

The earliest Badenian *Planostegina* bloom deposit: reflection of an unusual environment in the westernmost Carpathian Foredeep (Czech Republic)

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The Miocene sedimentation history of the Brus denudation relict (the western part of the Carpathian Foredeep, Czech Republic) has been inferred from 20 m of silt/siltstones, sand/sandstones and limestones penetrated by the Brus-1 borehole. Detailed multiproxy lithofacies and biofacies analyses have allowed facies and palaeoenvironment interpretations. The presence of molluscs, brachiopods and fish fauna, as well as large benthic and epiphytic foraminifera indicates a generally shallow, subtropical, marine environment. Despite the scarcity of biostratigraphical markers, the section can be correlated with the lowermost Badenian (~15–16 Ma). In the siltstones in the lower part of the borehole, there are abundant low-salinity foraminifera, which may indicate increased rainfall. Linked to this is the nutrient enrichment of the sea bottom water inferred from the presence of the high-nutrient taxa accompanied by abundant calcareous nannoplankton eutrophic taxa such as *Coccolithus pelagicus* and eutrophic planktonic foraminifera of the *Globigerina bulloides/praebulloides* group. The main *Planostegina* bloom was recorded in a sandstone in the interval 12.5–7 m, and was not influenced by a shift from high-organic content *Valvulineria* assemblage of small foraminifera to an epiphytic one. The boundary between siliciclastic and carbonate sedimentation (–7.5 m) shows a drop in K and Th concentrations, and in the Th/U ratio, but a rise in the Th/K ratio. This change in radioactive element content may generally indicate a significant decrease in terrestrial sediment input which is further supported by the onset of limestone deposition. Reversal of the deposition regime and a decrease of clastic input into the basin may be related to the changing of the precipitation regime, probably triggered by orbitally-forced cyclicity.

Key words: Middle Miocene, Central Paratethys, siliciclastic sedimentation, carbonate sedimentation, large benthic foraminifera, palaeoecology.

INTRODUCTION

A mass occurrence of *Planostegina* (= *Heterostegina* of the older literature; for commentary see e.g., Cicha et al., 1998) has been described from several stratigraphical horizons of the Central Paratethys Middle Miocene (Krach, 1947; Papp, 1978; Gutowski, 1984; Szelmeczi et al., 2004; Martinuš et al., 2013).

A new record of the *Planostegina* bloom in the Brus borehole (Zborník et al., 2013) represents the first finding of this horizon in the Moravian part of the Carpathian Foredeep, at a stratigraphical level correlated with the Early/Middle Miocene transition (Tomanová-Petrová, 2016). Preliminary studies indicate an unusual evolution of the Miocene infill in the western-

most part of the Carpathian Foredeep (Eliáš, 1999) during the Early/Middle Miocene transition.

To determinate the precise age and specific palaeoenvironment of the *Planostegina* bloom in this part of Carpathian Foredeep, a detailed study of the history of this area has been made. The results of sedimentological, gamma-spectrometric, calcareous nannoplankton, foraminiferal, mollusc, brachiopod and fish (otolith) faunas are described in this work.

GEOLOGICAL SETTING

The western part of the Carpathian Foredeep (Czech Republic) is a peripheral foreland basin which formed as a result of the tectonic emplacement and crustal loading of the Western Carpathian thrust front onto the passive margin of the Bohemian Massif (Nehyba and Šikula, 2007; Fig. 1). The sedimentary infill of the basin is composed of deposits of the Egerian to the Badenian age (Brzobohatý and Cicha, 1993).

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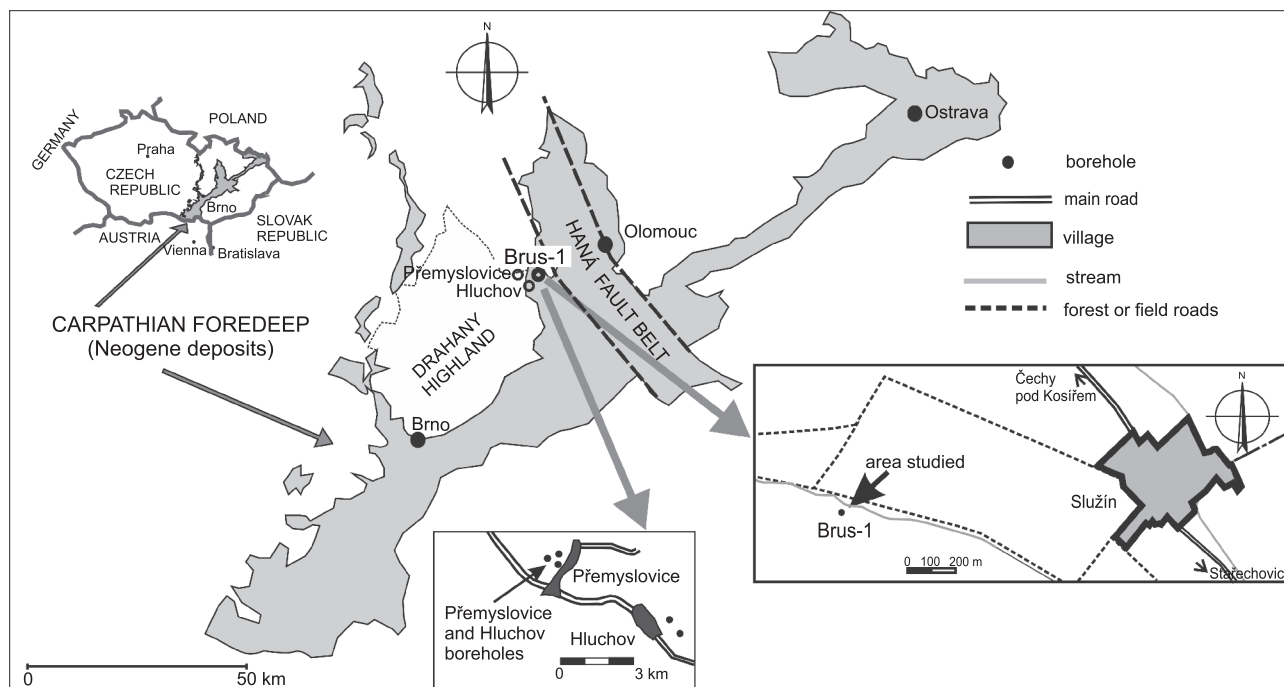


Fig. 1. Location of the area under study

The reactivation of NW-trending faults of the Haná Fault Belt (Fig. 1) during the Alpine Orogeny played an important role in reshaping the topographic relief of the basin passive margin, thus changing its accommodation space. The fault-related high Neogene relief included narrow depressions and intrabasinal highs oriented at a high angle to the basin axial zone (Zapletal, 2004). During the Badenian, the Carpathian Foredeep geometry was re-organized due to the transformation of the NW- to NNW-oriented structural compression of the Carpathian orogenic wedge towards NNE- and NE-oriented compression (Oszczypko, 1998, 2006; Kováč, 2000; Nehyba, 2000), with the depocentres migrating generally from the west towards the east (Meulenkamp et al., 1996; Oszczypko et al., 2006). Nevertheless, isolated outcrops of marine deposits indicate that the Carpathian Foredeep extended much farther to the west and that its present-day western boundary is related to erosional processes occurring mainly after the Miocene (Nehyba and Šikula, 2007).

The Neogene deposits of the area studied represent the sedimentary infill of the westernmost part of the Carpathian Foredeep (Eliáš, 1999; Fig. 1). The oldest Neogene marine deposits in the broad surroundings of the study area are of Karpatian age, but their occurrence is connected with the Brus locality (Vysloužil, 1981; Bubík and Dvořák, 1996). The basin-fill consists mainly of Lower Badenian deposits with their maximum thickness (>100 m) in the Prostějov and Lutín depressions, to the east of the present study area (Kalabis, 1961; Novák, 1975; Jašková, 1998; Zapletal et al., 2001). Numerous isolated relicts of Neogene deposits in the Drahaný Highland represent an extension of the Prostějov Depression towards the NW (Jašková, 1998; Zapletal et al., 2001; Zapletal, 2004, Zágoršek et al., 2012, Hladilová et al., 2014). The pre-Neogene basement is formed of Lower Carboniferous/Culmian rocks of the Drahaný Highland that overlie Precambrian crystalline basement (Mísař et al., 1983).

The Miocene deposits at Brus are represented by calcareous silts and siltstones, sandy siltstones, quartzose sands, calcareous sandstones, algal limestones and silty limestones (Zborník et al., 2013).

The Brus locality with Miocene deposits was first described by Tietze (1893). Early palaeontological studies were published

by Spitzner (1898; 1906) and Schubert (1900), who reported large benthic foraminifera (*Heterostegina* sp.) from this site. Kalabis (1934, 1937a, b, 1949) studied the locality in detail, also describing the occurrence of *Lithothamnion* sp. and other algae, sponge spicules, and macrofossils including echinoids (*Clypeaster* sp.), marine molluscs, and shark and fish teeth. Kalabis (1961) also compared occurrences of Tertiary rocks in the broader surroundings of Prostějov. The locality has also been mentioned by Remeš (1908, 1933), Blekta (1932), Schwartz (1946), Barth (1957), Chlupáč and Kalabis (1966) and Novák (1975). Most authors considered the age of the deposits to be Early Badenian. However, Vysloužil (1981) and Bubík and Dvořák (1996) also described Karpatian deposits here, which form the lower part of the sedimentary succession.

Vysloužil (1981) described basal sandy-clayey beds in direct superposition on pre-Neogene bedrock. Whereas the lower portion of these beds is interpreted to be Karpatian in age, for the higher portion (formed by grey calcareous clays) of the beds, a stratigraphic interpretation is missing. The basal beds are covered by beds of breccia and “*Lithothamnion* limestones”, which are Lower Badenian in age, and were characterized by Doláková et al. (2008).

The newly drilled borehole, marked as Brus-1, was produced to obtain data for the stratigraphic revision of the sedimentary succession. The position of the borehole is shown in Figure 1, with a simplified geological map of the locality.

MATERIAL AND METHODS

The Miocene sedimentation history of the Brus denudation relict was studied using the material from the Brus-1 borehole, drilled to a depth of 20 m and consisting of variably consolidated siltstones, sandstones and limestones (Fig. 2). The borehole core was sampled at 0.5 m intervals over the 3.0 to 20.0 m depth interval.

Lithofacies analysis was based on techniques described by Tucker (1988), Walker and James (1992) and Nemeč (2005), using the evaluation of sedimentary structures and textures. Because the deposits are mostly un lithified, the sedimentary structures were commonly destroyed or deformed by the drilling process. The

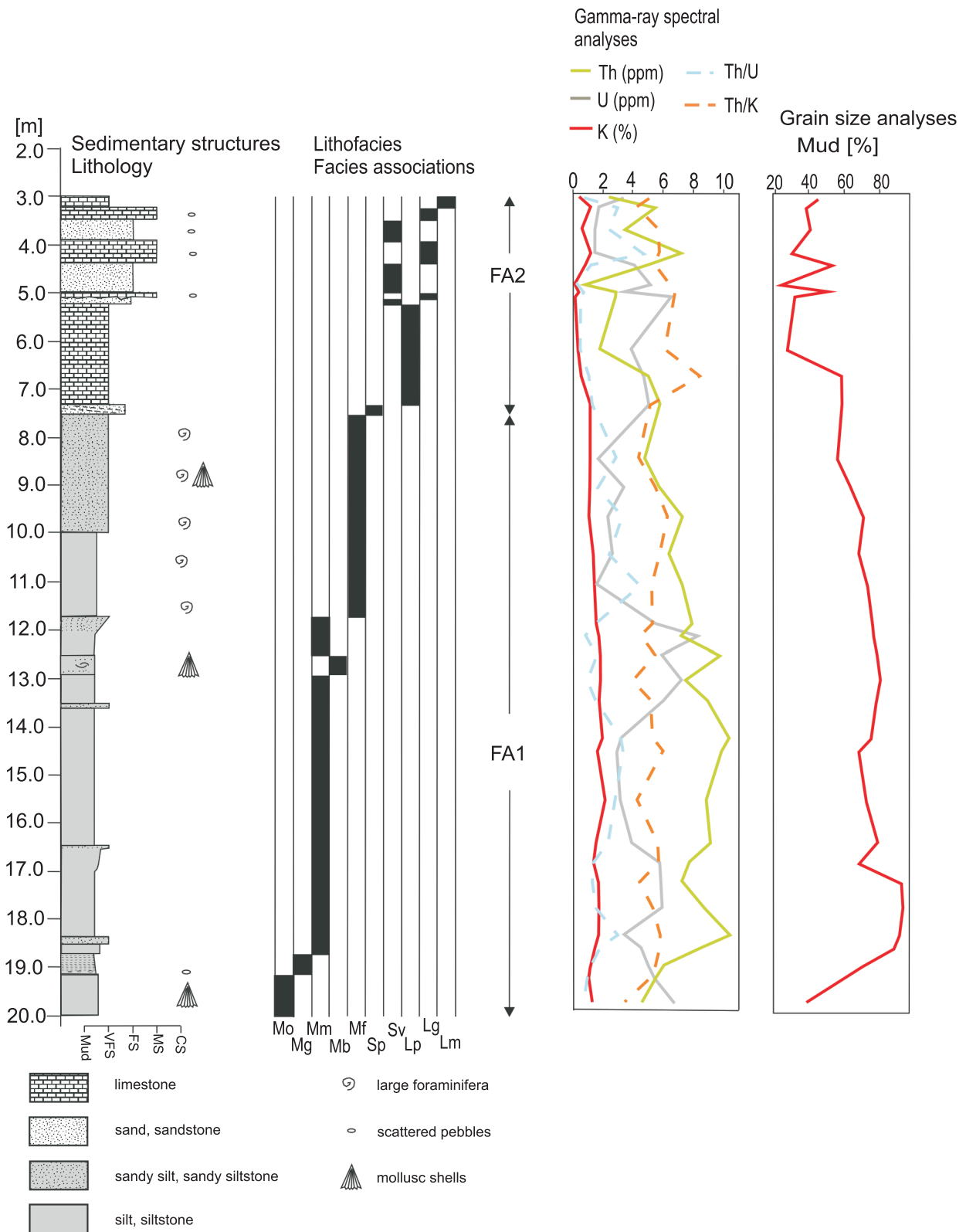


Fig. 2. Lithostratigraphic log of the Brus-1 borehole (Zborník et al., 2013, modified; for other explanations see Table 1)

VFS – very fine sand, FS – fine sand, MS – medium sand, CS – coarse sand

shape and roundness of the coarsest grain fraction (>4 mm) were estimated visually using the Powers (1982) method.

Combined sieving and laser methods were used for grain size analysis (34 analyses). A Retch AS 200 sieving machine was used to analyze the coarser grain fraction (0.063–8 mm, wet sieving), while a Cilas 1064 laser diffraction granulometer was used for the finer fraction (0.0004–0.5 mm). Ultrasonic disper-

sion, distilled water and washing in sodium polyphosphate were used prior to analysis in order to avoid flocculation of the particles analysed. The average grain size is represented by the graphic mean (Mz) and the uniformity of the grain size distribution/sorting by the standard deviation (σ ; Folk and Ward, 1957).

Heavy minerals were separated in the 0.063–0.125 mm grain-size fraction. The mineral compositions of selected heavy

Table 1

List of facies (Zbornik et al., 2013, modified)

Facies symbol	Description
Sp	Light yellow-brown to yellow-grey, silty very fine sand to sandy silt, calcareous, small admixture of shells to the base, cross-stratified. $Mz = -5.5$, $I = 2.2$. This facies represents 1.2% of the succession.
Sv	Light reddish-brown, light brown whitish mottled or green-grey, calcareous fine to very fine massive sand, poorly sorted due to local admixture of pebbles of Culmian shales and greywackes up to 3 cm across. High content of red algal shells. Locally poorly preserved inclined planar parallel lamination. This facies represents 6.8% of the succession.
Mb	Light grey-green calcareous silt, massive, well-sorted massive. Irregular generally small admixture of fine to very fine sand, irregularly distributed. Common occurrence of bivalve shells. $Mz = -5.9$, $I = 1.8$. This facies represents 2.4% of the succession.
Mf	Light yellow-grey to grey-yellow calcareous sandy silt with a remarkably high content of <i>Planostegina</i> tests and rare admixture of bivalve shells, massive, well sorted. $Mz = -5.1-5.8$, $I = 2.0-2.7$. This facies represents 24.3% of the succession.
Mg	Light grey-green, calcareous silt to siltstone with irregularly distributed admixture of granules up to 3 mm across along the base of the bed. Upper portions of the bed are significantly better sorted. This facies represents 2.7% of the succession.
Mo	Light grey, whitish mottled, calcareous clayey silt to siltstone with high content of shell debris (oysters). Crude planar stratification. This facies represents 5.0% of the succession.
Mm	Light grey to grey-green massive calcareous silt to siltstone. Well-sorted with small admixture of fine sand which mostly formed thin laminae. Rare white calcareous concretions. $Mz = -5.3-5.9$, $I = 1.8-2.0$. This facies represents 39.1% of the succession.
Lp	Whitish, green-grey sandy limestone, with high content of allochems (rhodoliths). This facies represents 12.4% of the succession.
Lm	Whitish calcareous siltstone to silty limestone, massive. Relatively well-sorted. Lithification varies. This facies represents 1.2% of the succession.
Lg	Whitish, yellow to brown, white mottled sandy limestone, high content of granules and pebbles (Culmian greywackes and shales) up to 1.7 cm across. Planar lamination, small admixture of allochems (shells), rare thin silty laminae. This facies represents 4.9% of the succession.

minerals (garnet – 36 analyses, rutile – 20 analyses) were determined using a *Camera SX 100* electron microscope at the Joint Laboratory of Electron Microscopy and Microanalyses of Masaryk University and the Czech Geological Survey, Brno. The gamma-ray spectra (GRS) were measured by a *GR-320 enviSPEC* laboratory spectrometer with a 3 × 3 inch NaI (TI) scintillation detector (Exploranium, Canada). Counts per second in selected energy windows were directly converted to concentrations of K (%), U (ppm) and Th (ppm). One measurement of 30 minutes was performed for each sample measured (34 samples – min. 300 g).

For biofacies analysis based on micropalaeontological studies, different types of grain size fraction were used for each core sample. Therefore, the sediments were washed under running water through 0.063 mm, 0.4 mm and 2.0 mm mesh sieves after a one-day soaking in warm water with sodium carbonate for disaggregation.

Foraminifera were studied in 35 samples of the 0.063–2.0 mm fraction (planktonic and small benthic foraminifera) and 35 samples of the >2.0 mm fraction (large benthic foraminifera). Species abundance was very variable in the samples; therefore, for quantitative evaluation only samples with more than ~100–150 specimens were used. Post-mortem assemblage changes were evaluated using the criteria of Holcová (1999).

Calcareous nannoplankton was studied from each of the core samples. Light microscope techniques were used for the examination of smear slides, which were prepared using the method described by Zágorský et al. (2007). The abundance of nannoplankton was expressed semi-quantitatively as the number of specimens in the visual field of the microscope. Approximately 200 to 500 calcareous nannoplankton specimens were determined from individual samples and used for the quantitative evaluation of assemblages.

Benthic and planktonic foraminiferal assemblages, as well as calcareous nannoplankton, were statistically analysed using the palaeontological software *PAST* (Hammer et al., 2008). For

the classification of samples, non-metric multidimensional scaling (n-MMDS) was used.

The SEM study of foraminifera test walls showed strong recrystallisation which precluded carbon and oxygen stable isotope analysis and Sr-dating.

The mollusc and brachiopod assemblages were studied from the washed samples of grain size >2.0 mm. The systematics and palaeoecological evaluation of the molluscs was based on work by Bagdasaryan et al. (1966), Steininger et al. (1978), Studencka (1986), Studencka et al. (1998), Schultz (2001), Mandić and Harzhauser (2003) and Mandić (2004).

Brachiopods were found in 20 samples, but were numerous in only a few. For the SEM study, the specimens selected were coated with platinum and examined using a *Philips XL20* microscope at the Institute of Paleobiology, PAS, Warszawa.

Otolith associations were studied from the >0.4 mm fraction. Every sample was analyzed using the palaeobathymetric method proposed for otoliths by Nolf and Brzobohatý (1994).

RESULTS

FACIES ANALYSES, SEDIMENTARY PETROGRAPHY, GAMMA-RAY SPECTRAL ANALYSES

Ten lithofacies were recognized according to grain size, (rarely preserved) sedimentary structures, and shell content (both quantity and shell spectra). The description of lithofacies is shown in Table 1. The lithofacies have been combined, based on their spatial grouping and depositional architecture, into two facies associations (Reading and Collinson, 1996). The distribution of both lithofacies and facies associations is marked in the lithostratigraphic log (Fig. 2).

The first facies association (FA1) is formed of five lithofacies (Mo, Mg, Mm, Mb, Mf; see Table 1) and was recognized at the depth of 7.5 to 20.0 m. The base of the FA1, which is also the base of the Neogene succession, was not reached by the bore-

hole. The lower part of FA1 is typified by the dominant role of the lithofacies Mm, whereas the upper part is marked by the dominant role of lithofacies Mf. Fragments of *Ostrea* shells were recognized in the lowest portion of FA1. Granules and pebbles of Culmian rocks (greywackes are more common than shales) reveal mostly discoidal or bladed shapes and are predominantly angular to subangular. Pebbles are generally relatively small (mostly <1 cm across), with the largest one reaching 1.8 cm. A rise in sand content upwards in the succession of FA1 is also documented. The upper portion of FA1 is typified by its relatively high content of *Planostegina* tests.

Deposits of FA1 (22 analyses) have relatively low and stable concentrations of K (1.08–2.07%, with an average concentration 1.50%, standard deviation SD 0.29), as compared with the concentration of the average of the Earth's crust. The GRS logs show a considerable degree of vertical organization. A trend of some upward decline of K content can be recognized. The content of U varies greatly (1.69–8.23 ppm, 4.56 ppm, SD 1.81), as does the content of Th (4.65–10.37 ppm, 7.71 ppm, SD 1.66). A significant drop in the concentration of both Th and U is traceable in the upper part of the FA1 (from 13 m). However, concentrations of Th also reveal a general trend of upward decline. The average value of the Th/U ratio is relatively low (2.04) and relatively stable (SD 0.67). The average value of the Th/K ratio reaches 5.14, but the value is less stable (SD 1.0). The K and Th concentrations show high correlation (linear regression coefficient; $R = 0.79$). On the other hand, negative or no correlation was recognized for concentrations of Th and U ($R = -0.05$); the correlation for K and U is relatively low ($R = -0.22$). Thus we can presume a similar source of signal for Th and K, but a different one for U. Correlations between the total content of natural radionuclides and concentrations of K, Th and U reveal that U is the most important source of the signal ($R = 0.84$). The roles of K ($R = 0.43$) and Th ($R = 0.27$) are lower. There are low negative correlations between clay contents: the content of U ($R = -0.34$), of K ($R = -0.35$) and of Th ($R = -0.28$).

The second facies association (FA2) is also formed of five lithofacies (Sp, Sv, Lp, Lg, Lm). Lithofacies Lp plays a dominant role especially in the lower portion of FA2. The base of FA2 is interpreted at the depth of 7.40 m, where the relatively thick and monotonous deposition of Mf sharply changes into traction deposits of lithofacies Sp. There is a higher admixture of granules and pebbles of Culmian rocks than in FA1, which is generally typical of FA2 except for the occurrence of limestones. Pebbles are generally relatively small (mostly <1 cm across; maximum observed 2.7 cm). The pebbles and granules are mostly angular to subangular, whereas subrounded ones are less common. They are predominantly discoidal; less commonly bladed or rod-shaped. Culmian greywackes or shales strongly dominate, forming up to 80% of the pebble spectra. Quartz, Ca concretions and bioclasts form the rest of the spectra.

GRS (11 measurements) reveal that deposits of FA2 have relatively low and stable concentrations of K (0.37–1.23%, 0.72%, SD 0.3). The concentrations of Th are also relatively low, but more variable (0.93–7.15 ppm, 3.89 ppm, SD 2.9). Concentrations of U are slightly higher (1.53–6.44 ppm, 3.74 ppm, SD 1.51) than the ones for FA1. The average value of the Th/U ratio is 1.46 (SD 1.32) and that of the Th/K ratio is 5.75 (SD 1.13). These values are generally lower than the ones obtained for FA1 (except Th/K). Correlations between the total content of natural radionuclides and concentrations of K, Th and U reveal that Th is mostly the principal source of the signal ($R = 0.63$), whereas the roles of U ($R = 0.33$) and especially K ($R = 0.0$) are significantly lower. The K and Th concentrations show high positive correlation (linear regression coefficient;

$R = 0.89$). Negative correlations were recognised for concentrations of Th and U ($R = -0.42$) and for K and U ($R = -0.62$). There were very low positive correlations between clay content and the content of U ($R = 0.14$), the content of Th ($R = 0.14$), and the content of K ($R = 0.13$).

The GRS logs of FA2 show vertical variability, which seems to reflect lithofacies changes (Fig. 2). The sandy lithofacies Sp and Sv have relatively stable concentrations of Th (2.90–5.81 ppm), a variable content of U (1.53–6.44 ppm) and lower concentrations of K (0.61–1.14%). Limestone lithofacies (Lp, Lg and Lm) reveal significantly higher variations in the content of Th (0.93–7.15 ppm), a slightly more stable content of U (1.49–4.76 ppm), and similarly low concentrations of K (0.37–1.24%). The source of the radioactive elements in FA2 is thus slightly different and connected with siliciclastic input in general.

The composition of garnet reflects a relatively broad mineralogical spectrum, where 12 types of garnet have been identified (despite the reduced amount of data). Table 2 shows the relative abundance of the garnet types in the samples studied. The results of the analyses reveal a strong dominance of almandines. The upper part of the Myslejšovice Formation (Moravo-Silesian Paleozoic, Drahany Culmian facies) contains predominantly pyrope-almandine garnets (Otava et al., 2000, 2002; Čopjaková et al., 2005; Čopjaková, 2007). So these rocks represent the dominant source area of the garnets studied.

Table 2

Garnet types of the studied deposits

Garnet type	[%]
ALM ₍₇₇₋₉₁₎	17.1
ALM ₍₆₀₋₈₀₎ -PRP ₍₁₁₋₂₄₎	20.0
ALM ₍₇₂₎ -PRP ₍₁₂₎ -SPS ₍₁₁₎	2.9
ALM ₍₆₁₋₇₃₎ -PRP ₍₁₃₋₁₇₎ -GRS ₍₁₁₋₁₆₎	5.7
ALM ₍₅₆₎ -GRS ₍₂₃₎ -SPS ₍₁₂₎	2.9
ALM ₍₆₅₋₇₉₎ -GRS ₍₁₁₋₂₂₎	17.1
ALM ₍₅₉₋₆₈₎ -GRS ₍₁₆₋₂₃₎ -PRP ₍₁₂₋₁₆₎	11.4
ALM ₍₆₆₎ -SPS ₍₂₀₎	2.9
ALM ₍₅₆₋₇₄₎ -SPS ₍₁₂₋₂₈₎ -PRP ₍₁₁₋₁₅₎	8.6
ALM ₍₆₀₎ -SPS ₍₁₇₎ -GRS ₍₁₅₎	2.9
SPS ₍₇₁₎ -ALM ₍₁₅₋₁₆₎	5.7
SPS ₍₄₄₎ -ALM ₍₃₇₎ -GRS ₍₁₄₎	2.9

ALM – almandine, GRS – grossular, PRP – pyrope, SPS – spessartine

Rutile as one of the most stable heavy minerals is commonly used for provenance analysis (Force, 1980; Zack et al., 2004a, b; Triebold et al., 2005; Stendal et al., 2006; Meinhold et al., 2008). The concentration of the main diagnostic elements (Fe, Nb, Cr, and Zr) varies significantly in the rutiles, in both FA1 and FA2. The majority (70.6%) of rutiles reveal concentrations of Fe >1000 ppm. The concentrations of Nb vary between 200 and 5180 ppm (AVG 1802 ppm); those of Cr vary between 40 and 3420 ppm (AVG 795 ppm); those of Zr between 60 and 1680 ppm (AVG 623 ppm), and the value of logCr/Nb is mostly negative (95%). These results indicate that the possible source area reveals the highest proportion of metamafic rocks (52.9%), a significant role of magmatic rocks (35.5%) and a less important role of metapelites (17.7%). Zr-in-rutile thermometry was applied for the metapelitic zircons only (cf. Zack et al., 2004a, b; Meinhold et al., 2008) and the results indicate that they all belong to the granulite metamorphic facies.

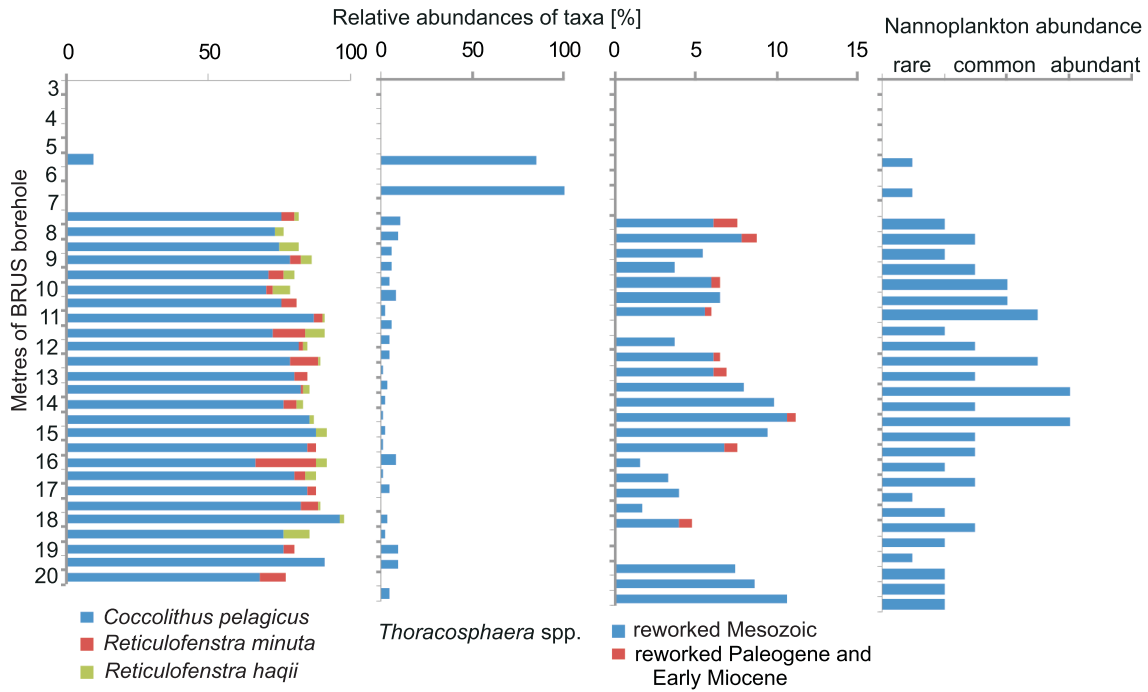


Fig. 3. Calcareous nannoplankton assemblages from the Brus-1 borehole

Nannoplankton abundance: rare: <10 specimens in visual field of microscope; common: 10–100 specimens in visual field of microscope; abundant: >100 specimens in visual field of microscope

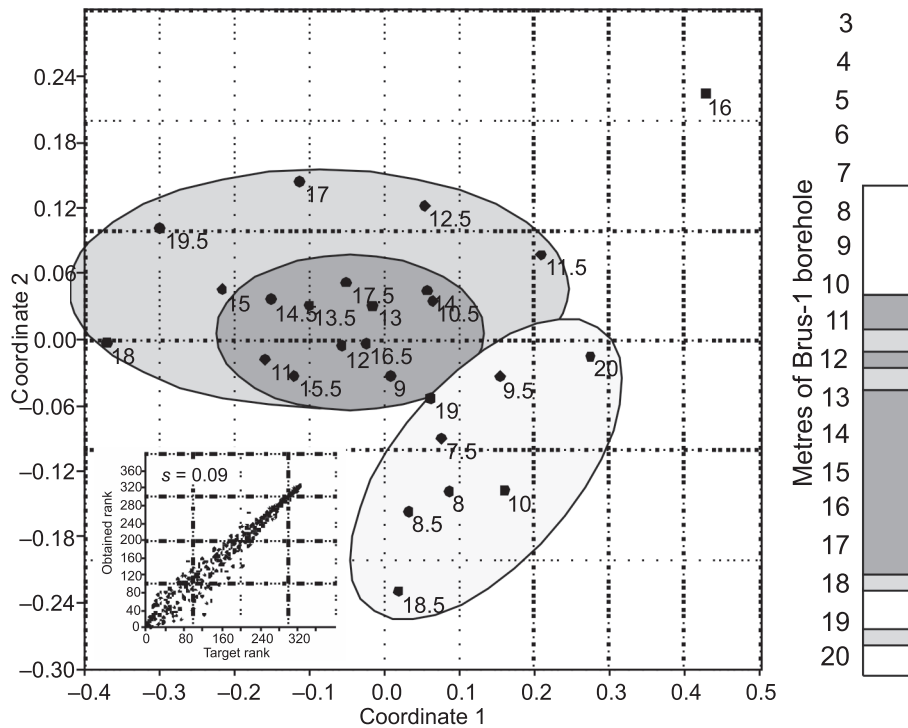


Fig. 4. Non-metric MDS of calcareous nannoplankton from the Brus-1

Shepard plot in the left bottom corner together with stress 0.09 indicate a high reliability of statistical results; column on the right shows the distribution of typical assemblages along the section

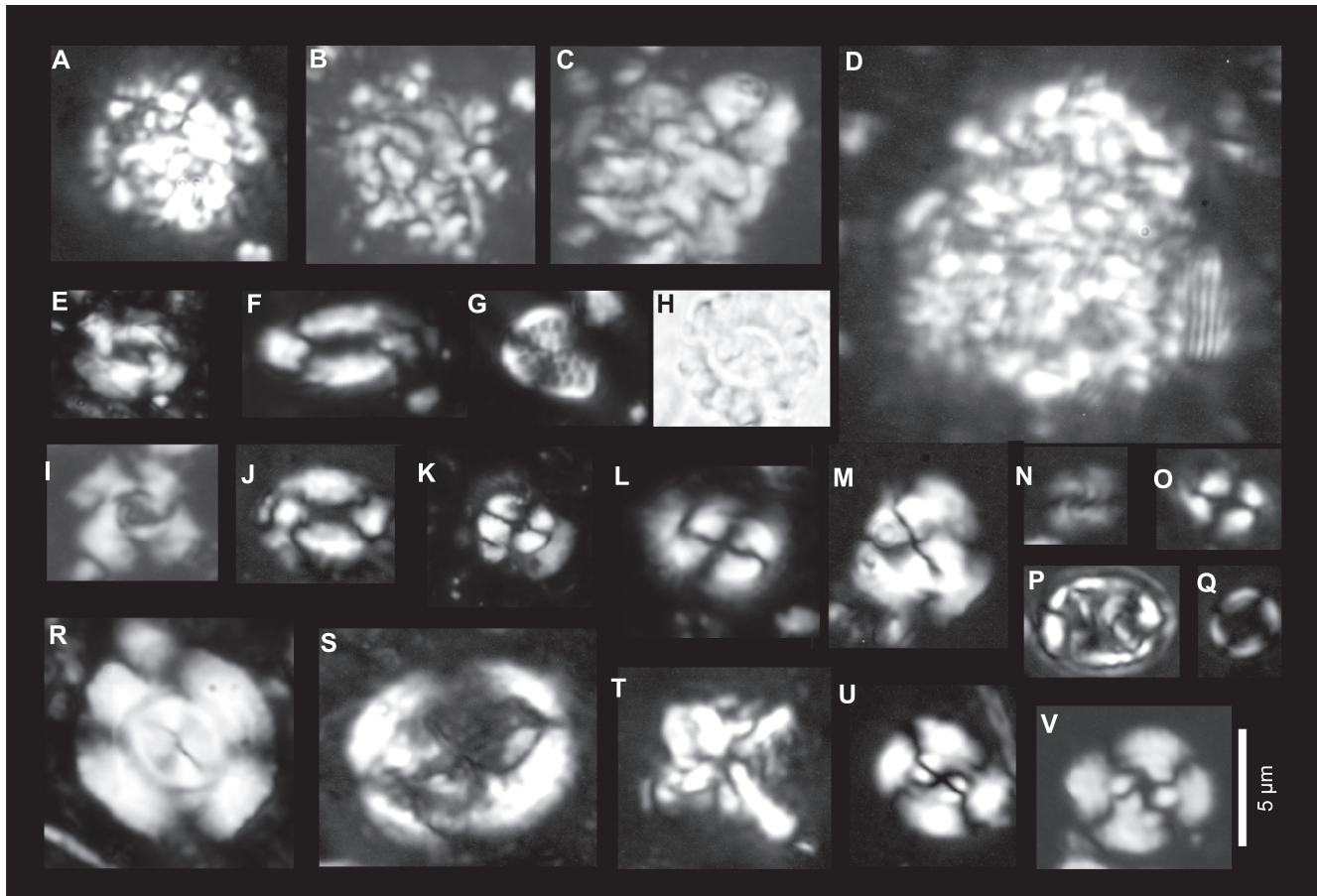


Fig. 5. Examples of calcareous nannoplankton from the Brus-1 borehole

A–D – *Thoracosphaera* sp.: A –13.0 m, B –9.0 m, C, D –10.5 m; **E, N, O** – *Reticulofenestra haqii* Backman: E, O –10.5 m, N –17.0 m; **G, H, J** – *Coccolithus pelagicus* Schiller: G –10.5 m, H –9.0 m, J –17.0 m; **I** – *Cyclicargolithus floridanus* Bukry, –10.5 m; **K–M** – corroded and broken specimens: K, L – undeterminable, K –13.0 m, L –9.0 m; **M** – *Reticulofenestra bisecta* Roth, –10.5 m; **P, Q** – reworked taxa: P – *Eiffellithus* sp. (Cretaceous–Eocene), –17.0 m; Q – *Diazomatolithus* sp. (Mesozoic), –17.0 m; **R** – *Reticulofenestra bisecta* Roth (Oligocene), –10.5 m; **S** – *Arkhangelskiella* sp. (Cretaceous), –17.0 m; **T** – *Micula* sp. (Mesozoic), –17.0 m; **U, V** – *Watznaueria* sp. (Mesozoic): U –17.0 m, V –9.0 m

FOSSIL ASSEMBLAGES

Calcareous nannoplankton. Assemblages of calcareous nannoplankton (Appendix 1*; Fig. 3) are rare to abundant and their composition is dominated by *Coccolithus pelagicus*. Only in samples –6.5 m and –5.5 m *Thoracosphaera* sp. dominated. In the upper part of the borehole (above the depth of 5.5 m), the calcareous nannoplankton disappears (Figs. 3 and 4). The coccoliths are corroded. There was recorded a high abundance of reworked mainly Cretaceous nannoplankton. The abundance of reworked taxa oscillated in three cycles: (1) base to –16 m; (2) –16 to –11 m; (3) –11 to –7.5 m (Fig. 3). For examples of calcareous nannoplankton species, see Figure 5.

Foraminifera. Planktonic foraminifera (Appendix 2) are well preserved without noticeable signs of transport. Nevertheless, planktonic assemblages are rare; they were found only in the interval of 8–16 m of the borehole. In all the assemblages, there was a low diversity of planktonic foraminifera with dominantly co-occurring *Globigerina praebulloides/bulloides* and *Globigerinella regularis* (Fig. 6). Other planktonic foraminifera species (i.e. *Globigerina falconensis*, *G. concinna*, *G. tarchanensis*, *Globigerinoides trilobus*, *Gl. quadrilobatus*, *Turborotalia quinqueloba* and *T. connecta*) occur only sporadically.

The percentage of planktonic foraminifera from the total foraminiferal assemblages (P/B-ratio) varies from 1 to 24%, with prevalence values up to 10% (Fig. 7). The cold-water eutrophic *Globigerina praebulloides/bulloides* (i.e. Sen Gupta, 1999) occurs as a predominant species in all the ranges of –16.0 to –10.5 m, with a maximum peak of 75% at the –15 m. At the depth of 8.0 to 8.5 m, there is a record of the occurrence of *G. praebulloides* with *Gl. regularis* with a relative abundance of only 47% (–8.5 m) and 32% (–8.0 m). At the depth of 9.0 m, there is a relative abundance of *Gl. praebulloides* (100%).

The warm-water oligotrophic species *Globigerinella regularis* (cf. Sen Gupta, 1999) occurs in the interval of –14.5 to –10.5 m. The relative abundance of this species is generally >20% with the maximum of 75% at –14.5 m. Other occurrences of this species were found at the depths of 15.5 m (relative abundance of 50%), 8.5 m (26%) and 8 m (22%).

The benthic foraminiferal assemblages (Fig. 6 and Appendices 2, 3) include two types of foraminifera: small benthic foraminifera and large benthic foraminifera. Tests of small benthic foraminifera, similarly to planktonic foraminifera, are not affected by transporting, only by recrystallisation. Small benthic foraminifera are abundant in all the assemblages, with a relative abundance of generally >90% (76–100%). Similar to planktonic

* Supplementary data associated with this article can be found, in the online version, at doi: 10.7306/gq.1398

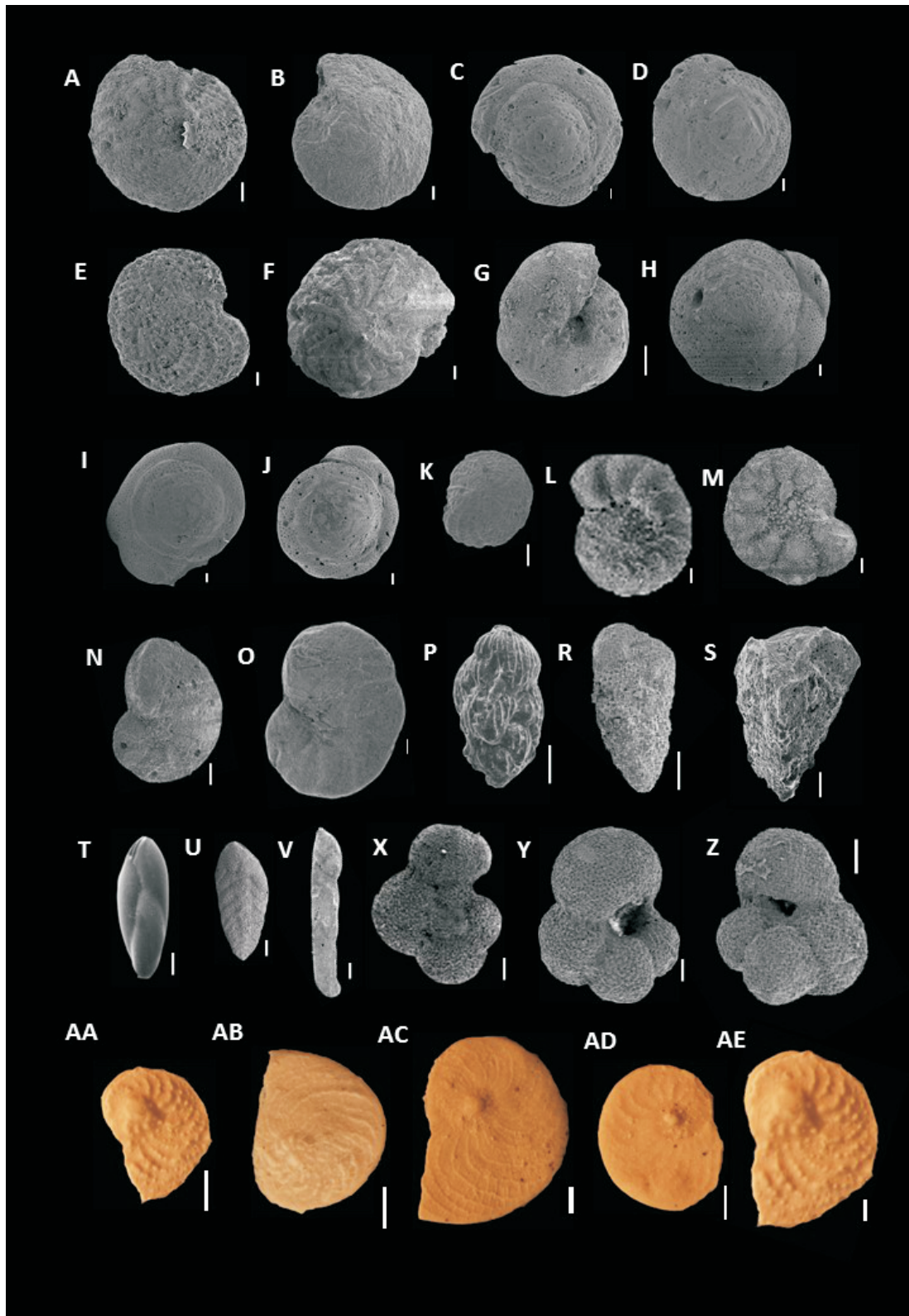


Fig. 6. Examples of foraminifera from the Brus-1 borehole, SEM images

A – *Elphidium crispum* (Linne), –6.0 m; B – *Cibicidoides* sp., –4.0 m; C, D, I – *Asterigerinata planorbis* (d’Orbigny), C, D –9.0 m, I –7.5 m; E – *Elphidium fichtelianum* (d’Orbigny), –18.5 m; F – *Elphidium rugosum* (d’Orbigny), –6.5 m; G – *Melonis pompilioides* (Fichtel & Moll), –10.0 m; H, J – *Heterolepa dutemplei* (d’Orbigny), H –7.5 m, J –10.0 m; K – *Elphidium crispum* (Linne), –18.0 m; L – *Cibicidoides ungerianus ungerianus* (d’Orbigny), –5.5 m; M – *Porosononion granosum* (d’Orbigny), –16.5 m; N, O – *Nonion commune* (d’Orbigny), N –12.5 m, O –14.0 m; P – *Uvigerina acuminata* Hosius, –12.0 m; R – *Bolivina pokorny* Cicha & Zapletalova, –7.5 m; S – *Reussella spinulosa* Reuss, –12.5 m; T – *Fursenkoina acuta* (d’Orbigny), –12.5 m; U – *Bolivina hebes* Macfayden, –11.5 m; V – *Laevidentalina elegans* (d’Orbigny), –9.5 m; X – *Globigerinella regularis* (d’Orbigny), –12.5 m; Y – *Globigerina bulloides* d’Orbigny, –11.5 m; Z – *Globigerina praebulloides* Blow, –13.0 m; AA, AE – *Planostegina granulata* (Papp & Küpper), AA –11.0 m; AE –14.5 m; AB, AC – *Planostegina costata* (d’Orbigny), AB –8.0 m, AC –10.5 m; AD – *Planostegina costata* (d’Orbigny), –7.5 m; scale bars: A–Z: 100 µm, AA–AD: 1 mm

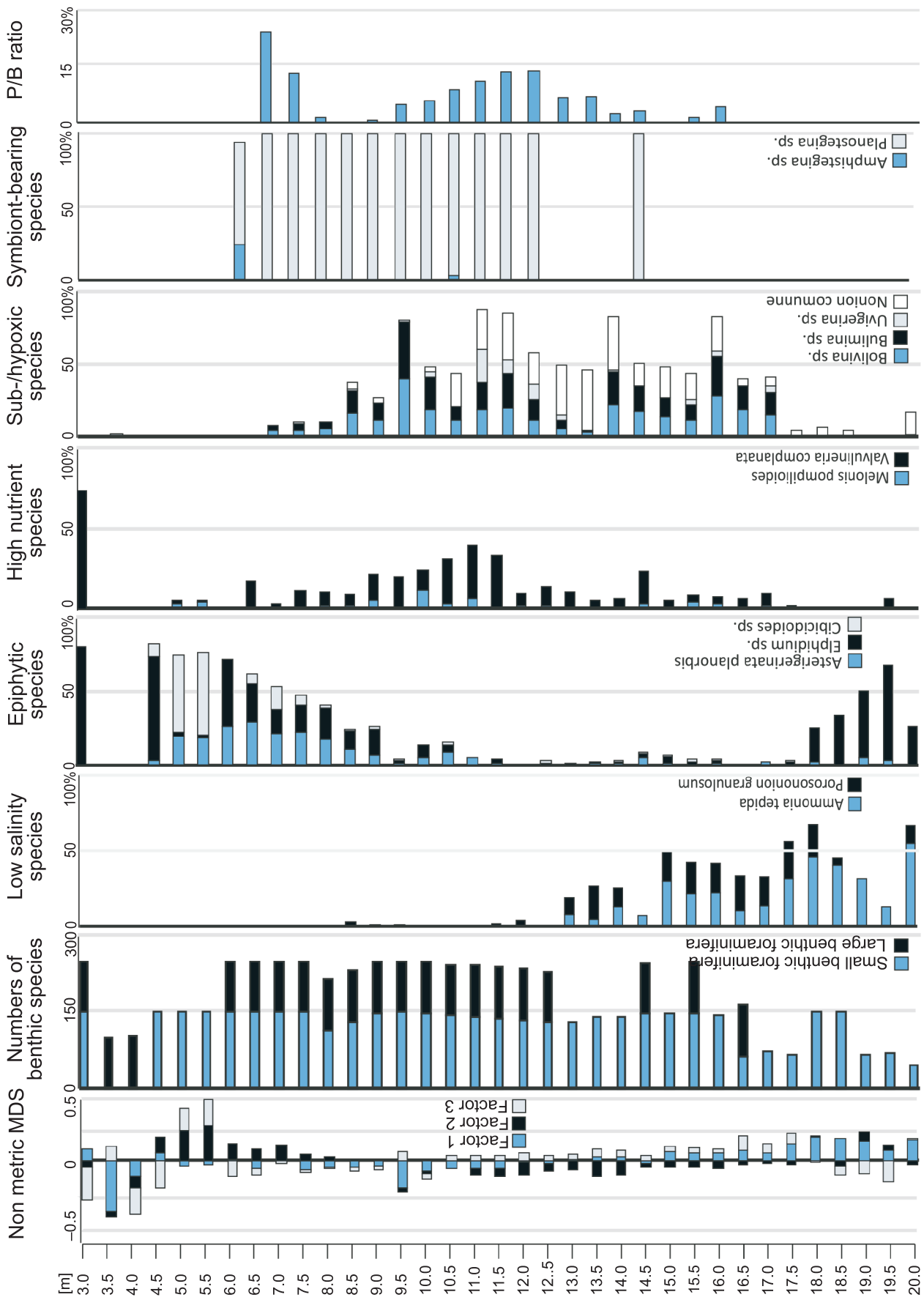


Fig. 7. Foraminifera assemblages from the Brus-1 borehole

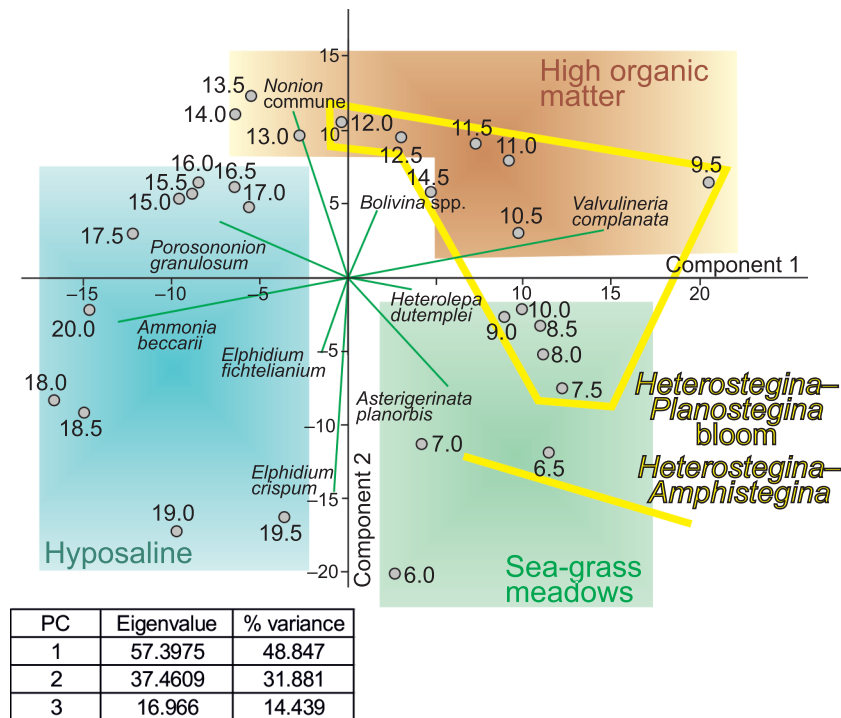


Fig. 8. Small benthic foraminifera of the Brus-1 borehole: separation of hyposaline, high nutrient and epiphytic assemblages

foraminifera, small benthic foraminifera diversity is rather low. It was calculated using the Shannon-Weaver index at a value of 1.9 (0.5–2.6). The numbers of species in individual samples vary around 20 (15–25) at –17.5 to –8.0 m; nevertheless, in the lower and upper part of the profile (–20 to –18 m, –7.5 to –3 m), the number of species drops below 10 per sample.

The lower part of the profile is characterized by a dominance of the epiphytic *Elphidium* spp. (see Langer, 1993) and the low-salinity taxon *Ammonia tepida*, *Porosonion granulosum* (see Chendes et al., 2004), though a very low diversity. At the levels of –17.0 to –10.5 m, there is a significant decrease of these taxa, while the abundance of the suboxic taxa *Bolivina* spp., *Bulimina* spp., *Uvigerina* spp. (cf. Kaiho, 1994) increases. The relative abundance of suboxic taxa oscillates between 4 and 80%, with peaks at the levels of –16.5 m, –14.5 m, –12.0 m and –10.5 m. At the –17.0 to –10.5 m levels, there is also a slight increase in diversity (Fig. 7).

Along with the suboxic taxa, there are also the high-nutrient taxa *Nonion* spp., *Valvulineria complanata* and *Melonis* spp. (see Miller and Lohman, 1982; Jorissen et al., 1992; Murray, 2003) with high relative abundance oscillating between 26–64%. The last occurrence of suboxic/stenohaline *Nonion* spp. is recorded at the level of –9.0 m; suboxic taxa (*Bolivina* spp., *Bulimina* spp., *Uvigerina* spp.) at –8.0 m; and high-nutrient taxa at –6.5 m. In the upper part of the profile, there is an evident recurrence of epiphytic taxa. In the interval –10.5 to –6.0 m, there is a co-occurrence of *Asterigerinata* spp. and *Elphidium* spp. with *Cibicidoides* spp., which is significantly in the minority. At the levels of –6.0 to –3.0 m, there is an increase in the abundance of *Cibicidoides* spp. along with *Elphidium* spp.; their relative abundances vary between 85–95% (Fig. 7).

The multivariate statistics (the PCA) showed clear separation of three typical assemblages of small benthic foraminifera (Fig. 8): (1) hyposaline *Ammonia*–*Porosonion* (–20 to –15 m); (2) high-nutrient *Valvulineria*–*Nonion* commune (–14.5 to –9.5 m), and (3) epiphytic *Asterigerinata*–*Elphidium* assemblages (–9 to –3 m).

Large benthic foraminifera (Fig. 6 and Appendix 3) are recorded at the level of –14.5 m and in the interval –12.5 to –7 m, with low diversity in all the samples. Tests of large benthic foraminifera are flat without size sorting, only showing signs of corrosion and abrasion, which could be due to bedload transport (Holcová, 1999). Generally, large benthic foraminifera are typical for the reef and carbonate shelf environment and they depend on algal symbiosis and on oligotrophic conditions (Hallock and Glenn, 1986; Buxton and Pedley, 1989).

The assemblages are characterized by a dominance of the taxa *Planostegina* spp., represented mainly by *P. costata* and the minority species *P. politatista*, *P. granulata* and *P. giganteiformis*. The relative abundance of these taxa oscillates generally between 76 to 100% (with a low abundance of 8% at –12 m and 19% at –7.0 m). At –12.5 m, –11.5 m, –11.0 m, –7.5 m and –7.0 m, there are co-occurrences with *Planostegina costata*, which is dominant at –12.0 m and –7.0 m. The last occurrence of large benthic foraminifera in the profile studied is recorded at –7.0 m, where is a co-occurrence of *Planostegina* spp. and *Amphistegina* spp. (Fig. 7). These taxa are wide-ranging in their bathymetric distribution, limited only by water transparency due to their symbiosis with photosynthetic organisms (Saraswati et al., 2002; Mateu-Vicens et al., 2010). Their thin and flat tests indicate a deeper shelf environment, mostly up to 70 m (e.g., Hallock, 1984; Hallock and Glenn, 1986; Hohenecker, 1994, 1995; Mateu-Vicens et al., 2010).

Brachiopods. Four brachiopod taxa have been identified in the samples from the Brus-1 borehole: the inarticulate *Discradisca* sp. and the megathyrids *Argyrotheca cuneata*, *A. bitnerae*, and *Joania cordata* (Fig. 9 and Appendix 4). *Discradisca* sp. was detected in all the samples. Valves show signs of having been transported. About 200 broken dorsal valves and fragments of various sizes were found. This brachiopod has not previously been reported from the Miocene of the Czech Republic (see Zágorský et al., 2012; Bitner et al., 2013; Pavézková et al., 2013; Hladilová et al., 2014).

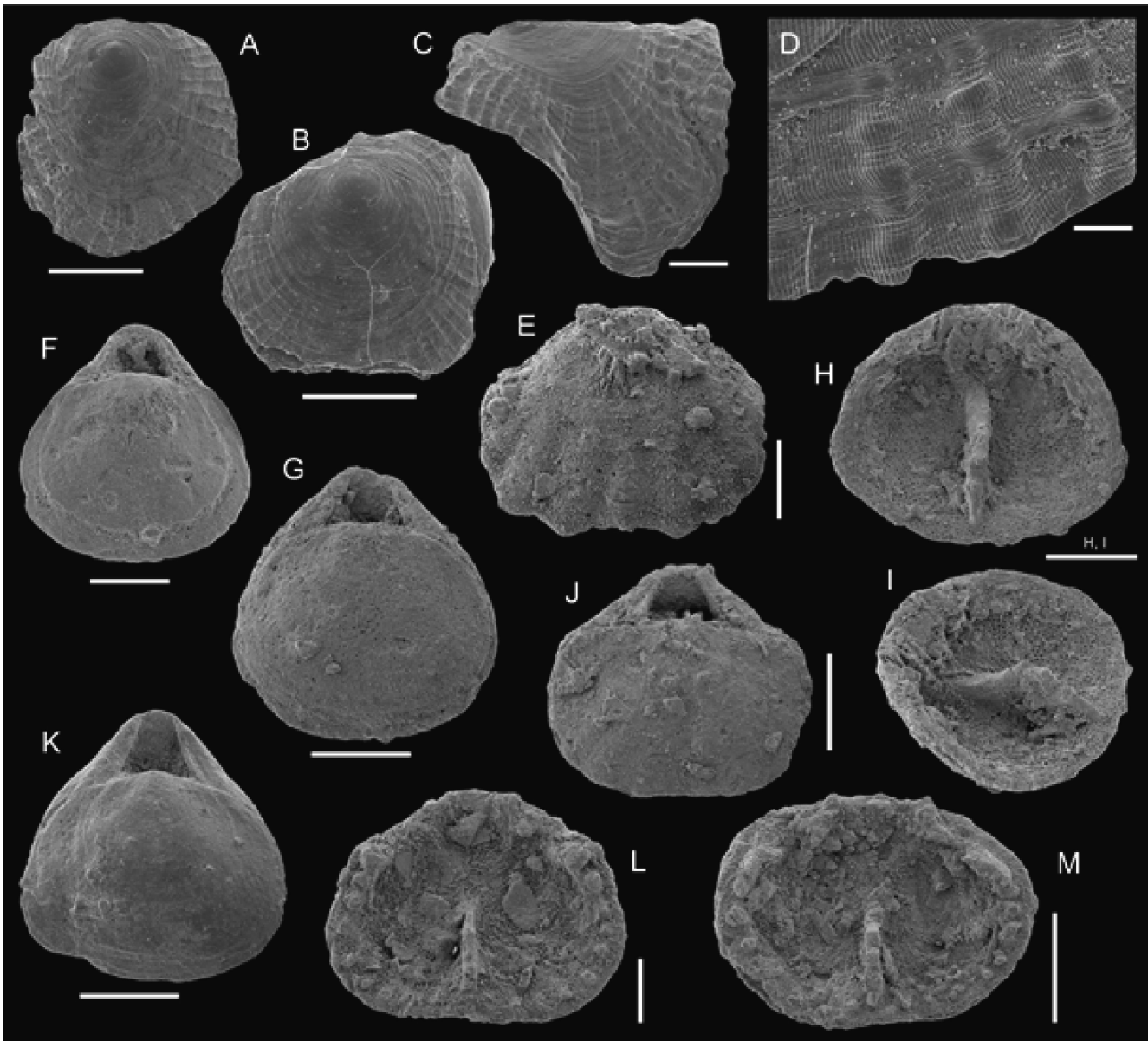


Fig. 9. Examples of Brachiopoda from the Brus-1 borehole, SEM images

A–D – *Discradisca* sp., broken dorsal valves and enlargement to show tuberculate ribs and numerous radial microlines (D): A –5.5 m; B, D –7.0 m, C –6.5 m; **E** – *Argyrotheca cuneata* (Risso), outer view of ventral valve, –5.5 m; **F–I** – *Argyrotheca bitnerae* Dulai: F, G – dorsal views of complete specimens, –6.0 and –7.5 m, respectively; H, I – inner and oblique views of dorsal valve, –7.5 m; **J–M** – *Joania cordata* (Risso), J, K – dorsal views of complete specimens, –5.5 and –6.5 m, respectively; L, M – inner views of dorsal valves, visible marginal tubercles, –5.5 m; scale bars: A, B, H–K, M – 1 mm; C, E, F, G, L – 500 μ m, D – 100 μ m

The dominance of *Discradisca* makes the assemblage from Brus unique among Paratethyan assemblages. Although discinid brachiopods have already been recorded from Paratethyan communities (Radwańska and Radwański, 1984; Kroh, 2003; Radwański and Wysocka, 2004; Dulai, 2015; Bitner and Motchurova-Dekova, 2016), they are rare to very rare. Today *Discradisca* lives in the shallow-water of tropical and subtropical areas, restricted mainly to the continental shelves (Emig, 1997), thus its abundance in the material studied indicates a shallow-water, warm environment.

Megathyrids are much less frequent. *A. bitnerae* was found in the interval of –5.0 to –8.5 m; *J. cordata* was found at a level of –17.0 m, in the interval of –6.5 to –5.5 m and at the level of

–3.5 m. *A. cuneata* is very rare and was found only in the sample from the level of –5.5 m; only one sample (at a depth of –5.5 m) contains all four species.

Molluscs. The molluscan fauna (Appendix 5) is highly fragmentary, which radically limits the precision of their determination, and it consists predominantly of bivalves – generally, fragments of pectinids (significant *Aequipecten malviniae*, *Flabellipecten solarium*, *Hinnites crispus*, “*Chlamys*” *trilirata*) and oysters; scaphopods are much less frequent; gastropods are completely absent. In the lower parts of the profile (–20 to –16.5 m), a relatively higher amount of bivalves was recorded, namely oysters in the sections –20 to –18.5 m and –17 to –16.5 m, and pectinids in the remaining ones (Appendix 5). In

the interval –16.5 to –15 m, the amount of bivalves begins to decrease in comparison with the lower parts; in the rest of the profile (–14.5 to –3 m), bivalves occur only sporadically, being completely absent in samples from –10, –12, –14 and –16 m.

Fish fauna. Fish species are few and fish specimens are rare in the profile studied (Appendix 6). The fish fauna consists of isolated teeth of Elasmobranchii (3 taxa) and isolated teeth and otoliths of Teleostei (9 taxa), allowing occasional species determination. Teleostei are represented mostly by the teeth of *Diplodus* spp.; less frequent are *Sparus* spp. and *Pagrus* spp. as well as indeterminable taxa of the Sparidae and ?Labridae. Otoliths represent only the Gobiidae family with the species *Lesueurigobius vicinalis* and *Thorogobius* ex gr. *intimus* and the indeterminable taxa *Gobiidae* sp. 1 and *Gobiidae* sp. juv.

INTERPRETATION AND DISCUSSION

BIOSTRATIGRAPHY

The presence of large benthic foraminifera and the bivalve pectinid species *Aequipecten malvinae*, *Hinnites crispus*, *Chlamys triliata* and *Flabellipecten solarium* point to a Badenian age. The occurrence of *Amphistegina mammilla* (7 m) and *Planostegina* spp. (–14.5 m, –12.5 to –7.0 m) indicate the base of the Badenian (cf. Piller et al., 2007). The presence of *Planostegina costata* (–16.0 m, –12.0 m, –11.5 to –11.0 m, –9.5 m, –7.5 to –7.0 m) allow correlation with the "Moravian Substages" (NN5 Zone) of the Badenian (cf. Grill, 1943; Papp, 1978).

The genus *Planostegina* was described as *Heterostegina* from the *Heterostegina* sands in Korytnica Basin, Central Poland (e.g., Szymanko and Wójcik, 1982; Rögl and Brandstätter, 1993; Krzywiec, 2001; Dulai and Stachacz, 2011). With respect to the common occurrence with *Orbulina suturalis* the *Heterostegina* sands are correlated with the Lower Lagenidae Zone (cf. Rögl and Brandstätter, 1993; Dulai and Stachacz, 2011; sensu Hohenegger et al., 2009, 2014). A co-occurrence of *Heterostegina* sp. and *O. suturalis* was also described from Styrian Basin (cf. Hansen et al., 1987) and from the Tapolca Basin (Hungary; cf. Selmecci et al., 2004).

However, by contrast, in the Brus-1 borehole no planktonic index taxa of the early Middle Miocene have been recorded (*Helicosphaera ampliaperta*, *H. waltrans*, *Praeorbulina* spp., *Orbulina* spp.). Besides their absence from the shallow-water environment, this may also indicate a short interval of the Early Badenian (sensu Hohenegger et al., 2014) without *Helicosphaera ampliaperta*, *H. waltrans* and orbulinas and with only very rare *Praeorbulina glomerosa*. These intervals were recorded in the Leitha Limestone in the Styrian Basin (Hohenegger et al., 2009; Spezzaferri et al., 2009) and in the Slovenian Corridor (Bartol et al., 2008). However, in the Carpathian Foredeep *H. ampliaperta* and *H. waltrans* co-occur (Švábenická, 2002).

The dominance of *Coccolithus pelagicus* in calcareous nannoplankton assemblages indicates rather the Karpatian or base of Badenian (Early Badenian according Hohenegger et al., 2014). A marked decrease of the *Coccolithus pelagicus*/*Reticulofenestra minuta* ratio can be correlated with the FO of *H. waltrans* and approximately with the LO of *Helicosphaera ampliaperta* (Tomanová-Petrová and Švábenická, 2007; Spezzaferri et al., 2009). Because in our material *Coccolithus pelagicus* significantly prevails over *Reticulofenestra minuta*, the upper boundary of the borehole can be dated to ~15 Ma (Early Badenian according to Hohenegger et al., 2014). This interval underlies the FO of

Orbulina suturalis and thus it is probably earlier than the Leitha Limestone and *Heterostegina* sands of the Korytnica Basin. The situation is similar to the Korytnica clays underlying the *Heterostegina* sands where *Heterostegina* spp., *Amphistegina mammilla* and *A. bohdanowiczi* co-occur with the planktonic biostratigraphic marker *Praeorbulina glomerosa* and this co-occurrence characterizes the Early Badenian beneath the *Orbulina suturalis* Zone (cf. Rögl and Brandstätter, 1993). Previous study by Tomanová-Petrová (2016) based on sporadic occurrence of the foraminifers *Cassigerinella boudecensis*, *Globigerina ottnangiensis*, *Pappina breviformis* and the ostracods *Cytheridea paracuminata* suggested that these strata were older, and correlated them with the Karpatian–Lower Badenian boundary. However, the species might be reworked from Karpatian sediments. Cicha et al. (1998) defined the onset of the *Heterostegina*/*Planostegina* group at the base of the Badenian with possible overlap of *Planostegina costata* in the Karpatian.

DEPOSITIONAL ENVIRONMENT

The profile of the Brus-1 borehole studied is represented by two lithologically different facies associations: FA1 (–20.0 to –7.5 m) and FA2 (–7.5 to –3.0 m). Facies association FA1 is lithologically relatively monotonous. It is inferred to represent a shallow-marine depositional environment below normal wave base, above the photic zone and at storm wave base. The input of sand, granules and pebbles is reduced and may be explained by storm action. The low and scattered distribution of such coarser grains together with a very high content of silt and significant content of clay may reflect an area of deposition that was relatively protected from wave and current action.

Moreover, the results of the grain size analyses can be used as a proxy for water depth (Dunbar and Barrett, 2005). A relatively high content of mud and its gradual decline upwards confirm a relatively deep environment and a gradual shallowing trend upwards to FA1 (see Fig. 2). The upper part of FA1 (–13.0 to –3.0 m) reflects a gradual decrease in siliciclastic supply to the basin.

The FA1/FA2 boundary shows a further drop of K and Th concentrations and of Th/U ratio; however, there is a rise in the Th/K ratio. This change in radioactive element content may indicate a significant decrease in terrestrial sediment input (Langmuir and Herman, 1980), which is further confirmed by the onset of limestone deposition.

However, the start of deposition of FA2 reflects dune movement on the sea bottom and shallower conditions than interpreted for FA1 (lower to middle shoreface?). The upper carbonate facies of FA2 represents a wave-worked, shallow-marine littoral environment. In FA2, U is relatively enriched compared to other natural radionuclides, which is also consistent with the low Th/U ratio (similarly Berstad and Dypvik, 1982). The identical position of the lowermost value of the Th/U ratio and concentrations of both K and Th may point to conditions connected with the maximum flooding surface = MFS ("absolute minimum of terrigenous input"; cf. Lüning and Kolonic, 2003; Doveton and Merriam, 2004; Halgedahl et al., 2009; Nehyba et al., 2016). The occurrence of limestones locally with a high content of clastic angular to subangular particles, up to pebble size, indicates periodically increased clastic input. Such a situation may reveal the role of storms and the relative proximity of cliffs or climatic changes. The second possibility could be reflected by the alternation of limestone lithofacies with siliciclastic ones. Such climatic changes could have affected the weathering processes in the source area, the current regime in the sea and changes in the temperature and chemistry of the sea-water.

The high positive correlation of Th and K points to a common source for both FA1 and 2, but a different one for U. The negative correlations between the content of clay and the concentrations of Th, K and U in FA1 point to the important role of sand fraction for the signal source rather than mud. The low content of sand is then responsible for the generally low values of these elements in FA1. The source of K and Th is traced in both heavy and light minerals, especially in detrital mica/feldspar that are present in the sand and silt fraction, whereas the clay fraction is probably rich in K-poor smectite (see Berstad and Dypvik, 1982). Similar trends in GRS were documented by Hladilová et al. (2014) for the Lower Badenian deposits from the nearby locality of Hlučov. Significant variations in the content of Th probably reflect variations in the content of the sand fraction.

Whereas the upper portion of the sedimentary profile (FA2) is similar in Brus and the nearby Lower Badenian locality of Hlučov, the lower portion of the profile (FA1) significantly differs (cf. Hladilová et al., 2014). Moreover, the results of both garnet and rutile provenance differ from the supposed provenance for these minerals in the nearby Lower Badenian localities.

The sedimentary succession of the Brus-1 borehole does not contain either the “basal-clayey beds” or the “younger sedimentary breccias” described by Vysloužil (1981). Although the base of the Neogene succession was not reached by the Brus-1 borehole, the silty facies of FA1 differ significantly from the deposits described by Vysloužil (1981). The base of the Neogene succession is situated at the depth of 21.5 m below the surface according to ground-penetrating radar data (Hubatka, 2012). The lithofacies of FA2 can be compared to those of Lower Badenian outcrops surrounding Prostějov (Zágoršek et al., 2012; Hladilová et al., 2014). Other similar depositional environments in the Moravian part of the Carpathian Foredeep have been described in the Kralice, Kroužek, Podbřežice, Rousínov and Židlochovice areas (Nehyba et al., 2008; Zágoršek et al., 2009; Doláková et al., 2014; Holcová et al., 2015; Hrabovský et al., 2015).

PALAEOENVIRONMENT EVOLUTION

The palaeoenvironment represented by the Brus-1 profile can be interpreted as a shallow-water marine environment of inner shelf with mixed siliciclastic and carbonate sedimentation with an oscillation of salinity and nutrient input. The presence of some molluscs (pectinids, oysters), brachiopods (*Discradisca* sp., *Argyrotheca* spp., *Joania cordata*), fish (*Diplodus* spp., *Sparus* spp., *Pagrus* spp.), large benthic foraminifera and epiphytic foraminifera (*Elphidium* spp., *Asterigerinata planorbis*, *Cibicides* spp.) point to shallow, subtropical, marine environments from the littoral to neritic zones.

Based on the sedimentological and palaeobiological records, combined with nMDS results of the section, the profile can be subdivided into the following intervals:

Interval –20.0 to –15.0 m is characterized by the A1 siliciclastic facies formed by calcareous silts to siltstones with varying degrees of sorting. The sea-floor was settled by the low-salinity taxa *Porosonion granulorum* and *Ammonia tepida*, together with epiphytic taxa with a predominance of *Elphidium* sp., *P. granulorum* and *A. tepida*, which usually inhabit a marine to brackish-marine environment (Resig, 1974; Patterson, 1990). Decrease in salinity may have been caused by freshwater input, which may have affected the seasonal upwelling system (described also in the recent Mediterranean, Coll et al., 2006; cf. e.g., Salat, 1996; Agostini and Bakun, 2002) and this may be associated with the occurrence of the eutrophic species *Coccolithus pelagicus*.

The occurrence of *P. granulorum* also simultaneously indicates an infralittoral (tidal) zone with continental input and vigorous water circulation (Goubert et al., 2001) in a warm-water environment as shown by the presence of the teleost genera *Diplodus* sp. and *Sparus* sp. and the brachiopod genus *Discradisca* sp. The higher input of terrestrial material is also shown by the relatively high K and Th concentrations, as well as the Th/U ratio.

Epiphytic foraminifera represented mainly by *Elphidium* sp. occupied a shallow-water sea up to 50 m deep (Rögl and Spezzaferri, 2003; Murray, 2006) and the well-oxygenated environment above the photic zone (Ramade, 1993; Kaiho, 1994). *Elphidium* spp. are also primary consumers that feed on the biofilm of microalgae and bacteria growing on seagrass blades. This corresponds also with the sporadic occurrence of epibionts of the Pectinidae and Ostreidae pointing to a rocky infralittoral zone with hard substrata and seagrass (cf. Mandić and Harzhauser, 2003).

In this context, the high dominance of these taxa indicates that epiphytic foraminiferal communities were responsive to a nutrient-enriched environment (Richardson et al., 2006), which starts to be significant in the following sections of the profile.

Interval –14.5 to –13.0 m is lithologically formed by the same facies as the previous one. At the base of this interval, there is a significant decrease of hyposaline *Ammonia–Porosonion* as well as epiphytic taxa while there is rapid increase in high-nutrient suboxic taxa (*Nonion commune*) and hypoxic taxa (*Bolivina* spp., *Bulimina* spp.). Reduction of the oxygen content in the environment is also shown by a rapid decrease in mollusc and brachiopod fauna. Stabilization of normal salinity enabled successful immigration and the first bloom of *Planostegina* assemblages. However, the start of deposition of FA2 indicates dune migration on the sea bottom and shallower conditions than interpreted for FA1 (lower to middle shoreface?).

There was also significant high food availability and organic carbon content in the sediments accompanied by the occurrence of *Bulimina* spp. and simultaneously a slight increase in the high-nutrient taxa *Valvulineria complanata* and *Melonis pompilioides*.

These benthic foraminiferal assemblages are accompanied by nannoplankton assemblages of *Coccolithus pelagicus* from –16.0 m of the section and by the planktonic foraminiferal species *Globigerina praebulloides/bulloides* and *Globigerinella regularis*. In this case, the occurrence of *C. pelagicus* points to nutrient enrichment of the surface sea-water (McIntyre and Bé, 1967; Rahman and Roth, 1990; Roth, 1994).

Gamma-spectrometric records show a rapid decline in the concentration of U and a gradual increase in the concentration of K and Th, as well as in the value of the Th/K ratio, while there was oscillation in the value of the Th/U ratio. In the interval of –14.0 to –13.0 m there is an obvious rapid increase in the concentration of U and a simultaneous decline in the concentration of Th, as well as a decline in the value of the Th/U ratio. This was accompanied by a slow decline of hypoxic and high-nutrient foraminifera. This may indicate a short-term decrease in the input of terrestrial material into the basin.

This may have been the result of an increase in rainfall, causing an input of terrestrial material as well as in nutrient supply to the basin. The rainfall probably was conducive to water temperature fluctuations (to which *C. pelagicus* is tolerant; Cachao and Moita, 2000) associated with the co-occurrence of warm water *Gl. regularis* and cold water *G. praebulloides/bulloides*.

There was also a salinity decrease in the basin indicated by the co-occurrence of low-salinity, high-nutrient and sub-/dysoxic foraminiferal assemblages with episodic changes

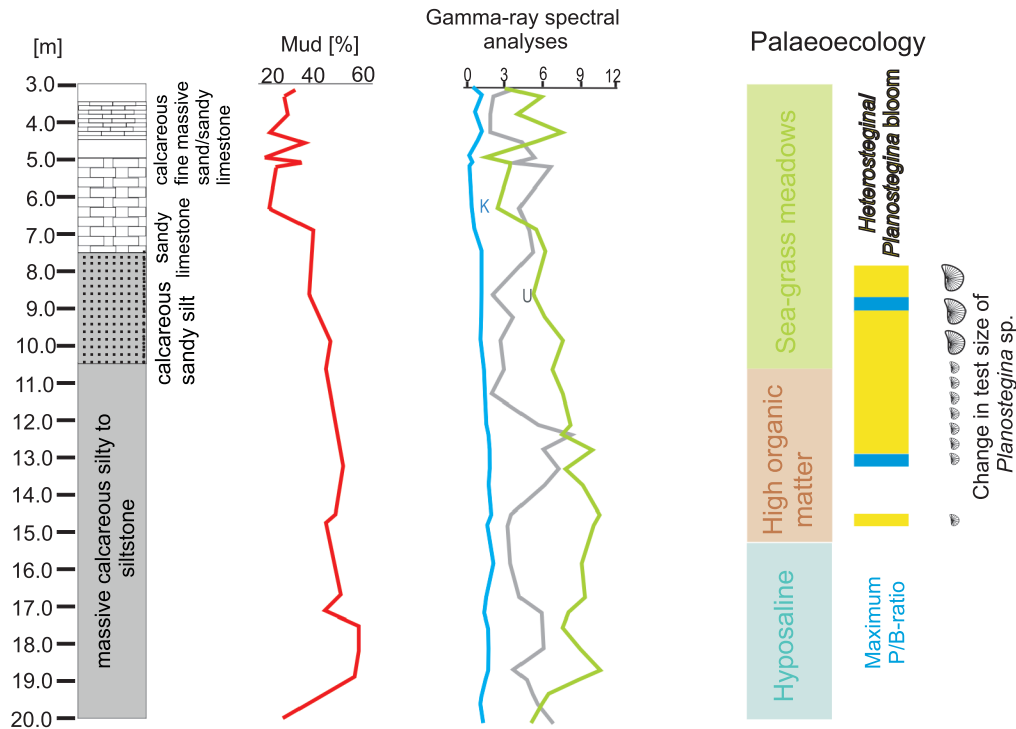


Fig. 10. Palaeoecology of the Brus-1 borehole

of regime in the interval from -14.0 to -13.0 m as shown by the oscillation in the high-nutrient and dysoxic foraminifera abundances.

Interval -12.5 to -8.0 m is formed by facies of well-sorted calcareous silts and siltstones. This part is characterized by the absence of low-salinity taxa and a low abundance of molluscs (Pectinidae, Ostreidae), brachiopods (*Discradisca* sp.) and fish (Gobiidae). The sea-floor was settled by the hypoxic foraminifera *Bolivina* spp., *Bulimina* spp. and *Uvigerina* spp., suboxic *Nonion commune* and by the high-nutrient species *V. complanata*. The P/B ratio oscillated between 5% and 13% in the range of -12.5 to -10.5 m. In the range of -10.0 to -9.0 m there is a rapid decline of the P/B ratio value (0–1%). In the upper part of this interval (-8.5 to -8 m), the P/B ratio values increases to 13% and 24%, respectively. In the interval -8 to -10 m high-nutrient taxa gradually disappeared and epiphytic taxa increased. The statistically determined boundary between high-nutrient and epiphytic taxa is located between -9.5 and -9.0 m.

This interval is particularly characterized by the presence of the abundant symbiont-bearing larger benthic foraminifera (LBF) *Planostegina costata*. The first continuous occurrence of LBF in the profile was recorded at -12.5 m, where there is a pre-dominance of *P. costata* together with peak of warm-water planktonic foraminifera.

The LBF show their largest expansion in the shallow oligotrophic environment of the circum-Tethyan ramps (Buxton and Pedley, 1989); their appearance is often related to periods of global warming, relative drought, raised sea levels, expansion of tropical and subtropical habitats, and reduced oceanic circulation (Hallock and Glenn, 1986). The present LBF individuals grew to giant size, which may indicate stressed conditions caused by low temperatures and insufficient food and/or light. These conditions are tolerable for growth, but outside of the range of tolerance for reproduction (Bradshaw, 1957). This is evident at -10 m, where abundances of high-nutrient taxa decrease while abundances of epiphytic foraminifera increase

(Figs. 5 and 6). There was a simultaneous increase in the test size of *Planostegina* sp. where the environment changed from one of high organic matter content to low organic matter content (sea-grass meadows; Fig. 10). However, Hallock (1985) and Drooger (1993) pointed to the relation between an increasing size of foraminiferal tests and an increasing depth of the habitat range. As the LBF occur together with high-nutrient and dysoxic foraminifera, it can be assumed that the main factor was the change in nutrient and oxygen contents. This is shown by the low diversity of LBF, because a reduction in species diversity may have been affected by oxygen depletion (see Golik and Phleger, 1977; Ingle et al., 1980).

The interval with high nutrient and low oxygen content and abundant LBF is characterized by a rapid decline of U concentration; simultaneously, this interval shows a gradual decline in K and Th concentrations, which may reflect a gradual reduction in the contribution of terrestrial material into the area. The reduction of terrestrial material input and the occurrence of giant tests of the LBF may indicate a short-term deepening of the sedimentation area or aridification of the climate, or a combination of both (Holcová et al., 2015). Deeper water was accompanied by the presence of *Planostegina* sp., which generally inhabits poorly illuminated sandy bottoms in calm deeper water (50–100 m; Hohenegger et al., 2000; Renema, 2006). Deeper environmental conditions also correspond to the thin and flat shells of the present *Amphistegina* sp. and *Planostegina* sp. Deeper water environments are characterized by lower light intensity and lower hydrodynamic energy. Under these conditions, LBF respond by flattening their shells, allowing symbionts to move closer to the outer wall, providing them with more light (Leutenegger, 1977; Hottinger, 2005). The absence of low salinity foraminifera in this case results from a reduction in precipitation, causing a gradual increase in salinity of the sea-water. The relatively low P/B ratio values also correlate with a high abundance of high-nutrient and hypoxic species (van der Zwaan et al., 1990).

Molluscan assemblages are consistent with the palaeoecological interpretation based on foraminifera and sedimentological data. *Costellamussiopecten* sp. prefers deeper quiet waters without strong currents and a rather soft clay substrate, being like many other pectinid species, an efficient active swimmer (Bagdasaryan et al., 1966). The species "*Chlamys*" *trilirata*, *Talochlamys multistriata* and *Aequipecten macrotis*, possessing thin shells, belong to epibionts usually exhibiting byssal attachment to the substrate. For the shell attachment they need primary and secondary hard substrata (for example rock surfaces, plants or sessile animals). They are predominantly recorded from rocky sublittoral environments (Mandic and Harzhauser, 2003), namely in a less exposed, somewhat deeper infralittoral (shallow subtidal) zone.

The presence of stenohaline bivalves from the family Pectinidae, together with the almost total absence of brackish and estuarine elements as well as the practically continuous presence of echinoids and occasionally frequent brachiopod shells, confirm a fully marine (of salinity of ~35‰) sedimentary environment in this part of the profile of Brus-1.

Among the bivalves recorded, suspension feeders dominated, indicating the marine environment to have been rich in organic detritus and planktonic micro-organisms. Representatives of bryozoans, balanids and brachiopods are also suspension feeders. The abundant remains of echinoderms, especially echinoids, represent another trophic level – carnivores/predators, and scavengers.

The FA1/FA2 boundary represents the most pronounced event in the Brus-1 borehole showing a further drop in K and Th concentrations, and the Th/U ratio, but a rise in the Th/K ratio. This change in radioactive element content may indicate a significant decrease in terrestrial sediment input (Langmuir and Herman, 1980) shown also by a decline in high-nutrient species likely caused by decrease in rainfall. Change in the precipitation regime is further supported by the onset of limestone deposition. This event might be correlated with the first aridification event defined by Hüsing et al. (2010) in the Mediterranean area and dated at ~15 Ma.

The start of deposition of FA2 (–7.5 to –3 m) reflects dune migration on the sea bottom. The upper carbonate facies of FA2 represents a wave-worked, shallow-marine littoral environment. In FA2, U is relatively enriched compared to other natural radionuclides, which is consistent with the low Th/U ratio (similarly Berstad and Dypvik, 1982). An identical position of the lowest value of Th/U ratio and concentrations of both K and Th could point to conditions connected with the maximum flooding surface MFS ("absolute minimum of terrigenous input"; cf. Lüning and Kolonic, 2003; Doveton and Merriam, 2004; Halgedahl et al., 2009). Occurrences of limestones locally with high contents of clastic angular to subangular particles, which can reach pebble size, indicate periodically increased clastic input. Such a situation may reflect storms and the relative proximity of cliffs or climatic changes. The second possibility may be reflected by alternation of limestone lithofacies with siliciclastic ones. Such climatic changes could have affected weathering processes in the source area, the current regime in the sea and changes in temperature and chemistry of the sea-water.

High positive correlation of Th and K points to a common source of signal for both FA1 and FA2, but a different one for U. Negative correlation between clay content and concentrations of Th, K and U in FA1 points to an important role of the sand fraction for the signal source rather than mud. Low content of sand is then responsible for generally low values of these elements in FA1. The source of K and Th is traced in both heavy and light minerals, especially in detrital mica/feldspar present in the sand and silt fraction, whereas the clay fraction is probably

rich in K-poor smectite (see Berstad and Dypvik, 1982). Similar trends in GRS were documented by Hladilová et al. (2014) for the Lower Badenian deposits from the nearby locality of Hlučov. Significant variations in Th content probably reflect variations in the content of sand fraction.

Foraminiferal assemblages in this interval are characterized by the absence of hypoxic species and by a reduction of high-nutrient species. At the same time, the planktonic foraminifera are completely missing; the symbiont-bearing LBF are replaced by epiphytic foraminifera. The interval at –7 to –6 m is characterized by an increased abundance of *Asterigerinata planorbis* and *Elphidium* spp.; the interval of –5.5 to –5.0 m by *Asterigerinata planorbis* and *Cibicides* spp.; and the interval of –4.5 to –3.0 only by abundant *Elphidium* spp. These foraminiferal assemblages inhabited the highly oxic environment of the inner shelf of seagrass meadows (Pezelej et al., 2013; Wiedl et al., 2014). The very low diversity and the very high abundance (pointing to transported forms) of epiphytic foraminifera (rotaliids) may indicate a sublittoral zone (cf. Gebelein, 1977). These palaeoecological conditions also correspond with a slight increase of the Teleostei taxa (mainly *Diplodus* sp. and Gobiidae) as well as the molluscan taxa (Pectinidae, Ostreidae) and the brachiopod taxa (*Discradisca* sp., *Argyrotheca* spp., *Joania cordata*). In the rare calcareous nanoplankton assemblages, *Thoracosphaera* spp. dominated, representing oligotrophy (Höll et al., 1998; Vink et al., 2002) and characterizing carbonate deposition in the study area (Holcová et al., 2015).

CONCLUSIONS

1. Deposits of the Brus-1 borehole represent the sedimentary infill of the westernmost part of the Carpathian Foredeep. Two facies associations were recognized within the sedimentary succession representing alternation of a siliciclastic facies association (FA1) and a limestone facies association (FA2). In the siliciclastic facies three types of environments alternated: (a) the base of the section with low-salinity foraminifera *Porosonion granosum* and *Ammonia tepida* and epiphytic foraminifera *Elphidium* spp. with Teleostei, Pectinidae and Ostreidae pointing to a littoral environment with warm brackish water caused by increasing rainfall and river flow input; input of terrestrial material is shown by relatively high K and Th concentrations; inasmuch as brachiopods are exclusively marine organisms, the inarticulate and megathyrid brachiopods present were probably redeposited from a normal marine environment; (b) the interval of low-salinity, high-nutrient (*Valvulinera complanata*, *Melonis pompilioides*) and sub-/dysoxic foraminifera (*Nonion commune*, *Bulimina* spp., *Bolivina* spp., *Uvigerina* spp.) and a rapid decrease/absence in mollusc, brachiopod and Teleostei fossils points to an environment with low salinity and high nutrient content. In the calcareous nanoplankton assemblages, the higher abundance of *Coccolithus pelagicus* also indicates a higher nutrient source for primary producers. Increased input of nutrients was associated with intense riverine input. This resulted in the disappearance of epiphytic foraminifera and an increase in infaunal high-nutrient foraminifera together with dysoxic species, the occurrence of which was related to intense decomposition processes on the sea-floor. Oscillations in the concentration of U, K and Th point to variation in the input of terrestrial material into the basin; (c) the interval with co-occurring high-nutrient and sub-/dysoxic foraminifera species and symbiont-bearing benthic foraminifera (*Amphistegina* spp., *Planostegina* spp.) which may indicate an environment with a gradual reduction in water column turbidity

as a result of gradual decrease of the terrestrial input. This is also consistent with the gradual reappearance of epiphytic foraminifera and rapid decline in K and Th concentrations.

2. Limestone facies with epiphytic foraminifera represented a dry period. The onset of arid conditions and carbonate sedimentation was associated with the rapid increase in U concentration and decline in K and Th concentrations. The environment is characterized by a decrease in nutrient input from the continent, oligotrophic conditions and the expansion of sea-grass meadows with well-oxygenated and sunlit conditions. Low diversity and very high abundance of the rotaliids accompanied by a slight increase of Teleostei and pectinids may indicate a neritic/sublittoral environment.

3. The biostratigraphic correlation of the profile is not exact. The presence of large benthic foraminifera (mainly *Planostegina* sp.) point to a Badenian age only. The mollusc species *Aequipecten malvinae*, *Hinnites crispus* and *Chlamys triliata* have a wide stratigraphic range during the Badenian. The absence of *Orbulina*, *Praeorbulina circularis* and *Helicosphaera waltrans* may indicate an interval older than 15 Ma. The dominance of *Coccolithus pelagicus* in the calcareous nannoplankton assemblages characterizes the base of Badenian (Early Badenian according Hohenegger et al., 2014). *Cassigerinella boudecensis*, *Globigerina ottnangiensis*, *Pappina breviformis* recorded by Tomanová-Petrová (2016) may be redeposited from the Lower Miocene or may indicate an older age of the base of Brus-1 borehole. In any case, this interval can be correlated with the Miocene Climatic Optimum.

4. Alternation of siliciclastic facies with carbonate ones may have been caused by an episodic change in the precipitation regime. The humid regime is represented by the FA1 facies, which is significantly affected by input of terrestrial material into the basin. This is shown also by relatively high concentrations of

Th and K and the presence of low-salinity foraminifera *Porosonion granulosum* and *Ammonia tepida*. Then, humidity was followed by an increase in aridity, while decline of input of terrestrial material and siliciclastic sedimentation was followed by carbonate sedimentation. This aridification event may be correlated with one of the aridification events recorded in the Mediterranean and dated to 15.074 Ma and 14.489 Ma (cf. Hüsing et al., 2010). The biostratigraphical data suggest correlation with the first aridification event is probable.

5. Generally, the lithologies and fossil assemblages of Brus-1 borehole differ from those of surrounding Lower Badenian deposits. Correlations with *Heterostegina* (*Planostegina*) events from the Korytnica Basin and Leitha Limestone remain questionable. Due to the absence of (prae-) orbulinas in the Brus-1 profile its deposits are probably older than the surrounding localities which are correlated with the Lower Lagenidae Zone with orbulinas (*sensu* Wagneich et al., 2014; Hohenegger et al., 2014). Occurrence of large benthic foraminifera (mainly *Planostegina* sp.) in the Brus-1 profile was probably related to water turbidity due to intense rainfall that occurred in the Early Badenian and preceded the arid period leading to the Wieliczka salinity crisis (13.81 Ma; cf. e.g., Peryt, 1997; Oszczytko et al., 2006; Kováč et al., 2007; de Leeuw et al., 2010).

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