by *Picea*, *Abies*, *Cathaya* and *Tsuga*. The character of the palynomorphs' preservation, together with the high ratio of dinoflagelates, acritarchs, foraminiferal test linings and fungi spores confirm their fast burial without damage in the basinal environment.

Sedimentology and depositional environments of the Ratkovce 1 well record

The sedimentary textures, structures and the shape of the SP and RT logs were described from bottom to top (Figs. 2, 5 and 6). The basal part of the well sequence is composed of conglomerates with intercalations of sandstones, siltstone and claystones, resembling the Jablonica Formation (e.g. Kováč et al. 1989). Sediments are composed of a matrix supported conglomerate with fine to coarse grained, subangular to well rounded pebbles, including carbonate, quartzite, granitoid and volcanic pebbles (some clasts reach up to 5 cm in diameter). The matrix is represented by coarse to fine grained sand. Some samples of the well core contain indistinct 5–15 cm thick fining upwards conglomerate layers, cross-bedding and clay intraclasts — armoured mud balls (Fig. 5). The lower cores (26–24; Fig. 2), in contrast to the upper cores (23–19; Fig. 2) do not contain Miocene volcanic admixture (Jablonica Formation s.s.). Occasionally, the conglomerates of upper cores pass into coarse grained lithic sandstone and brown claystone. This fabric points to high density gravitational flows during the high order cyclicity of relative sea level changes (parasequence sets). Heterolithic sediments composed of claystone and sandstone with possible ripple cross lamination indicate onshore environments (Fig. 5). In claystones abundant mica, macrofauna fragments (echinoids) and carbonized plate fragments were observed. The 70–90° dip of the bedding in rhythmically layered claystone and siltstone might have been caused by syn-sedimentary tectonics due to transtensional faulting during opening of the Blatné Depression (1753–1758 m); or by normal faulting in the delta front environment. The SP log shape is characterized by 3 funnel shape trends changing from a positive to a negative anomaly with a sharp border at the top of cycles. We interpret them as coarse grained deltaic facies with progradational parasequence sets and minor deepening in-between (Fig. 2). The first (oldest) cycle appears at 1990–1900 m; the second cycle at 1900–1750 m and the third at 1750–1680 m. The RT log confirms tight coarse clastic material in the first cycle, while the second and third cycles are not visible in the shape of RT curve. This fact can also be explained by the composition of well cores, which are no longer built up predominantly from conglomerate and sandstone but also contain claystone and siltstone (Fig. 5). The onshore sedimentary environment of the deposition of conglomerate and sandstone is also confirmed by the foraminiferal assemblage diversity ratio belonging to a marsh–brackish environment, as well as by pollen analysis with pollen mean dissemination values (sensu Dyakowska 1959) and character of preservation of their exine, pointing out dynamic transport conditions.

The overlying sequence can by divided into two parts. The lower part (1680–1300 m) is composed of pale brown to grey, bioturbated claystone and siltstone which contains mica, carbonized plant fragments, macrofauna (bivalves and


J17 Sc1
50–55 cm
C17 Sc1
40–50 cm
C17 Sc1
30–38 cm
C20 Sc2
25–40 cm
C19 Sc1
0–1 cm
C18 Sc1
35–37 cm
C23 Sc1
60–65 cm
C21 Sc1
50–62 cm
C23 Sc2
C23 Sc1
0–10 cm
C24 Sc4
C25 Sc1
58–64 cm
C27 Sc1
C25 Sc1
30–34 cm
C24 Sc2
30–50 cm

echinoid fragments) and scarce ripples. Layered diamictite (pebbly claystone) in the depth 1503–1508 m is poorly sorted (clasts reach up to 5 cm in diameter) and we interpret it as debris flows on the basin proximal slope (Fig. 6). The overlying sediments pass into turbidite sequences with horizontal — ripple cross — lamination and flame structures. On some lithoclasts $CaCO_3$ encrustation growth rings (pisoide) were observed, and this validates re-deposition of the grains from high energy shallow water conditions into a deeper low energy environment.

The upper (1300–670 m), predominantly mudstone sequence is composed of pale brown to grey claystone and siltstone; rare layers of fine grained sandstone are present, as well. The sedimentary succession contains occasional parting lineation indicating upper flow regime and distal thin bedded turbidity current transport in the offshore environment. Parting lineation could be confused with traction marks (Fig. 6).

The SP and RT logs from 1680 to 670 m show a serrated shape which represents alterations of thin layers of sandstone and claystone, indicating frequent changes of depositional conditions confirming interpreted turbidity current transport. Moreover, influence of strong storm activity cannot be excluded here (tempestites). The excursion of the RT log at around 1500 m correlates well with the diamictite recognized in the well core material (core 14, Fig. 6). Nevertheless this excursion on the RT log could also by explained by saturation with salt waters. Sedimentology and interpretations of the log's pattern (1680–670 m) correspond well with foraminifers' diversity ratio (Fig. 3) referring to an onshore shelf environment with gradual passage to the offshore deep marine environment. The foraminiferal associations display a reduction of the shallow water species towards the upper part of the sequence, which is confirmed additionally by pollen data pointing to their fast burial without damage on the basin floor.

The top part of the existing well cores is built up by conglomerate composed of angular fragments (possibly intraformational) of laminated sandstone and siltstone in siltstone to claystone matrix (Fig. 6); carbonized plate fragments are abundant. These sedimentary structures may be interpreted as coastal plain or tidal lag deposits (sense Mial 2010). On the SP log cylindrical and bell -shaped excursions were recorded (670–400 m). The basal cylindrical excursion can be interpreted as a channel fill. The fining upwards trend of the curved upper part refers to a shoreline — shelf system (Fig. 2), and documents a change from dynamic to calm environment (sensu Emery & Myers 1996). The RT log shows gradual increase in resistivity, possibly caused by increasing saturation of the sediment with ground water.

The uppermost part of the well belongs to the latest Middle and Upper Miocene (without well core material) and was interpreted only with the help of available data from the study area, as a brackish lake depositional environment (e.g. Kováč et al. 2006, 2011).

Sedimentary petrology and provenance of sediment in the Ratkovce 1 well record

The Ratkovce 1 well penetrates down to the basement rocks recognized already in the original drilling report as Triassic rocks formed by dark grey, dolomitized limestone cut by calcite veins and intercalated by dark grey graphitic shale (Gaža in Imrichová 1969; Biela 1978). Nevertheless, our results from the pre Neogene basement samples determined dark grey to black limestone (wackestone) and calcareous shale. Poorly recrystallized limestones (biomicrite) containing: abundant calcificated porifera spicules, filaments, ostracods, detritic quartz and pyrite alochems, all together indicating Jurassic age which is in contrast to the original determination.

Furthermore, petrological study of clasts from the Miocene sedimentary fill show that material was derived from the crystalline basement of the neighbouring Eastern Alpine–Western Carpathian complexes, covered by the Mesozoic and Paleogene sediments.

Granitoid lithoclasts contain quartz, plagioclase, microcline, perthitized feldspars and biotite crystals, plagioclase with zonal structures, as well as a lesser amount of fragments of mica schist to gneisses composed of mica and quartz which were derived from crystalline complexes (Fig. 7). They most closely correspond in character to the granitoids at

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Fig. 5. Sedimentary textures and structures: **Core 27, Sampler-card 1** — Dark grey, tectonically disturbed, layered limestone cut by abundant calcite veins; **Core 25, Sampler-card 1** — (58–64 cm from the bottom): Brown to dark blue carbonate conglomerate, (clasts reach up to 5 cm in diameter); **Core 25, Sampler-card 1** — (30–34 cm from the bottom): Pale brown to grey pebbly claystone with armoured clay intraclasts; **Core 24, Sampler-card 2** — (30–51 cm from the bottom): Pale yellow to grey, coarse grained lithic, pebbly sandstone to conglomerate. Clasts reach up to 4 cm in diameter; **Core 23, Sampler-card 1** — (60–65 cm from the bottom): Brown claystone, and pale yellow, lithic, sandstone with possible ripples (interpretation: heterolithic sediment indicating deposition in the neritic zone); **Core 23, Sampler-card 1** — (0–10 cm from the bottom): Pale grey coarse grained sandstone and fine grained conglomerate with possible cross bedding (interpretation: slight change in velocity or depth of flow); **Core 23, sampler-card 2** — laminated siltstone and claystone; **Core 21, sampler-card 1** — (50–62 cm from the bottom): Pale brown carbonate conglomerate (clasts up to 4 cm in diameter). The sandy matrix is poorly sorted; **Core 20, Sampler-card 2** — (25–40 cm from the bottom): Pale yellow, laminated siltstone and claystone. Layers dipping at a 60°–70° angle (*nearby fault*?); **Core 19, Sampler-card 4** — (0–1 cm from the bottom): Pale brown to grey claystone, abundant mica and macrofauna fragments (echinoids) visible on the bedding planes; **Core 18, sampler-card 1** — (35–37 cm from the bottom): Pale brown to grey claystone, with ripple cross lamination and flame structures, abundant occurrence of mica; **Core 17, Sampler-card 1** — (30–38 cm from the bottom): Brown and pale yellow lithic sandstone and brown claystone with carbonized plant fragments; **Core 17, Sampler-card 1** — (40–50 cm from the bottom): Brown and pale yellow medium grained sandstone and grey claystone with carbonized plant fragments, containing flame structures; **Core 17, Sampler-card 1** — (50–55 cm from the bottom): Pale grey sandstone and grey claystone with carbonized plant fragments and leniticular bedding. Used scale 1 cm.

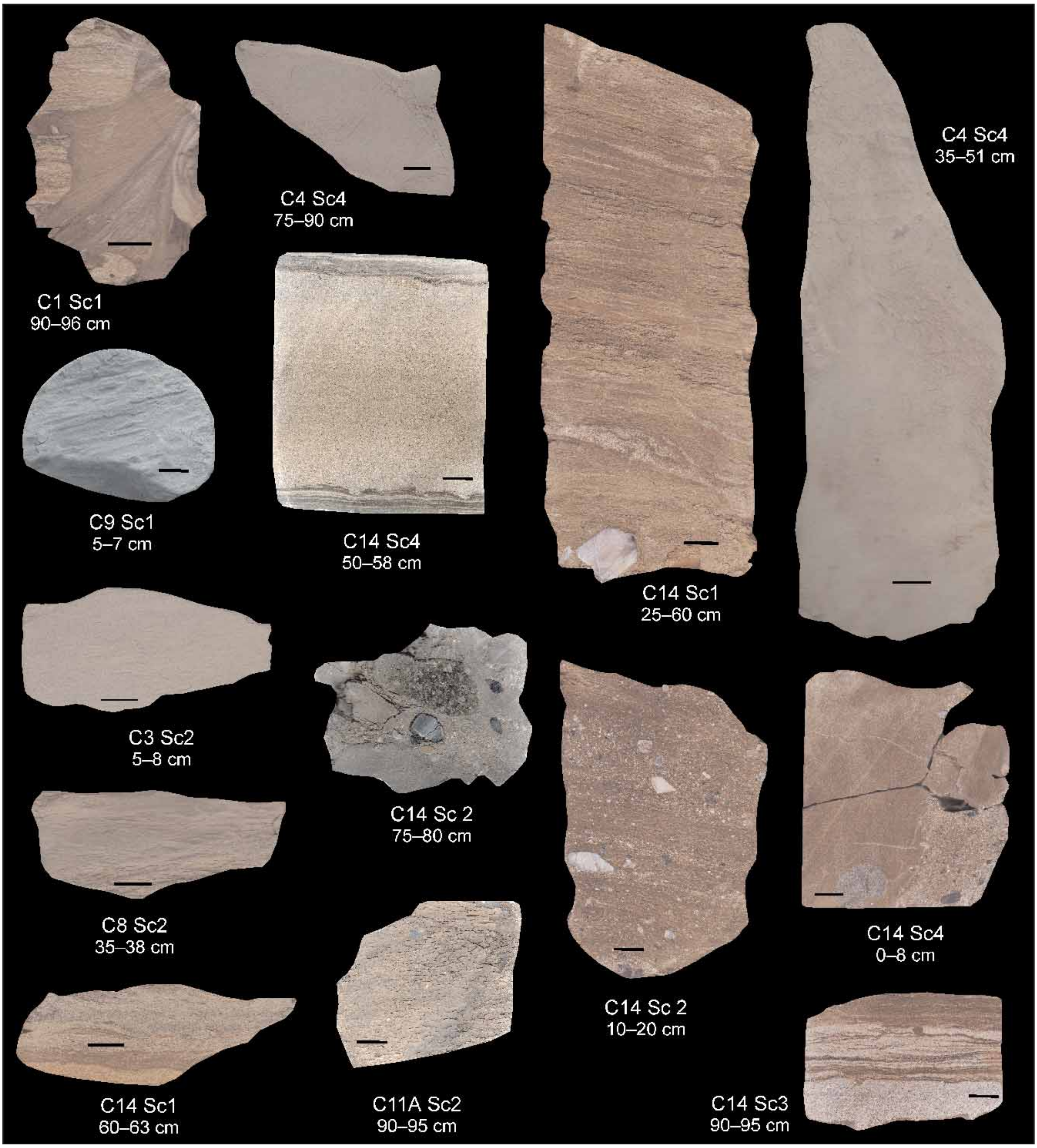

Fig. 6. Sedimentary textures and structures: **Core 14, sampler-card 2** — (75–80 cm from the bottom): Grey to green polymict conglomerate with claystone intraclasts reaching up to 5 cm in diameter (interpretation: gravity flow deposits); **Core 14, Sampler-card 3** — (90–95 cm from the bottom): Grey to brown bioturbated siltstone and sandstone with carbonized plant fragments. Contains parallel lamination, ripple cross lamination and flame structures; **Core 14, Sampler-card 4** — (0–8 cm from the bottom): Grey conglomerate with large claystone intraclasts (more than 8 cm in diameter); **Core 14, Sampler-card 2** — (50–58 cm from the bottom): Brown layered claystone and sandstone with flame structures at the base of the core; **Core 11a, Sampler-card 2** — (90–95 cm from the bottom): Grey pebbly claystone with carbonized plant fragments (interpretation: debry flow deposit); **Core 9, Sampler-card 2** — (5–7 cm from the bottom): Grey siltstone and fine grained sandstones with parting lineation on the bedding planes; **Core 8, Sampler-card 2** — (35–38 cm from the bottom): Grey to brown layered claystone; **Core 4, Sampler-card 4** — (35–51 cm from the bottom): Grey layered claystone; **Core 4, Sampler-card 4** — (75–90 cm from the bottom): Grey layered claystone; **Core 3, Sampler-card 2** — (5–8 cm from the bottom): Grey layered claystone to siltstone; **Core 1, Sampler-card 1** — (90–96 cm from the bottom): Possible intraformational conglomerate with sandstone clasts in siltstone to claystone matrix. Carbonized plate fragments are abundant (interpretation: lag deposit). Used scale 1 cm.

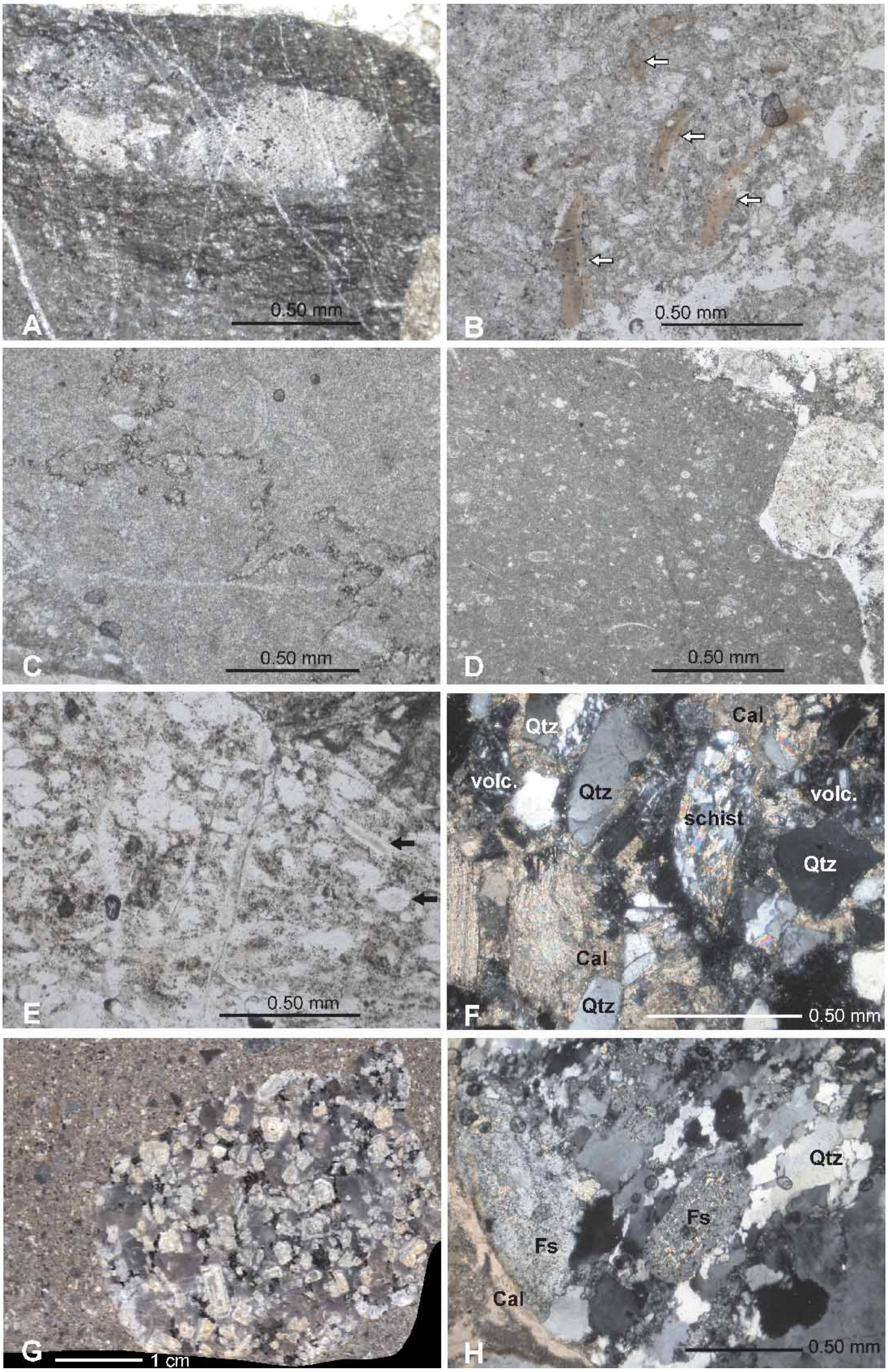

Fig. 7. A–D — Carbonate debris (plane — polarized light): A — biomicrite with fragment of Echinodermata and pyrite, B — recrystallized limestone with phosphatized fragments of vertebrates, C — biomicrite with styloliths, D — Calpionella biomicrite; **E** — Spongolite (plane — polarized light); **F** — Lithic arenitite composed of schist, volcanic debris, quartz, carbonate bioclast and calcareous cement (X micols); **G** — Zonated feldspar in granitoide pebble (core 24); **H** — Granitoide debris composed of quartz and sericitized feldspar (X nicols, core 25).

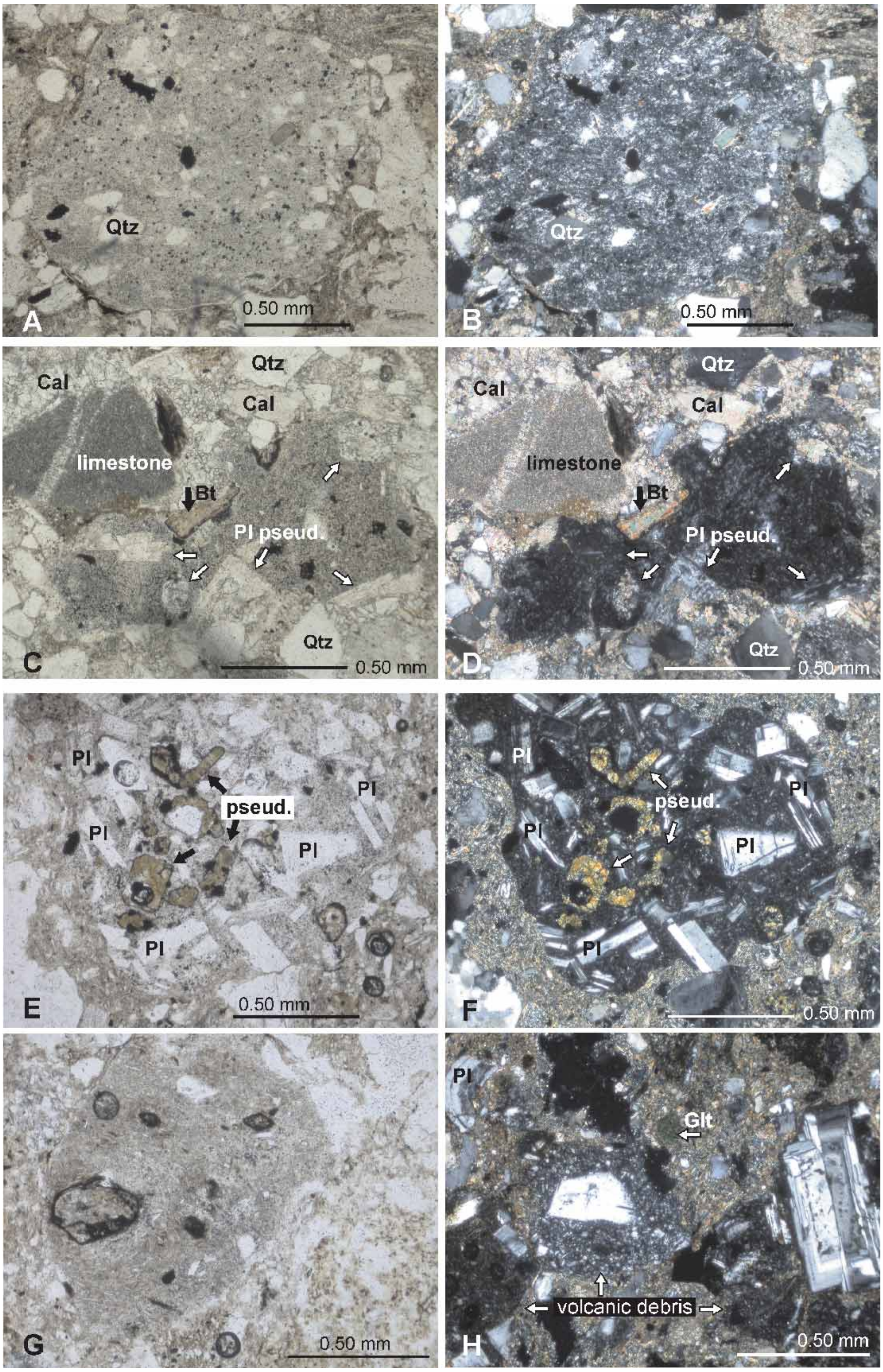

Fig. 8. A–B — Recrystalized acid volcanic debris — Permian: A — plane — polarized light, B — X nicols; **C–D** — Volcanic debris with fresh biotite and pseudomorphosis after plagioclase filling secondary minerals and calcite: C — plane — polarized light, D — X nicols; **E–H** — Volcanic debris with fresh plagioclase and pseudomorphosis after dark minerals filling secondary minerals: E+G — plane — polarized light, F — X nicols, G — lithic arenite composed mainly of volcanic debris (X nicols).

present outcropping in the Hlohovec block of the Považský Inovec Mts, and in the Tríbeč Mts (Broska & Uher 1988).

The Triassic source material is documented by fragments of poorly recrystallized mudstone with stylolites (Fig. 7), dolomitized mudstone, oolitic grainstone, quartzites and dark partly phylitized silica rich shales (lydite). The Jurassic rocks are represented by spongolites and wackstones (Fig. 7) with abundant porifera spicules, brachiopods, bivalves, echinoderm fragments, sparite with phosphatized skeletons of vertebrates, a high amount of pyrite and carbonate siltstones (composed of detritic quartz in carbonate matrix). The Lower Cretaceous age of source material is proven by the Beriassian Calpionella limestone fragments (Fig. 7). Some of the carbonate clasts are sparitic. Carbonate breccia clasts and sedimentary cherts with no internal structure are also present, but the age of such source material is unknown.

Volcanic debris is an important part of the source material and may be divided into several categories: 1) rather rare, significantly altered fragments of acidic volcanic rocks, which take on the character of the quartzite greywacke and felsites (Fig. 8), and can clearly be associated with the Permian sediments of the Malužiná Formation of the Ipoltica Group (Vozárová & Vozár 1988); 2) volcanic fragments of andesite composition are subdivided into: a) rare highly altered volcanic clasts found from 1858 m to 1639 m depth including recrystallized glassy matter. Phenocrysts of biotite are preserved and plagioclase phenocrysts are completely replaced by calcite (Fig. 8). The high level of alteration suggests that they originate from the Permian sediments, but their affinity to the Miocene volcanic rocks cannot be excluded; b) volcanic fragments composed of very well preserved phenocrysts of the zonal plagioclase in poorly recrystallized glass matter (appearing from the depth of 1801 to 1353 m) with abundant pseudomorphs of amphibole shape, filled with secondary minerals (Fig. 8). Based on the degree of glassy matrix recrystallization in lithoclasts and absence of quartz phenocrysts, we believe that these volcanic epiclastic fragments (dacite/andesite composition) are certainly of the Miocene age. The epiclastic origin of this volcanic material is supported by different stages of alteration and recrystallization of lithoclasts. Moreover their roundedness and absence of heavy minerals (amphibole and pyroxene) supports this claim. The overlying strata (up from core 9) were not used for determination of the provenance of sediments, because of the very fine grain size (clay to silt deposits).

Miocene paleogeography and geodynamic aspects of the north-western Danube Basin's evolution

The opening of the Danube Basin — Blatné depocenter can be dated to the end of NN4 Zone accompanied by a lowermost Badenian fan delta development at its southern margin (LO of *H. ampliaperta* ~below 14.91 Ma). The basin's development followed after strong changes of tectonic pattern and paleogeography of the Western Carpathians domain. The Early Badenian (Langhian) subsidence is documented in the sedimentary record by gradual change from near shore environment to rapid tectonically controlled deepening of the basin. The development of the distal shore — slope depositional system with gravity currents and turbidite deposition took place during the NN5 nannoplankton Zone (LO of *H. ampliaperta* ~abowe 14.91 Ma). The gradual transition from onshore — proximal slope to offshore environment is marked by the last occurrence of coarse grained sediments above the base of the Špačince Formation (Fig. 2). In these cores the presence of *O. suturalis* was detected for the first time (core 14), and continued in the deep water deposits up to the Upper Badenian sediments of the Báhoň Formation (up to core 5). The Lower Badenian deep water environment's continuation up to the lower part of the Late Badenian NN6 Zone is not supported by the presence of *S. heteromorphus* (LO 13.53 Ma — sensu Kováč et al. 2007; Hohenegger et al. 2014), because its last occurrence was documented in the middle of the Lower Badenian sedimentary record (in core 12). In the Upper Badenian (Early Serravalian), dated by the FO of *Globigerina druryi*, *Sphenolitus abies* and *Helicosphaera walbersdorfensis* (Fig. 2), the offshore deep water facies development gradually changed to a shallow water environment during the NN6 nannoplankton Zone (~13.82–12.83 Ma — sensu Hohenegger et al. 2014), which confirms the assumed calming of tectonic activity and filling of the basin. During the Sarmatian and Pannonian (Upper Seravalian–Tortonian), a shallow water coastal plain, brackish to lacustrine environments were followed by development of an alluvial plain (~12.8–11.6–8.9 Ma) — sensu Kováč et al. (2011).

As already mentioned, the provenance analysis of the clastic material suggests sources in granitoids and mica shists/gneisses. This can be additionally confirmed by the composition of the heavy mineral fraction, which is relatively poor and consists of: Gt, St, Ap, Tur, Rt, Zr, Py, Ilm, Bt, Cl, Glt. Among the transparent heavy minerals, garnets of almandine composition are dominant (Fig. 9, Table 1) and they contain inclusions of titanite, turmaline, rutile and ilmenite. In addition the crystallo-chemical composition corresponds to garnets occurring in granitoids and schist. Nevertheless a small amount of garnets might have been derived from the Miocene volcanic rocks or recycled from dissolved Mesozoic carbonate rocks.

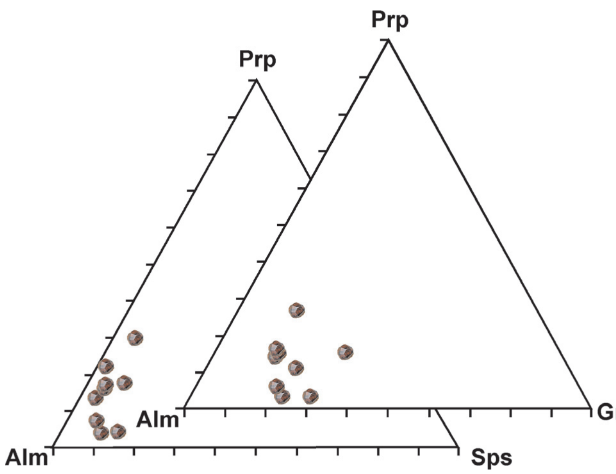

Fig. 9. Composition of garnets.

Table 1: Chemical composition of garnet calculated on the 8 cations base. Fe^{3+} was calculated to ideal stoichiometry.

Ratkovce 1	1	2	3	4	5	6	7	8	9	10
SiO_2	37.31	36.85	37.74	37.82	37.57	38.34	37.13	37.21	38.49	37.25
Al_2O_3	20.88	20.71	21.42	20.92	20.81	21.63	20.84	20.69	21.22	20.64
Cr_2O_3	0.01	0.04	0.00	0.01	0.00	0.00	0.00	0.03	0.02	0.00
TiO_2	0.18	0.03	0.04	0.38	0.30	0.08	0.35	0.10	0.36	0.37
MgO	0.82	1.50	2.76	3.74	3.84	3.90	3.45	0.81	6.64	3.51
FeO	27.47	31.47	29.99	31.18	29.76	24.25	31.27	30.96	26.72	31.46
MnO	4.52	2.54	1.31	1.62	3.42	0.55	1.74	3.42	2.00	1.67
CaO	9.31	6.51	7.60	5.68	5.08	11.44	5.52	7.37	5.20	5.50
Total	100.50	99.65	100.85	101.34	100.78	100.18	100.29	100.60	100.66	100.41
Si	2.983	2.978	2.976	2.970	2.968	2.987	2.952	2.989	2.980	2.959
Al^T	0.017	0.022	0.024	0.030	0.032	0.013	0.048	0.011	0.020	0.041
Al	1.951	1.951	1.967	1.906	1.905	1.972	1.905	1.948	1.917	1.891
Ti	0.011	0.002	0.002	0.023	0.018	0.004	0.021	0.006	0.021	0.022
Cr	0.001	0.003	0.000	0.000	0.000	0.000	0.000	0.002	0.001	0.000
Fe^{3+}	0.038	0.045	0.031	0.071	0.077	0.023	0.075	0.044	0.060	0.086
Fe^{2+}	1.799	2.082	1.946	1.977	1.889	1.556	2.004	2.036	1.670	2.003
Mg	0.098	0.181	0.324	0.438	0.452	0.452	0.409	0.097	0.767	0.416
Mn	0.306	0.174	0.087	0.108	0.229	0.036	0.117	0.233	0.131	0.113
Ca	0.797	0.564	0.642	0.478	0.430	0.955	0.470	0.634	0.431	0.468

Defining the precise provenance area of the basal conglomerates (Jablonica Formation) in the Ratkovce 1 well, we assume sources in a part of the pre-Neogene basement of the Danube Basin central zone, which were uplifted during the Oligocene–Early Miocene. In the early Lower Badenian, the pebbles were transported from here toward the north. The uplifted mountain chains around the basin not only contained crystalline complexes (similar to the granitoids in the Hlohovec block) and the Mesozoic nappe-stack, but were also covered by younger sediments, which were completely exhumed, eroded and transported by river systems toward the Blatné Depression. The presence of strata which formed the paleo-surface of the provenance area up to the beginning of the Middle Miocene is documented by redeposits of the Upper Cretaceous to Paleogene microfossils in the well core samples.

Extensional rifting of the basin (Blatné Depression) led to deposition of a sedimentary sequence about 300 m thick derived from volcanic epiclastic material (Figs. 2, 8 and 10). A marine sedimentary environment is confirmed by the presence of framboidal pyrite, glauconite, pisoides and bioclasts (Fig. 10). Nevertheless individual volcanoes must have reached above sea level and are today buried below the sedimentary fill of the northern Danube Basin. Their existence is supported by the interpretation of seismic lines (line: 558–86 and MXS2-93 — Hrušecký 1999), as well as by the lithology of cores in surrounding wells (Biela 1978).

Conclusions

• Re-evaluation of the Ratkovce 1 well core using advanced methods of biostratigraphy, paleoecology, sedimentology and geophysics helped us to understand the development of depositional systems in the northern Danube Basin, as well as bringing important data affecting "state of art" models of Central Paratethys paleogeography;

• In contrast to previous studies, the biostratigraphical results confirmed the presence of the NN4, NN5 and NN6 calcareous nannoplankton Zones and local CPN7 a CPN8 Zones of planktonic foraminifera correlated with N9, 10, 11 of the global foraminiferal zonation; MMi4a, MMi5 and MMi6 of Mediterranean foraminiferal zonation. The Mediterranean Langhian Stage (Lower Badenian of the Central Paratethys) is dated by the NN4 Zone, which is dated by the presence and LO of *H. ampliaperta* and *H scissura.* The NN5 Zone was detected by the FO of the planktonic foraminifera *Globigerinoides quadrilobatulus* (d'Orbigny) and *Globigerina regularis* (d'Orbigny), later by the FO of *Orbulina suturalis* (Brönnimann) of CPN7. The Early Serravallian (Upper Badenian) is dated by the NN6 Zone and by the FO of *Globigerina druryi* (Akers) together with *G. woodi decoraperta* (Takayanagi & Saito) correlated with the CPN8 biozone;

• The obtained palynomorph assemblages confirm subtropical and humid climatic conditions during the Middle Miocene time span. Mountain vegetation taxa indicate altitudinal zonation;

• A fandelta proximal to the distal basin slope and offshore deep water basin environment was documented in the Lower Badenian. The Upper Badenian deep water dysoxic environment changed gradually to the Sarmatian and Pannonian coastal to alluvial plain depositional systems in the northern Danube Basin. Sedimentary analysis of revised core material led to recognition of the various gravity transport mechanisms, including debris-flows and turbibity currents;

• Sedimentary facies described from the base to the top of the 2000 m deep well together with the results of paleoecology helped with a more precise determination of the depositional environments of formations: 1) The Jablonica Formation conglomerates deposited in fandelta to onshore shallow marine environment during the earliest Badenian (formerly included in the Karpatian stage); 2) Lower Badenian sediments of the gravitational currents in a proximal slope setting belong to the Špačince Formation lower part; 3) The upper part of the Špačince Formation is represented by the Lower Badenian distal slope gravitational deposits namely turbidites; 4) The Upper Badenian Báhoň Formation is represented by the deep water basinal dysoxic mudstones;

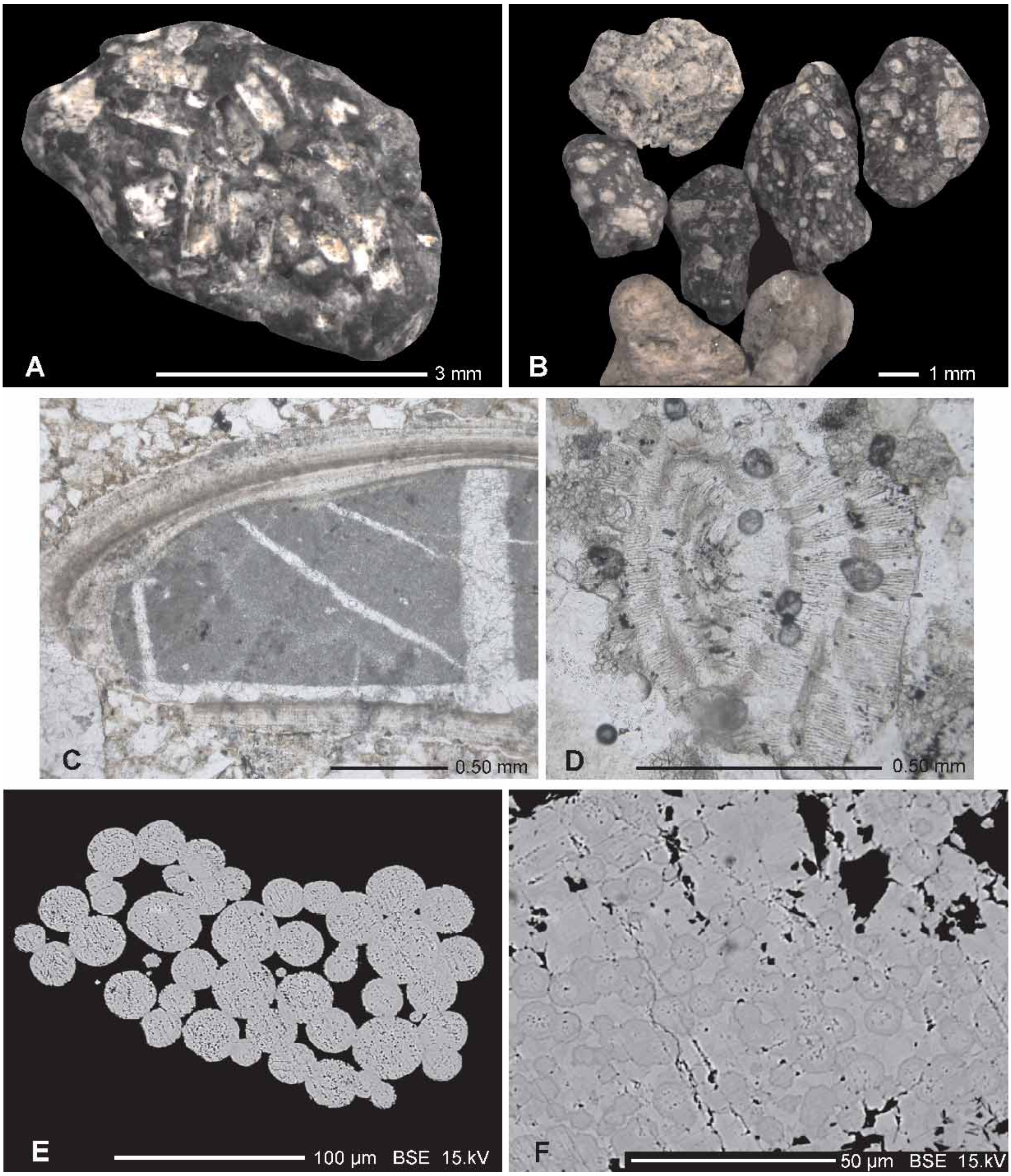

Fig. 10. A–B — Separated volcanic debris: A — core 21 (1796–1801 m), B — core 11A (1353–1357 m), C — pisolite (3 mm): nucleus = epiclastic carbonate (plane — polarized light); **D** — Redeposited bioclast *Amphistegina* sp. (plane — polarized light); **E–F** — Different type of framboidal pyrite (bacterial origin).

5) Sarmatian coastal plain marine to brackish sediments deposited in littoral to neritic zone belong to the Vráble Formation; 6) Pannonian to Pliocene shallow brackish to lacustrine and finally alluvial plain sediments form the Ivanka and Volkovce formations;

• The sources of the early Lower Badenian clastic material in the Ratkovce 1 well cores provide evidence of an uplifted mountain chain in the hinterland of the basin (present pre Neogene basement of the Danube Basin central part). Pebbles were derived from granitoids and gneisses of crystalline rock complexes with similarity to the Hlohovec Unit of the Považský Inovec Mts. Permian, Lower Cretaceous and Paleogene sediments were also a part of the catchment area at that time. This statement is supported by frequent occurrence of re-deposited Cretaceous and Paleogene microfossils;

• Permian volcanic rocks and more importantly the synrift volcanic rocks of the Early Badenian age are an inherent component of the sedimentary record.

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