From dysoxic sea to hypersaline lagoon: paleoenvironmental changes on the Badenian/Sarmatian boundary (borehole MZ102; Vienna Basin)

Jaroslava Babejová-Kmecová[1], Ivana Plašienková[1], Ľubomír Sliva[2], Eva Halásová[1] & Natália Hudáčková[1]

[1] Univerzita Komenského, Prírodovedecká fakulta, Katedra geológie a paleontológie, Ilkovičova 6, 842 15 Bratislava, Slovenská republika; kmecova45@uniba.sk
[2] Nafta a. s. 821 09 Bratislava, Slovakia

AGEOS

Abstract: The main objective of this work was to interpret the environment during a very dynamic paleoenvironmental change from the Badenian to the Sarmatian in the Central Paratethys, as well as to determine ecologic factors, diversity, and the relationship between the foraminiferal morphogroups in the northern part of the Vienna Basin. The samples of this study come from the MZ 102 borehole, which had been drilled near the town of Malacky in the northern part of the Vienna Basin (Slovakia) (Fig.). Based on sedimentology and fossil occurrence, we interpreted a paleoenvironment of the northern part of the Vienna Basin during the middle Miocene. By examining changes in the occurrence of foraminifera (*Articulina sarmatica, Cycloforina stomata*, *Tenuitella* acme) and calcareous nannofossils (*Coccolithus miopelagicus*) in the studied samples, we detected the position of the Badenian/Sarmatian boundary. Low-oxic conditions in the uppermost Badenian (Studienka Fm.) and upper Sarmatian (Skalica Fm.) sediments were interpreted, as well as fluctuation from a normal marine to hypersaline shallow water paleoenvironment in the middle and upper Sarmatian sediments (Skalica Fm.). Macrofauna was represented mostly by bivalves and gastropods shells and fish remains. Samples were compared with samples from the nearby MZ 93 borehole to fill in the gaps in the MZ 102 borehole record.

Keywords: Vienna Basin, Foraminifera, Paleoenvironment, Middle Miocene, Calcareous nannoplankton, sedimentology

1. INTRODUCTION

The nutrient content, salinity, type of substrate, and change of oxygen concentration in water at sediment surface may play an important role in the presence and distribution of benthic foraminifera (Sen Gupta, 2003). One of the classical Cenozoic basins for the study of foraminifers in the Central Paratethys is the Vienna Basin, which has been of great interest since the pioneer monograph of d'Orbigny (1846). The Vienna Basin is 200 km long and 55 km wide Neogene basin, oriented SSW-NNE, and nowadays situated in three states: Slovakia, Austria, and the Czech Republic (Kováč et al., 2004). The geological, geodynamic, and tectonic development of the basin has been previously described in various studies (e.g., Ratschbacher et al., 1991a,b; Csontos et al., 1992; Kováč et al., 1994, 1997, 1998, 2016, 2017a; Matenco, 1997; Konečný et al., 2002; Schmid et al., 2008; Ustaszewski et al., 2008; Handy et al., 2010, 2015; Studencka et al., 2016). Central Paratethys has been studied in detail by Seneš (1961a,b); Kováč et al. (1994, 1998, 2003, 2016, 2017b); Meulenkamp et al. (1996); Oszczypko (1998, 1999); Popov et al. (2004); Oszczypko & Oszczypko-Clowes (2006); Piller et al. (2007); Gozhyk et al. (2015) and Neubauer et al. (2015).

During the middle Badenian, sea regression took place, which caused changes in water salinity (Harzhauser & Piller, 2004; Koubová & Hudáčková, 2010) and extinction or endemicity of fauna and flora (Harzhauser & Piller, 2007; Palcu et al. 2015). In the upper Badenian/Sarmatian boundary, transgression occurred, causing low-oxic bottom waters with Bolivina-Bulimina zonation (Kováč et al., 2017b). At the end of the Pannonian age, the sedimentary environment became hyposaline (Kováč et al., 2008a,b) with changes of foraminifera assemblages to very low diversified to monospecific (Hudáčková et al. 2018, 2019).

The aim of this work was to interpret the origin and environment of collector sediments. Main goal was to interpret the paleoenvironment of the northern part of the Vienna Basin around the Badenian/Sarmatian boundary based on the foraminiferal associations from the studied borehole, and to determine ecologic factors which provoked the change in species diversity. Finally, we compared the functionality and complexity of two methodological approaches for the paleoecological interpretations: foraminiferal species versus foraminiferal morphogroups study.

1.1. Geological settings and methods

Samples come from the MZ 102 borehole, which had been drilled in the northern part of the Vienna Basin, west of the town of Malacky. The natural gas field Malacky-West represents an important geological structure, which in the past produced almost 1.3 billion m^3 of gas, while most of the production comes from the sandy horizons of the upper Badenian and Sarmatian deposits (Badenian and Sarmatian sands specified by Nafta a. s.; Fig. 2)

Manuscript received 2021-12-10
Revised version accepted 2022-06-06

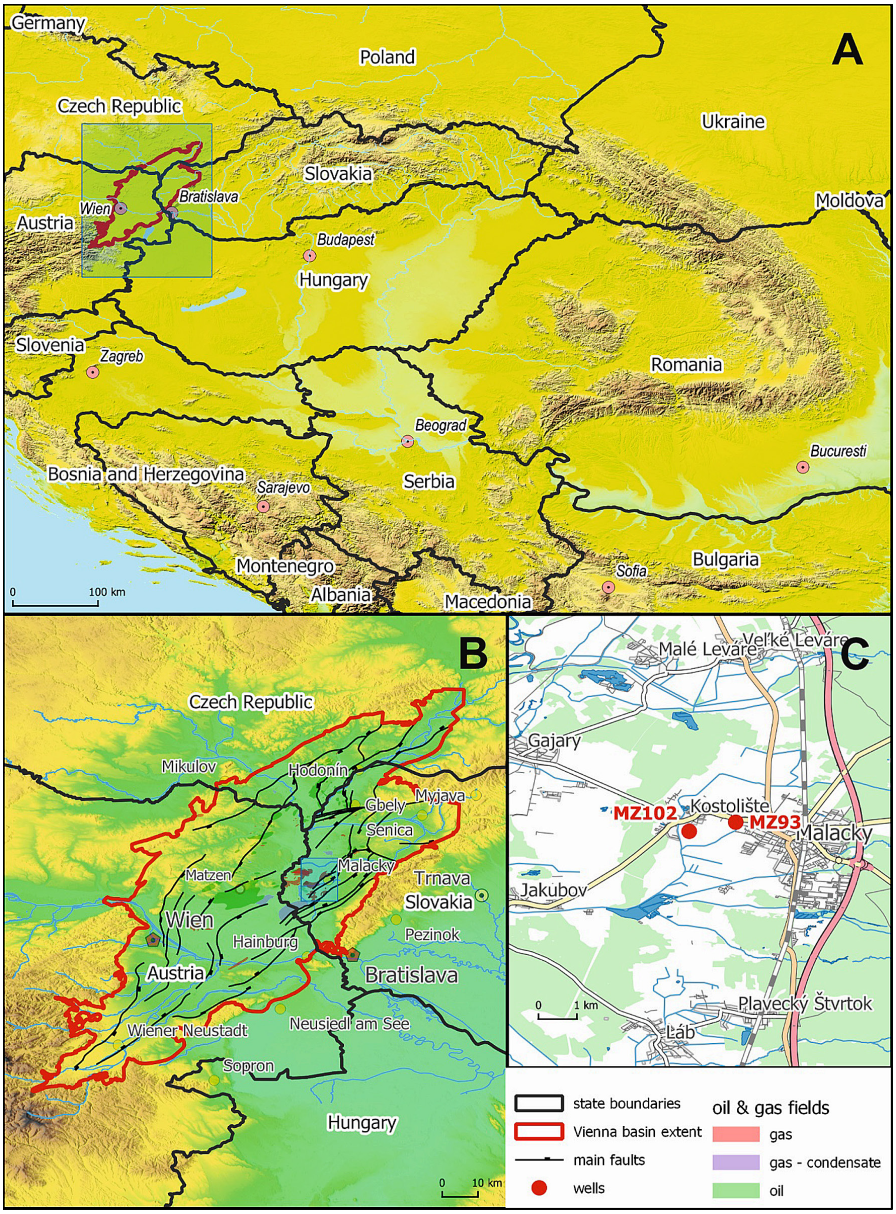


Fig. 1. Localization map (A – Europe; B – Vienna basin, C – boreholes MZ 93 and MZ 102).

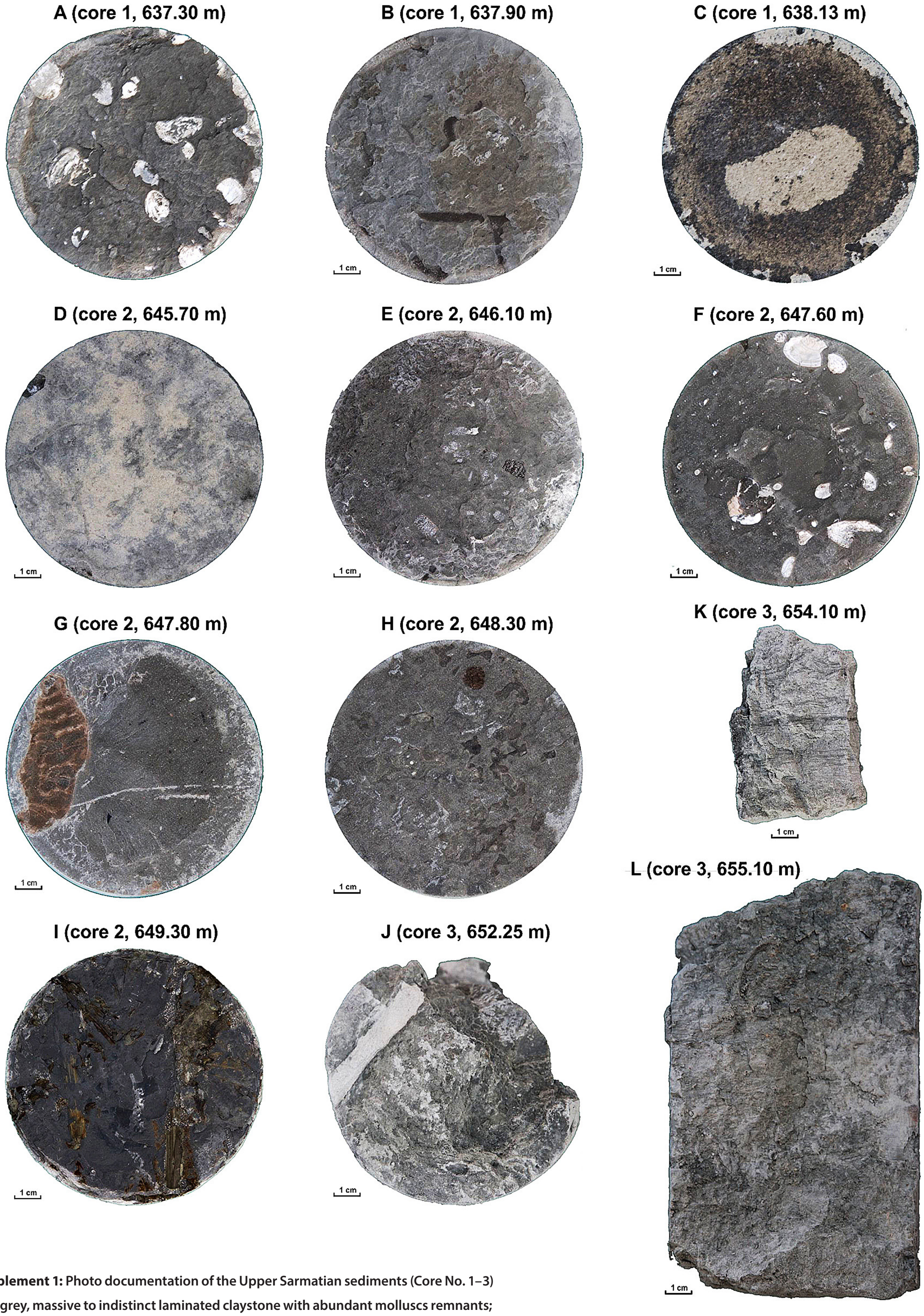
(Hudeček & Šály 1995). The depleted gas field is currently being converted into an underground gas storage facility (UGS). The geological structure of the upper Badenian and Sarmatian sediments is well-documented in this area by drilling and 3D seismic data. The MZ 102 borehole was drilled in April 2013 in the SW part of UGS Malacky, the final depth reaching 1215 m.

1.2. Sedimentology

The aim of the borehole was to verify the existence, thickness, and reservoir parameters of UGS objects (1st Badenian – Main sand and 1st Sarmatian sand; see Fig. 2), as well as to specify the geological setting of the upper Badenian, Sarmatian, and Pannonian strata in the Malacky area. A special goal of the borehole was the extraction of rock samples from the drill cores to determine detailed petrophysical parameters of UGS objects and their sealings (Wallner et al. 2014). Both studied boreholes, MZ 102 and MZ 93, are located near the town of Malacky in the area of the Záhorská nížina plain (Figs. 1, 2). Although samples from borehole MZ 102 were taken from the entire solid rock profile, studied borehole (Figs. 3A–F) data consists of parts that anticipated a Badenian/Sarmatian boundary and the upper Sarmatian: core No. 2 (644–651 m), No. 3 (652.2–659.8 m), No. 4 (1034–1043.1 m), No. 5 (1043.1–1051.6 m) and No. 6 (1051.6–1060.1 m). The core sample predominantly consists of fine-grained, pale to dark grey siltstones with intercalations of well-sorted sandstones. Borehole samples were obtained in the Gbely core repository of the NAFTA Ltd. petroleum company. Visual sedimentological interpretation was refined using a CT scan of the cores. Lithofacies were described according to Bouma et al. (1985), Miall (2006), Nielsen et al. (2007), Talling et al. (2012) and Rossi et al. (2017). Basic borehole logs (Fig. 2; spontaneous potential and resistivity) were evaluated according to Rider & Kennedy (2011).

1.3. Foraminifera and calcareous nannoplankton

Samples taken from the MZ 102 borehole for Foraminifera and calcareous nannoplankton were performed every 10 cm. Each of the 406 samples were marked in the borehole profile (Fig. 3A–F). The samples were first dried out and separated into 100 g of borehole core material, diluted by hydrogen peroxide and wet screened on wire screens ranging between 0.071 mm – 1 mm and 1 mm and more; whenever possible, 250 specimens of benthic and planktonic foraminifera were picked out of the residua. Foraminiferal tests were separated by using the binocular stereoscopic microscope Leica MZ and then observed under an electron scanning microscope (SEM) QUANTA FEG 250. The obtained foraminifers were determined into species level based on Loeblich & Tappan (1992), Cicha et al. (1998), and on Luczkowska (1972, 1974), the last two specialized on miliolide foraminifera systematics. Paleoecologic interpretation was obtained from the findings of Boltovskoy & Wright (1976), Jones & Charnock (1985), Murray (1973, 1991, 2006), van der Zwaan et al. (1990), Orpin at al. (1999), Berkeley et al. (2007, 2008), Filipescu (2004) and Patterson et al. (1990). Specimens were grouped into morphogroups according to Langer (1988) and Murray (2006) (Fig. 4) (Tab. 1, Supplement table). Diversity was expressed by



Supplement 1: Photo documentation of the Upper Sarmatian sediments (Core No. 1–3)

A, F: grey, massive to indistinct laminated claystone with abundant molluscs remnants;

B: grey, slightly laminated claystone with algae remnants; C, D: distinctly laminated claystone with thin carbonate laminas; E: grey, slightly laminated claystone with small plant fragments and coprolites; G, H: distinctly laminated claystone with fish scales and (G) calcareous concretions; I: dark grey claystone with coalified wood fragments; J: grey, massive, bioturbated (sand filled) claystone ; light grey, fine grained laminated , slightly cemented sand; L: grey, massive silty sand.

Supplement 2: Photo documentation of the Upper Badenian and Lower Sarmatian sediments (Core No. 4–10)

A, D: grey, laminated (A) and massive (D), bioturbated (sand filled) claystone, B, E: laminated claystone with (B) diffuse or distinct (E) silty laminas; C: grey, massive claystone with juvenile gastropods; F, G, H, J: light grey, fine grained, horizontally to cross laminated sandstone; organodetritic limestones with fragments of red algae and molluscs; K: grey silty claystone with small sand ripples and coalified plant fragments; L: coarse grained, gravelly sandstone with abundant molluscs and red algae fragments; M: grey claystone with thin silty lenses and laminas and large coalified wood fragments; N: light grey, coarse grained, gravelly sandstone

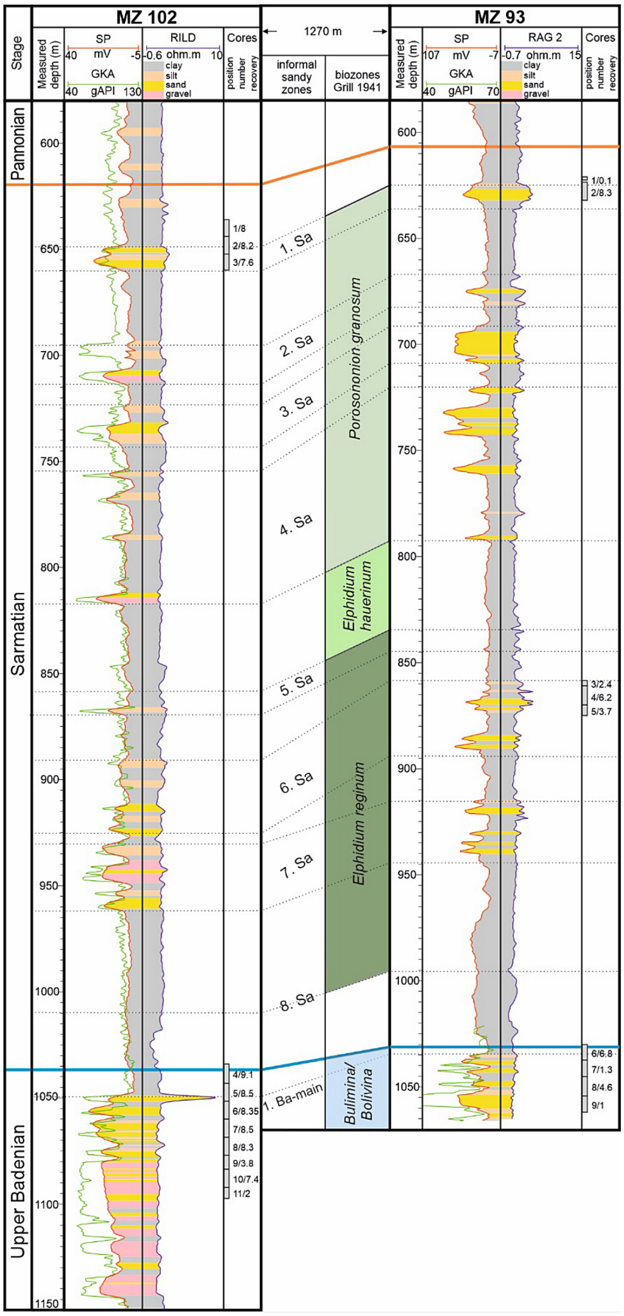


Fig. 2. Lithological scheme of the boreholes MZ 102 and MZ 93 with localization of the studied borehole cores, main sand bodies, and biostratigraphic interpretation.

Tab. 1. Morphogroups of benthic foraminifera adapted according to Langer (1988) and Murray (2006). Epiphytes A, B, C and D, and IN-infauna.

Species	Morphogroup (Langer, 1988) Infaina (Murray, 2006)	Species	Morphogroup (Langer, 1988) Infaina (Murray, 2006)
Adelosina sp.	EP-D	*Elphidium hauerinum*	IN
Ammonia beccarii	IN	*Elphidium macellum*	EP-C
Ammonia ex. gr. viennesis	IN	*Fissurina laevigata*	parasite
Ammonia parkinsoniana	IN	*Fissurina mironovi*	parasite
Ammonia sp.	IN	*Hansenisca soldanii*	IN
Ammonia tepida	IN	*Haynesina cf. depressula*	IN
Articularia articulinoides	EP-D	*Haynesina* sp.	EP-C
Articulina multitubullata	EP-D	*Heterolepa sp.*	EP-B
Articulina problema	EP-D	*Hoeglundina elegans*	IN
Articulina sarmatica	EP-D	*Lobatula lobatula*	EP-B
Aubignyna perlucida	IN	*Martinottiella* sp.	IN
Biasterigerina planorbis	EP-B	*Melonis pompolioides*	IN
Bolivina cf. dilatata	IN	*Miliammina* sp.	EP-D
Bolivina dilatata dilatata	IN	*Miliolinella* sp.	EP-D
Bolivina ex gr. dilatata	IN	*Miliolinella subrotunda*	EP-D
Bolivina papulata	IN	*Nodosaria dina*	IN
Bolivina sarmatica	IN	*Nodosaria* sp.	IN
Buccella frigida	IN	*Nonion biporus*	IN
Bulimina aff. elongata	IN	*Nonion commune*	IN
Bulimina elongata	IN	*Nonion* sp.	IN
Bulimina sp.	IN	*Nonionella* sp.	IN
Bulimina striata	IN	*Porosononion hyalinus*	EP-C
Cassidulina laevigata	IN	*Porosononion gr. granosum*	EP-C
Caucasina gutsulica	IN	*Porosononion granosum*	EP-C
Cibicides boueanus	EP-B	*Pseudotriloculina onsobrina*	EP-D
Cibicides dutemplei	EP-B	*Pseudotriloculina microdon*	EP-D
Cibicides sp.	EP-B	*Pullenia bulloides*	IN
Cibicidoides ex.gr. ungerianus	EP-A	*Pullenia quinqueloba*	IN
Cibroelphidium excavatum	IN	*Quinqueloculina akneriana*	EP-D
Conorbella erecta	EP-B	*Quinqueloculina pseudobuchiana*	EP-D
Cycloforina stomata	EP-D	*Quinqueloculina selene*	EP-D
Dogielina sarmatica	EP-C	*Quinqueloculina seminulum*	EP-D
Elphidiella arctica	IN	*Quinqueloculina* sp.	EP-D
Elphidiella cf. minuta	IN	*Rosalina austriaca*	EP-B
Elphidium aculeatum	EP-C	*Rosalina obtusa*	EP-B
Elphidium advenum	EP-C	*Saccammina sarmatica*	IN
Elphidium aff. crispum	EP-C	*Siphonaperta lucida*	EP-D
Elphidium antonium	IN	*Siphonodosaria lepidula*	IN
Elphidium cf. fichtellianum	EP-C	*Spiroloculina dilatata*	EP-D
Elphidium cf. flexuosum	IN	*Stilostomella* sp.	IN
Elphidium cf. margaritaceum	EP-C	*Triloculina* sp.	EP-D
Elphidium ex. gr. macellum	EP-C	*Valvulineria* sp.	IN
Elphidium fichtelianum	EP-C	*Varidentella rotunda*	EP-D

the Shannon_H index and Fisher alpha formula (Murray, 2006). For specifying the oxygen depletion, the Ammonia – Elphidium index (IAE) was used (Supplement table). The index is given by IAE = [NA/ (NA + NE)] x 100, where NA and NE are the numbers of individuals of *Ammonia* and *Elphidium* (Pregnolato et al., 2018). Samples with more than 50 individuals were included in the statistical analysis (Hammer et al., 2001). Data were stored in a Viendat database (edited by Hudáčková & Hudáček, 2001) and analysed with the aid of the programs PAST – Paleontological Statistics, ver. 1.70 (Hammer et al., 2001) and POLPAL (Walanus & Nalepka, 1999). Samples with a predominance of

Fig. 3 A-F. Detailed sedimentology, samples position (circles) and fossil content (symbols) of the studied cores of the borehole MZ 102. Explanation in Fig. 3 F.

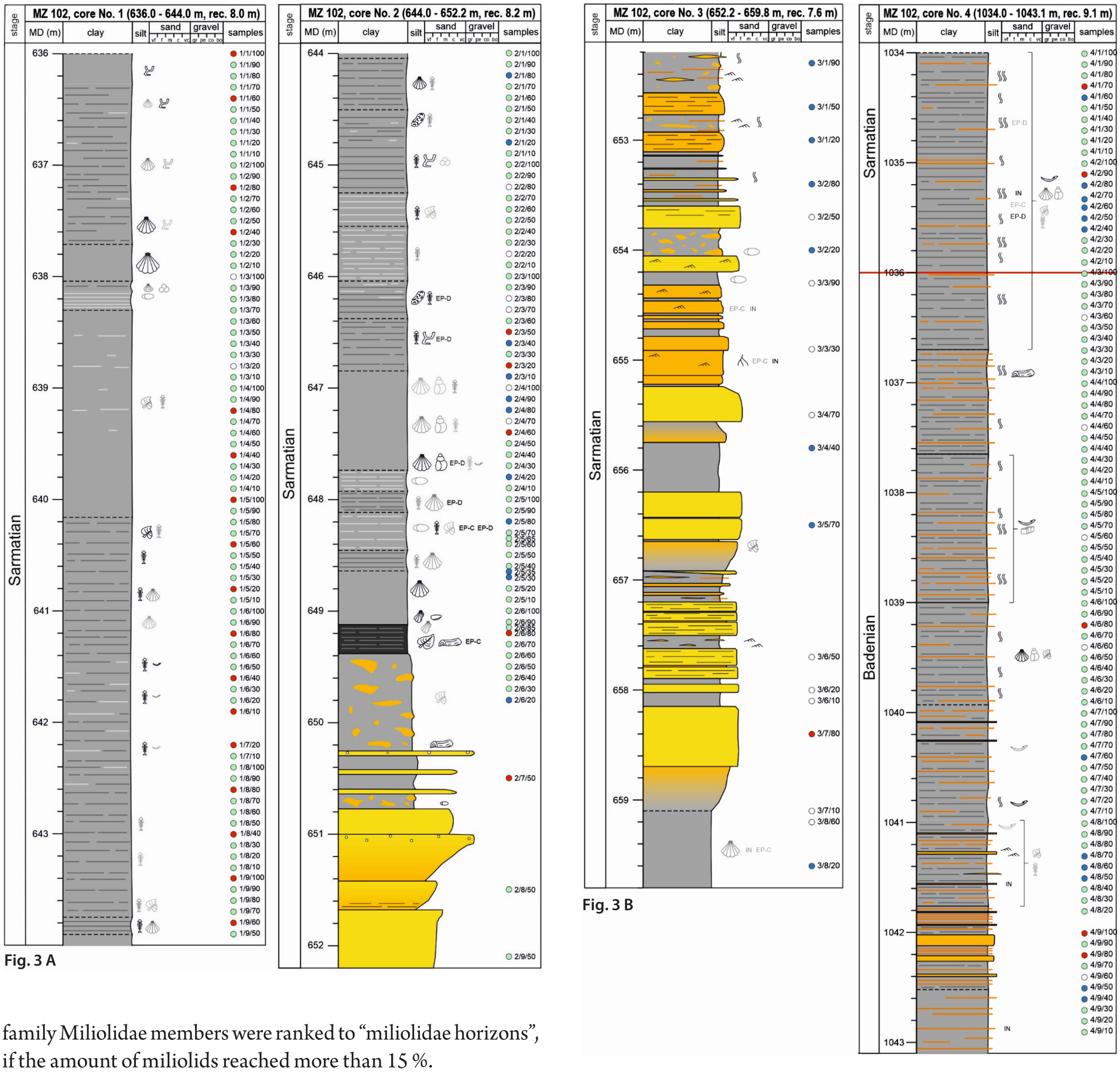


Fig. 3 A

Fig. 3 B

family Miliolidae members were ranked to “miliolidae horizons”, if the amount of miliolids reached more than 15 %.

Calcareous nannofossil samples were prepared by the method of decantation using smear slides. The resulting suspension was mixed with distilled water on a glass slide. The combination created a thick suspension, which after it dried out was ready for observation and compared under the polarized light microscope, Olympus BX 50, at 1250x magnification. Coccoliths were determined into species according to the Nannotax database (Young et al., 2003) and documented by Infinity 2 camera and the QuickPHOTO camera 2.3 program with 10μ magnification.

2. RESULTS

2.1. Sedimentology

The core samples from the borehole MZ 102 predominantly consists of fine-grained, pale to dark grey siltstones with intercalations of well-sorted sandstones. The studied core part of the sedimentary record in borehole MZ102 represents sediments of the 1st Badenian - Main sand (cores 11-4, the upper Badenian, and the lower Sarmatian) 1st Sarmatian sand (cores 3-1, terminal Sarmatian) (Fig. 2).

On the well-log curves of the MZ 102 borehole, the Sarmatian sediments begin with a transgressive mudstone (in the northern part of the Malacky field, interrupted by thick 8th Sarmatian sand), which pass locally into the regressive 7th, 6th and 5th Sarmatian sands. The following transgressive – regressive (TR) cycle begins with mudstones overlying the 5th Sarmatian sand, which continue into very distinctive packets of the 4th and 3rd Sarmatian sands (Fig. 2). The sand sedimentation continues with the 2nd Sarmatian sand, (more significantly-developed further south in the Jakubov area) and was terminated by the sands of the 1st Sarmatian sand (with the main depocenter in the Gajary

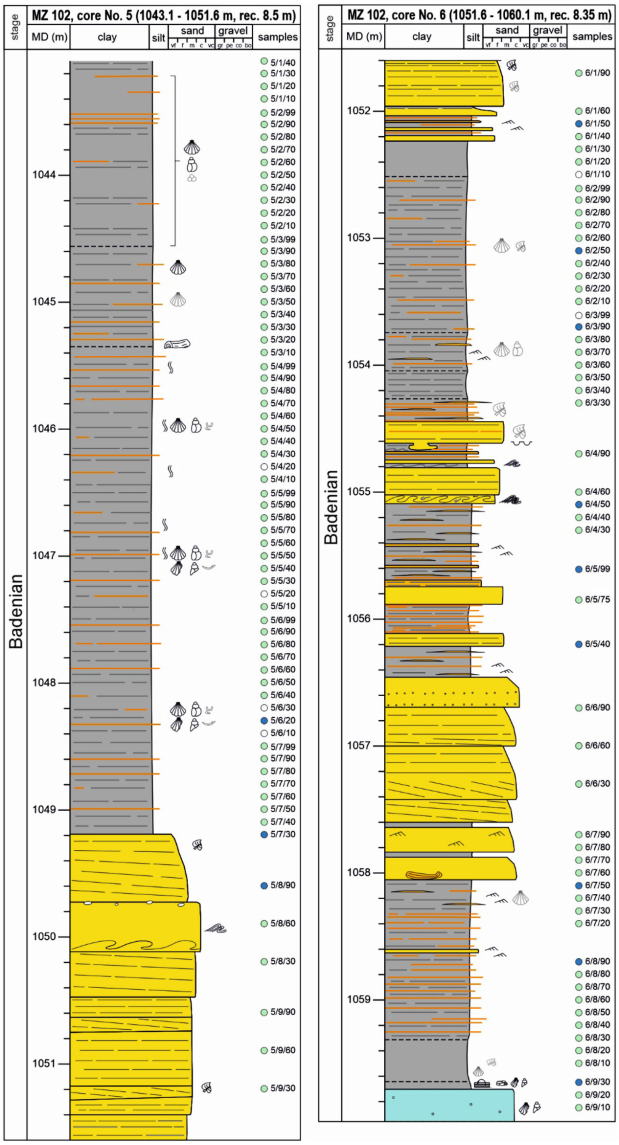


Fig. 3 C

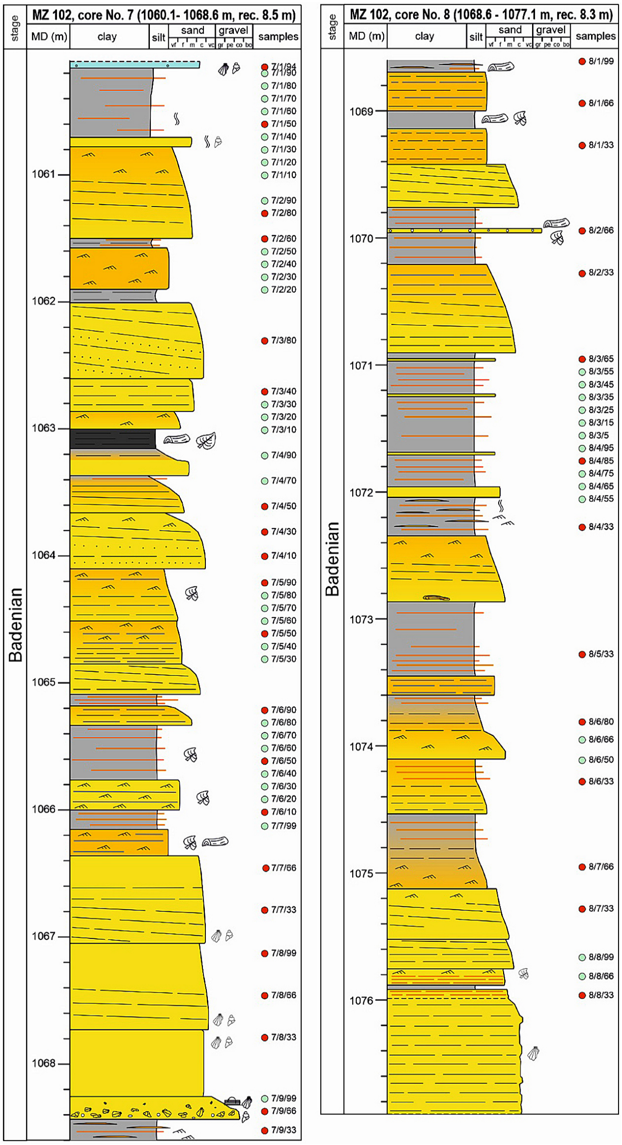


Fig. 3 D

area). Both third order TR cycles are divided into several smaller parasequential cycles.

In cores No. 6-5, the sands are relative well-sorted and, unlike the sediments in cores No. 11-7, they do not contain much gravel or silt. The organodetritic hardground at the base of core No. 6, which had been formed by small pebbles and fragments of tests and red algae was present (Fig. 2, 3, 4). Mudstones with abundant silty laminas form the upper part of core No. 5 and core No. 4. From a depth of 1039 m upwards, the proportion of pyrite concretions, fish remnants and juvenile shells increases. Core No. 3 and the lower part of core No. 2 are formed by silty claystones, siltstones, and weakly consolidated sandstones. In the upper part of core No. 2, as well as in core No. 1, the above-mentioned sedimentary sequence passes (at a depth of 649.15 m) into overlying fine-grained facies, characterized by massive claystones with abundant mollusc shells alternating with laminated claystones with frequent fish remains. Lamination was often marked by very thin laminas, formed by precipitated $CaCO_3$ (Fig. 3). Macrofauna was represented mostly by bivalve and gastropod shells, together with fish remains.

2.2. Calcareous nannoplankton

Calcareous nannofossils were studied in cores No. 6, 4, 3, and 2. Association in the studied samples (30) can be evaluated as low diversified, containing Neogene species and coccoliths reworked from Cretaceous and Paleogene sediments. The samples from depths of 1055.9 m and 1055 m (core No. 6) contain specimens of *Helicosphaera walbersdorfensis, Reticulofenestra minuta, R. haqii, R. pseudoumbilicus, Coccolithus pelagicus*. Core No. 4 in depth 1042.6 m – 1034.6 m (13 samples) contains association of coccoliths dominated by *Reticulofenestra minuta* species and Cretaceous/Paleogene nannofossils *(Ismolithus recurves, Dictyococcites bisectus, Discoaster multiradiatus)*. The sample from depth 1041.6 m contains abundant associations *(Coronocyclus nitescens, Coccolithus miopelagicus, C. pelagicus, Discoaster exilis, D. deflandrei, D. variabilis, Holodiscus macroporus, Helicosphaera carteri, H. carteri wallichii, H. walbersdorfensis, Pontosphaera multipora, Reticulofenestra pseudoumbilicus, R. haqii, Sphenolithus heteromorphus, Umbilicosphaera jafari, U. rotula)*. In the sample

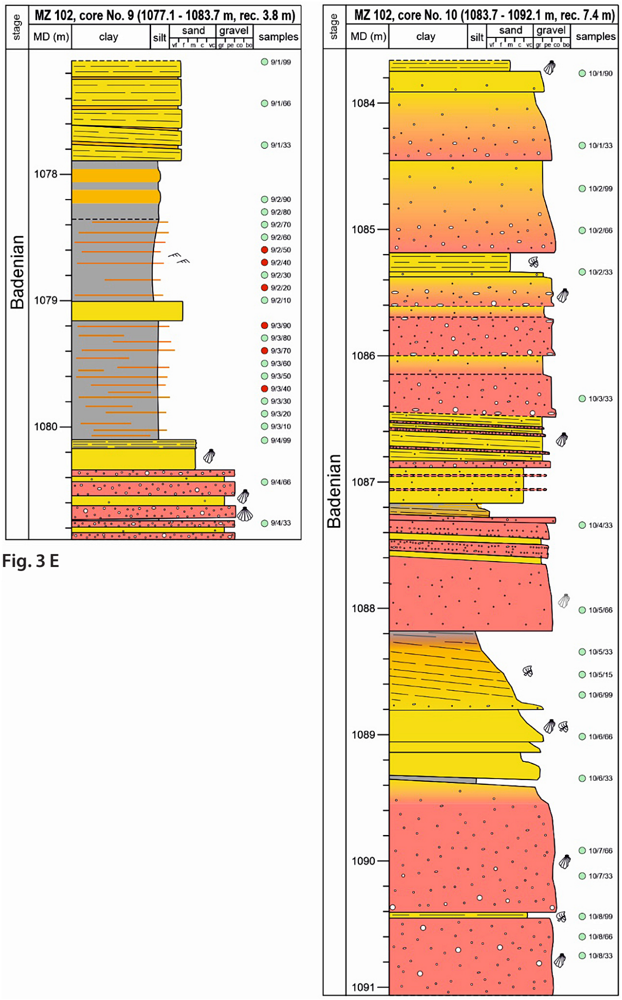


Fig. 3 E

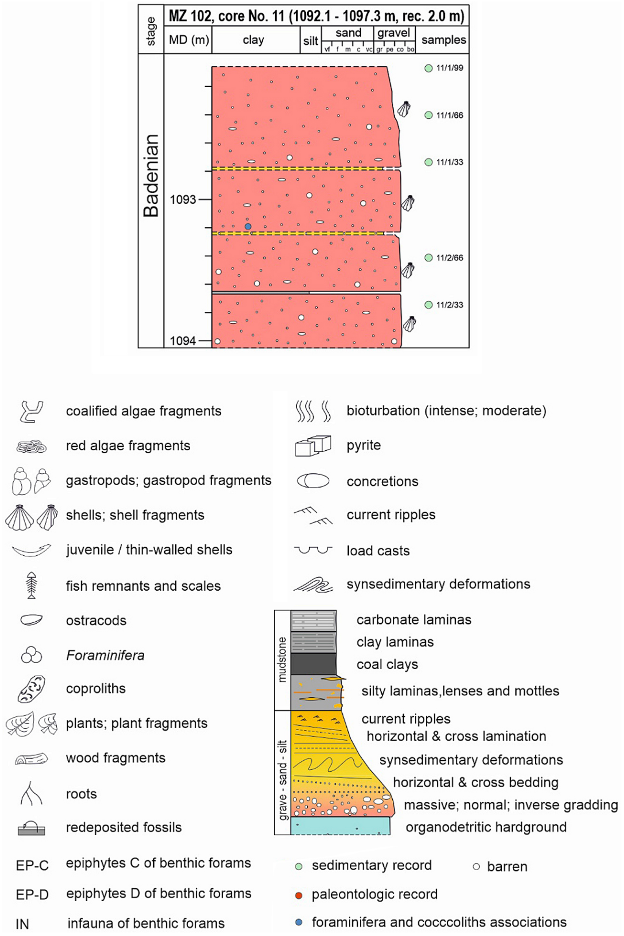


Fig. 3 F

from 1035.8 m, the acme of species *Reticulofenestra minuta* was identified. The core No. 3 (659.8 m – 652.4 m) contains only one sample (depth 655 m) with presence of calcareous nannoplankton with associations of *Braarudosphaera bigelowii parvula, Reticulofenestra pseudoumbilicus* and *Sphenolithus heteromorphus* and Cretaceous/Paleogene nannofossils *(Nannoconus steinmannii steinmannii, Cyclicargolithus floridanus)*. Core No. 2 yields sediments (648.3 and 644.8 m) with the acme of *Sphenolithus abies*, as well as monogeneric associations represented by *Braarudosphaera bigelowii* and *B. bigelowii parvula* together with abundant ascidian spicules (samples in depth 648.8, 648, and 647.2 m).

2.3. Foraminifera

Foraminifera from the MZ 102 borehole were determined into species level (Supplement table) and classified into morphological groups (Tab. 1). Overall, there were 141 systematically processed samples, from which 81 yielded fossil remains, and 39 of them yielded foraminiferal tests. 86 taxa of benthic and 12 taxa of planktonic foraminifera were determined, of which 16 of them stayed in open nomenclature due to poor preservation of the tests (Figs. 5, 6). According to our data, the benthos was more common than plankton in the entire studied part of the

Morphogroup	Features
EP-A 	sesile, attachment surface, flat, concave, or folded over, e. g. *Planorbulina, Cibicidoides*
EP-B 	temporary motile, apertural faces wide, motion by swimming on pseodopodial network, e. g. *Rosalina*
EP-C 	motile, pseudopods from canal system and multiple apertural openings, e. g. *Elphidium*
EP-D 	permanently motile, apertural faces narrowing the bottle-neck apertures, motion by striding on the apertural face in upright position, e. g. *Quinqueloculila*

Fig. 4. Morphogroups of epiphytes (EP–A, EP–B, EP–C, EP–D) with main behavioural and morphological features and examples from our study (edited by Langer, 1988). For detailed ranking of species into morphogroups, see Tab. 2.

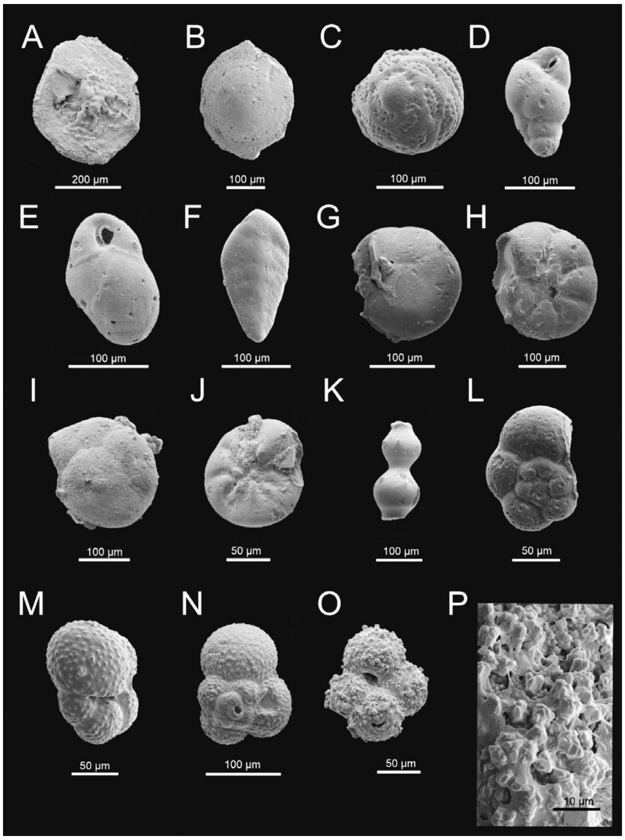


Fig. 5. A, B - *Biasterigerina planorbis* (depth: 1048,8 m); C - *Rosalina* sp. (depth: 1047.8 m); D - *Bulimina elongata* (depth: 1042.9 m); E - *Caucasina gutsulica* (depth: 1041.6 m); F - *Bolivina dilatata* (depth: 1042.9 m); G, H - *Ammonia viennesis* (depth: 655 m); I, J - *Ammonia parkinsoniana* (depth: 659.4 m); K - *Stilostomella* sp. (depth: 1041.6 m); L, M - *Globorotalia* sp. (depth: 1041.6 m); N - *Turborotalita quinqueloba* (depth: 1041.6 m); O - Tenuitella munda (depth: 1041.6 m); P – wall detail of *Tenuitella munda* (depth: 1041.6 m).

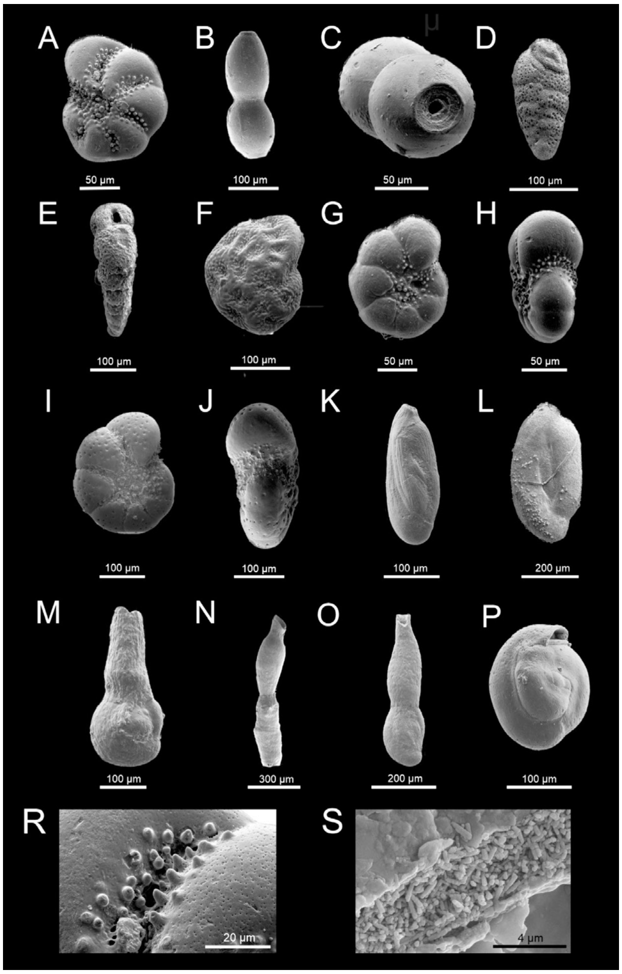


Fig. 6. A - *Cribroelphidium excavatum* (depth: 1035.7 m); B - *Nodosaria dina* (depth: 1035.6 m); C - *Articulina sarmatica* (depth: 648); D, E - *Bolivina sarmatica* (depth: 654.5 m); F - *Elphidium margeritaceum* (depth: 648 m); G, H - *Porosononion hyalinus* (depth: 1035.6 m); I, J - *Porosononion granosum* (depth: 649.2 m); K - *Pseudotriloculina consobrina* (depth: 654.5 m); L - *Quinqueloculina seminulum* (depth: 648.3 m); M, N – *Articulina problema* (depth: 648 m); O - *Articularia articulinoides* (depth: 647.8 m); P - *Miliolinella subrotunda* (depth: 647.8 m); R - wall detail of *Elphidium advenum* (depth: 654.5 m); S – wall detail of *Articulina problema* (depth: 648 m).

borehole. Morphogroups were figured by the POLPAL program, in which axis X represents the depth (in meters) and axis Y the percentual proportion of certain foraminiferal morphogroups and other dominated associations (Fig. 7).

2.3.1. Planktonic foraminifera

A low number of small, round planktonic forms (164 individuals), often with signs of size sorting were found in cores 6, 5, and the lower part of core 4 (1059.8 m – 1041.6 m), dominated by association of *Globigerina* sp. div., *Globigerinita uvula, Globorotalia (Obandyella) transsylvanica, Trilobatus quadrilobatus, Paragloborotalia opima opima, Turborotalita quinqueloba, Tenuitella* sp. div. indet. and *T. munda*.

2.3.2. Benthic foraminifera

The most common benthic foraminifera obtained from entire borehole profile are species from following genera: *Ammonia* (to 80 % in depth 656.9 m), *Elphidium* (90 % in sample 1041.6 m), *Cribroelphidium* (50–90 % in depth interval 1035.8 – 1034.6 m), *Porosonoion* and *Articulina* (30 % in depth interval 648 – 646.1 m) (Fig. 8). Predominance of miliolids (miliolid horizons, MH; more than 15 %) were found in the depths 1035.6 – 1034.6 m; 648.35 m; 648 – 647.7 m and 646.5 – 646.1 m.

The IAE index value ranged from 0 to 100 with the minima in the interval 648.3 – 646.1 m and with the highest values in 1048.8 – 1041.6 m; 656.9 – 652.4 m and 655 m.

The base of rock sequence (in depth 1059.8 – 1041.6 m) contains few species from morphogroup A/epiphyte (*Cibicidoides ungerianus* and *Cibicides boueanus*) and morphogroup B/epiphyte – planoconvex shape (*Ammonia viennensis* and *Asterigerinata planorbis*). We observed several flattened epifaunal species with planispiral involute (morphogroup C/epiphyte), such as *Porosononion granosum, Haynesina depressula, Elphidium macellum and Elphidium fichtelianum* (Figs. 7, 8). Occurrence of species *Cassidulina laevigata* and

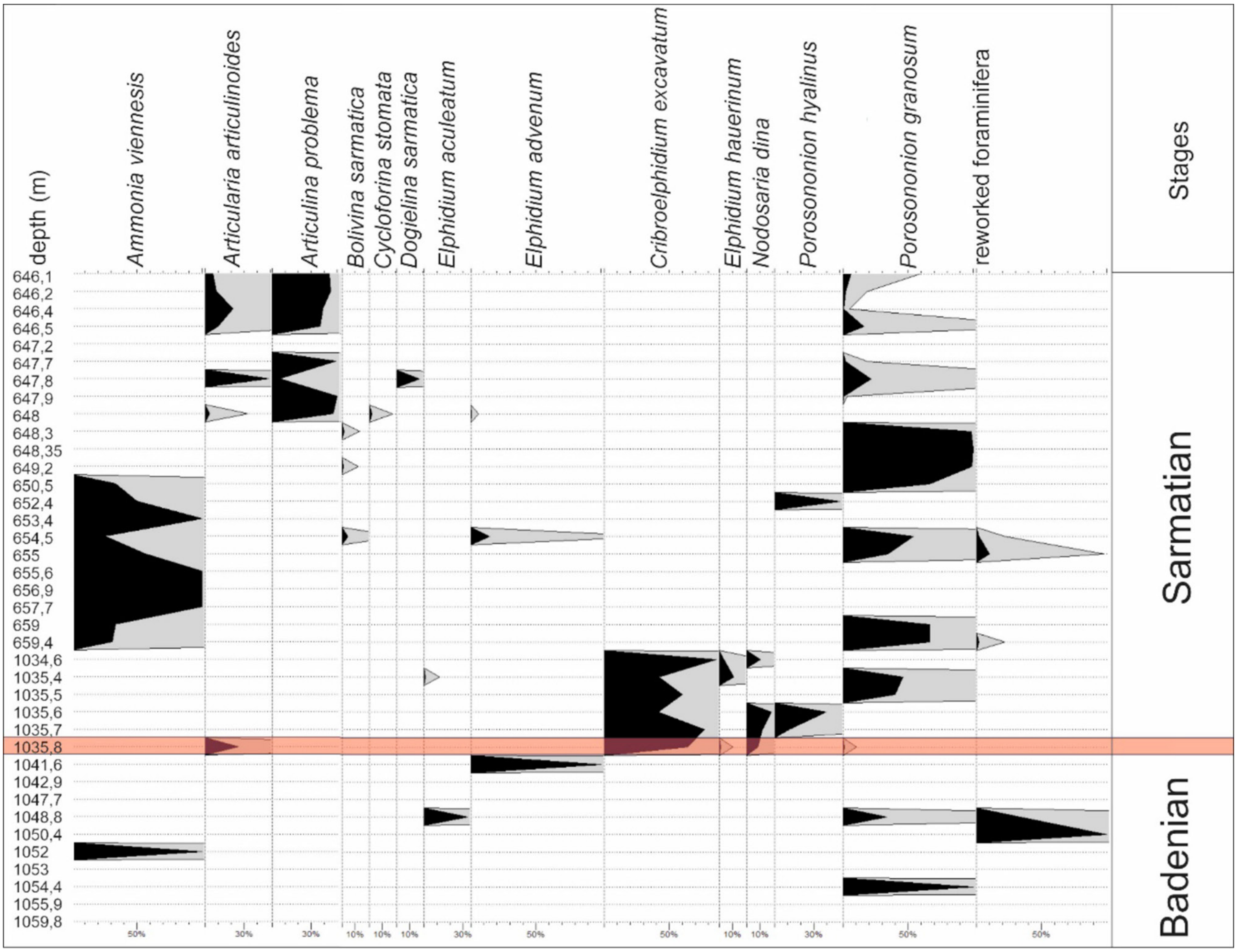


Fig. 7. The dominance of the significant taxa identified in non-barren samples of the MZ 102 borehole. The orange line shows revealed Badenian/Sarmatian boundary.

Globocassidulina crassa with a lenticular shape of the tests was rare. At the depth from 1059.8 to 1041.5 m, the presence of epiphytes was also rare; however, the *Caucasina gutsulica* and *Bulimina elongata* were observed. From the sample taken at 1035.8 m, *Porosononion granosum, Haynesina* sp., and *Ammonia* sp. dominate with *Cribroelphidium excavatum* (high abundances) making its first appearance in this part of the borehole. The size sorting of the rounded tests in this sample was observed.

The sample from core No. 3 at a depth of 659.8 m yields poor foraminiferal record of planoconvex trochospiral species (morphogroup B/epiphytes), such as *Biasterigerinata planorbis, Ammonia viennensis, Ammonia parkinsoniana and Aubignyna perlucida*. From a depth of 650.5 m, *Porosononion granosum* highly dominates (morphogroup C/epiphytes) together with miliolids (EP-D morphogroup) *Quinqueloculina seminula, Pseudotriloculina consobrina* and *Quinqueloculina rotunda*. From the sample taken at 648 m, the miliolidae foraminifera *Articulina problema, Articularia articulinoides* begin to dominate, accompanied by a few species of *Articulina sarmatica, Cycloforina stomata*, and *Dogielina sarmatica*. The sediments with this associations end at a depth of 646.1 m, above which the sediments are barren of foraminifera tests.

Infaunal associations dominated at depths between 1053 to 1035.7 m and 659.4 to 649.2 m. Epiphytes of group A and B were dominant in the lower parts of the borehole core; however, epiphytes of group C and D were abundant in the upper part.

2.4. Diversity

Diversity results show values on the Fisher alpha formula with the minimum being 1.3 and the maximum being 5.97, and on the Shannon_H formula with values being the minimum 0.77 and the maximum 2.41. Values were higher in the lower part of borehole MZ 102, yet lower in the upper part. In general, the relationship between the values of estimated diversities of the samples are presented in three groups (Fig. 9). The first group (A) specified the values of the Shannon_H index from 0.77 – 1.66 with the Fisher alpha index from 1.3 to 1.85 in the samples from depths of 646.2; 647.7; 647.9; 648; 648.3; 648.35; 649.2; 1034.6, and 1035.4 meters. These samples contain rich association of miliolids, such as *Articulina problema, Varidentella rotunda, Pseudotriloculina consobrina, Siphonaperta lucida, Quinqueloculina seminulum,* and numerous hyaline species, such as *Porosononion granosum* and *Cribroelphidium excavatum*. The second group

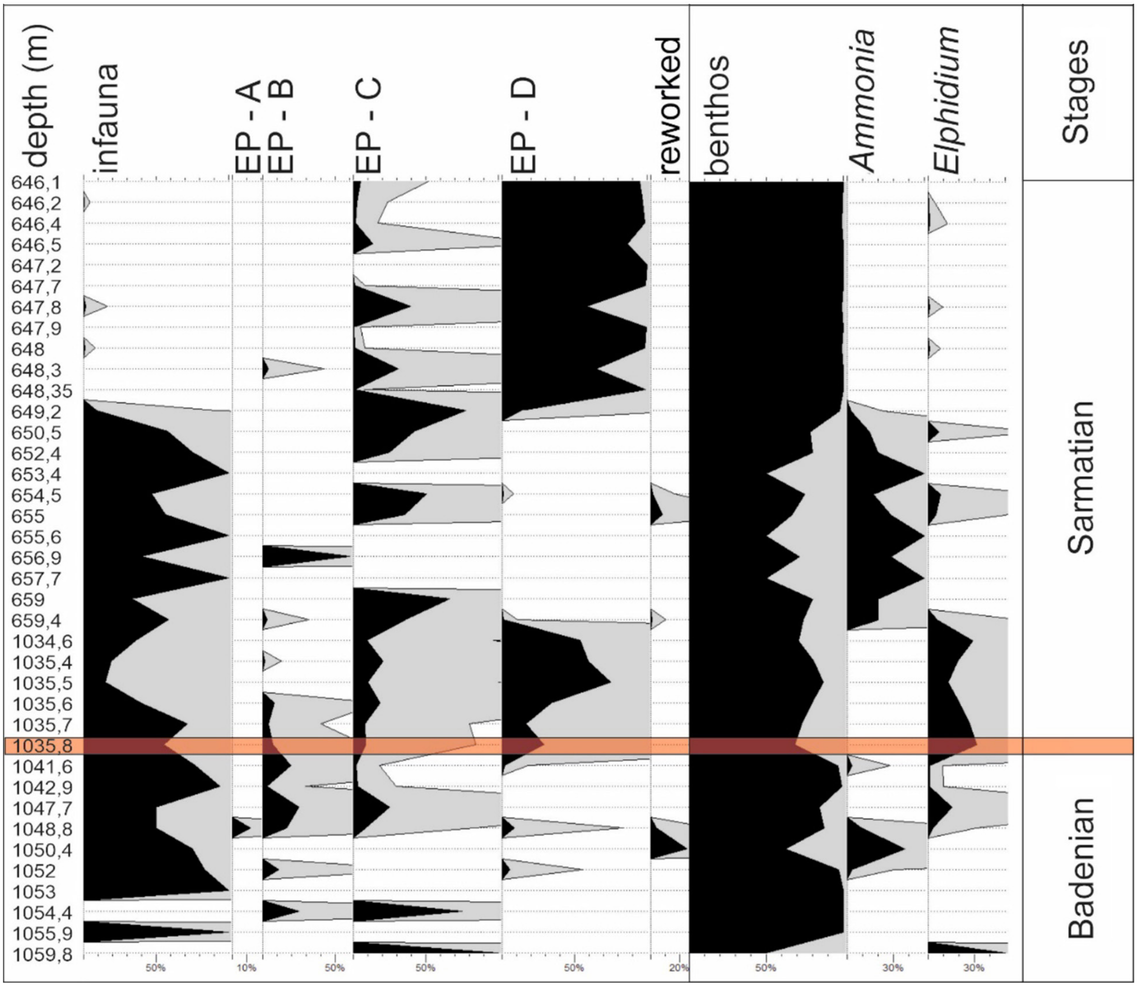


Fig. 8. Morphogroups abundance divided according to Langer (1988), infaunal abundance according to Murray (2006), redeposits, benthos, and Ammonia - Elphidium abundance.

(B) specified associations with the values of the Shannon_H index from 1.76 to 2 and the Fisher alpha index from 3.17 to 2.77. Group B contains samples from the depths of 646.1; 646.4; 646.5; 647.8; 655; 1035.6; 1035.7; 1035.8; 1041.6, and 1042.9 meters, with the possibility of defining a subgroup B-a consisting of samples 655, 1035.6, 1041.6 and 1042.9 meters. It contains rich association of miliolids, such as *Articulina problema, Varidentella rotunda, Articularia articulinoides, Milionella subrotunda* and *Quinqueloculina* sp. and hyaline species *Ammonia viennesis, Porosononion granosum*. In cores 4 and 5 (subgroup B-a), the species *Cribroelphidium excavatum, Nonion* sp., *Porosononion hyalinus,* and *Bolivina dilatata* dominate, as well as the miliolide *Varidentella rotunda* (Fig. 9). The third group (C) specified values of the Shannon H index from 2.22 – 2.41 with the Fisher alpha index from 5.14 to 5.97 in two samples (654.5 and 659.4 m) with *Porosononion* and *Elphidium* genera.

3. INTERPRETATION AND DISCUSSION

Part of the MZ 102 borehole cores (74 samples) were studied based on sedimentology, as well as foraminiferal associations and species supplemented by a calcareous nannoplankton study.

3.1. Biostratigraphy

Biostratigraphy was solved with the help of planktonic and benthic foraminifers and calcareous nanoplankton. The sediments from cores No. 6 – 4 (1059.8 m to 1041.6 m) of the MZ-102 borehole containing association of planktonic foraminiferal species were associated with the uppermost Badenian. Badenian age of the mentioned sediments was proved by presence of *Globorotalia (Obandyella) transsylvanica* and *Globigerinoides quadrilobatus*. Based on the common occurrence of *Tenuitella* sp. div. and small sized *Globigerina* sp. div. in accordance with the assemblage mentioned in Filipescu & Silye (2008), this interval was correlated with upper Badenian acme - zone Tenuitellinata (Filipescu & Silye, 2008). The calcareous nannoplakton index species *Discoaster exilis* confirms the NN6 Zone from the depth of 1041.6 m. We interpret the sediments as being upper Badenian, as well as having the age equivalent of Bulimina/Bolivina zone or younger due to signs of tests reworking.

The first occurrence of the Sarmatian index species such as *Nodosaria dina, Elphidium hauerinum,* and *Articularia articulinoides* (Cicha et al., 1975; Luczkowska, 1972) was documented in a sample from the upper part of core No. 4 (1035.8 m); thus, the Badenian/Sarmatian boundary was determined in this part of the MZ 102 borehole. However, index taxa of the lowermost Sarmatian biozones as the *Anomalinoides dividens* and *Elphidium reginum* (Grill, 1941, 1943; Luczkowska, 1972; Cicha et al., 1975) were not recorded within the studied samples, and the middle Sarmatian index species *Elphidium hauerinum* was rare. It is important to note, the benthic foraminiferal biozones strongly depend on the type of environment [mentioned mainly in the Sarmatian sediments: Harzhauser & Piller (2004); Koubová & Hudáčková (2010); Zlinská et al. (2010)] and one can speculate, that due to unsuitable conditions they can only be developed in certain parts of the basin with special conditions. We consider these associations may occur in the sediments of the non-cored part of the MZ 102 borehole (1034.6 – 659.8 m). In the nearby MZ 93 borehole (Fig. 2), the lower Sarmatian *Elphidium reginum* Zone was observed in the cores 5, 4 and 3 of the circa 860 – 875 m of depth (Koubová & Hudáčková 2010), and we correlate it with the non-cored part of the MZ 102 borehole (Fig. 2). In the samples from cores No. 3 and 2 (659.8 – 644.2 m) of the MZ 102, the associations with predominance of *Porosononion granosum* were assigned to the upper Sarmatian, Porosononion granosum Zone (Grill, 1943) of the Skalica Fm (Vass, 2002). The Sarmatian part of the NN6 Zone, based on Sphenolithus abies acme-Zone, was documented in core No. 2 in the depths of 648.3 and 644.8 m.

3.2. Sedimentology

The Upper Badenian sediments in this region have a clearly visible progradational to aggradational pattern of seismic reflexes, while the Sarmatian sediments do not have any significantly developed seismic clinoforms (Kováč et al. 2008a). Sedimentological interpretation of cores No. 6 – 5 revealed that the deltaic sands of the Upper Badenian are developed. The character of the sorting, as well as the upward fining trend of sediments, indicates a wave, transgressive reworking (Fig. 2). Transgression was documented by a higher content of reworked foraminiferal taxa (Figs. 7, 8). Size sorting during postmortal transport in the latest Badenian was documented in the MZ 93 borehole (depth of ~1060 m) by Koubová & Hudáčková (2010) as well.

From the upper part of core No. 4 (MZ 102) upwards, the fine silty clay with an increasing proportion of pyrite concretions and fish remnants indicates a deepening of the sedimentary environment (Kováč et al. 2008a,b). Increase of the infaunal foraminifera (sample 1035.7 m, Fig. 7), together with rich framboidal pyrite, can prove the low oxygen bottom zone (Jorissen et al, 1995).

The sedimentary analysis of cores No. 3 and 2 indicates sedimentation in the distal part of deltaic lobes and poorly-aerated lagoons and marshes (Figs. 2, 3A, B). In the upper part of core No. 2 and in the core No. 1, the lamination was often marked by very thin lamines formed by precipitated $CaCO_3$ (Fig. 3A), which could represent the so-called non-glacial varves, sensu Galović & Bajraktarević (2006).

3.3. Paleoenvironment

Paleoenvironmental analysis combine the results from calcareous nannoplankton, foraminifera, and sedimentology. Species-based paleoenvironmental interpretation corresponds with morphogroup distribution (Fig. 4, Tab. 1). In the lowermost part of the borehole (interval from 1059.8 to 1041.6 m), the low-oxygen environment was documented by the absence of the oxyphilic species and the occurrence of the species *Cassidulina laevigata* and *Globocassidulina crassa, Caucasina gutsulica,* and *Bulimina elongata* (Fig. 5 D, E), which can tolerate stress conditions from reduced oxygen (Bernhard, 1986; Kaiho, 1994). In this interval, we can also observe several planktonic species of foraminifera

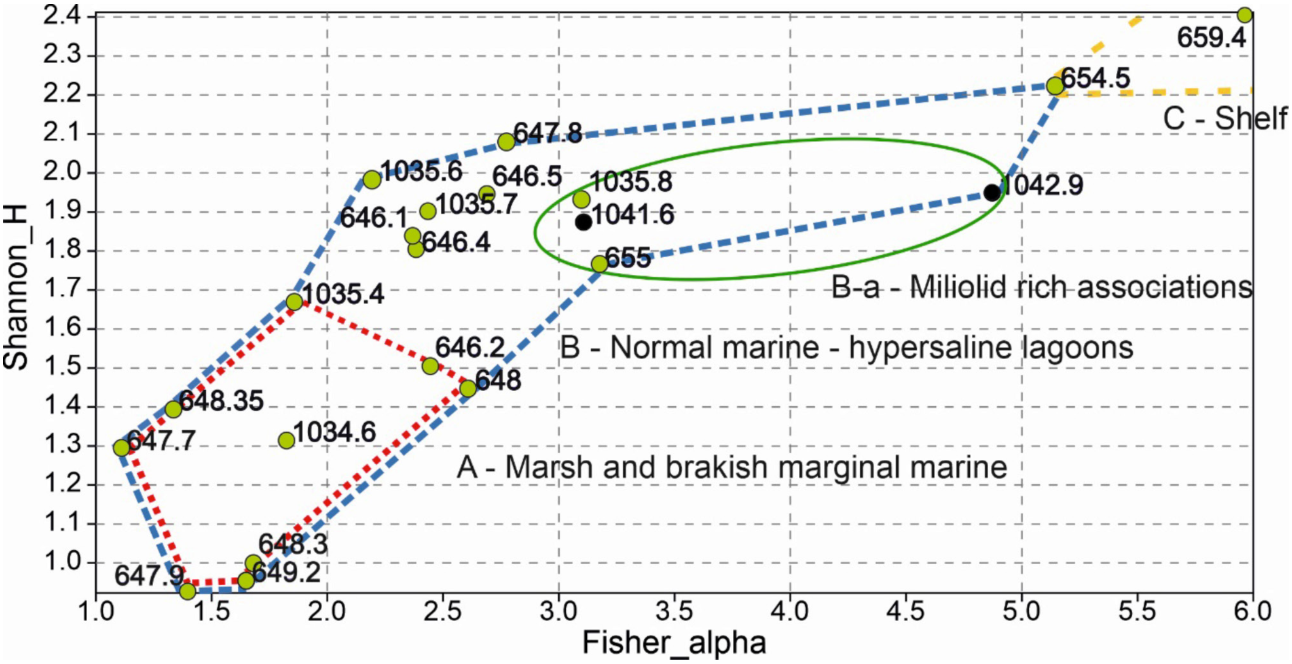


Fig. 9. Space-diversity data (Fisher alpha and Shannon H index) according to Murray (2006). Red dash line: group (A) – marsh and brackish marginal marine, blue dash line: group (B) – normal marine/hypersaline lagoons with green subgroup B-a – miliolid rich associations, yellow dash line: group (C) – shelf.

(*Globigerina* sp., *Globorotalia* sp., *Turborotalita quinqueloba*) together with coccoliths documenting open marine conditions with the possibility of stress conditions in the eutrophic water surface (van der Zwaan et al., 1990, Ćorić & Hohenegger, 2008). The presence of the infaunal species *Bulimina-Bolivina* (cone-shaped and elongated shaped morphogroups), together with members of *Nodosaria* and *Stilostomella genera* (cylindrical uniserial morphogroup), document a deeper shellfal environment with lowered oxygen in the water/sediment interface (Kaiho, 1994; Jorissen et al, 1995; Murray, 2006) and low $CaCO_3$ content caused by high input of organic material (Bernhard, 1986; Kaiho 1994). This is in accordance with the interpretation of low oxygen levels in upper Badenian sediments in the *Vienna Basin because* of changes of water in the current regime from an anti-estuarine to open marine (Báldi, 2006; Kováčová & Hudáčková, 2009; Kováč et al., 2017b). According to the species-diversity analysis of the benthic foraminifera samples, assemblages from the above-mentioned interval represent a normal marine environment (Fig. 9).

The stressed environment was documented by the prevalence of calcareous nannoplankton species *Reticulofenestra minuta* (depth 1035.8 m) similar to what was mentioned in borehole MZ 93 (Koubová & Hudáčková, 2010). In addition to the species considered to be index fossils for Sarmatian (*Nodosaria dina, Articularia articulinoides,* 1035.8 m), the size sorting of the rounded tests indicates reworking of Badenian planktonic forms in these horizons. A different type of foraminiferal associations was found in the interval of 1035.8 – 1034.6 m, dominated by *Porosononion granosum, Haynesina* sp., and *Ammonia* sp. species and the high abundance of *Cribroelphidium excavatum*. The pronounced dominance of epiphytic groups (morphogroups C, D/epiphytes) can document a distinct euphotic zone in interval from 1035.6 to 659 m proved by space-diversity analysis (Murray, 2006) documented in the marginal marine environment (Fig. 7, 9). Epiphytic association in coeval sediments in the Vienna Basin was documented in various localities of Holíč and the Skalica fms. (Fordinál & Zlinská, 1998; Koubová & Hudáčková, 2010; Zlinská et al. 2010, Hudáčková et al. 2021). Almost 400 meters of rock sequence was not cored. However, we can assume a continuing trend of shallow-water sedimentation based on geophysical and sedimentological (CT_P) analysis of the borehole MZ 102 (Sp; RILD curves; Fig. 2) and assemblages from MZ 93 cored part.

The rock record continues with core No. 3 at a depth of 659.8 m, which yields poor foraminiferal fossil record of planoconvex trochospiral-shaped species (morphogroup B/epiphytes), such as *Biasterigerinata planorbis, Ammonia viennensis, Ammonia parkinsoniana* and *Aubignyna perlucida*. This test morphology was advantageous for maintaining stability on the surface of the substrate (Corliss & Emerson, 1990). The forementioned foraminifera show wide salinity tolerance (Murray, 2006), which may indicate fluctuations in freshwater inflow from the mainland that can support the assumption of the marginal high-energy environment. The planispiral morphology forms, such as *Porosononion granosum, Haynesina depressula,* and *Elphidium macellum* are present here and can document enough nutrient supply. In the interval from 656.9 to 652.4, a higher abundance of *Ammonia* spp. was noticed (with 3 peeks 657.7; 655.6; 653.4 m), which corresponds to the highest values (> 33.3) of the IAE index (Pregnolato et al., 2018). We can observe associations dominated by *Ammonia tepida* and *Cribroelphidium excavatum* affected by the reduction of oxygen content, very similar to this in Burone & Pires-Vanin (2006) and Burone et al. (2006).

The sedimentary analysis of the borehole core No. 2 (644 – 652.2 m) indicates sedimentation in the distal part of the deltaic lobes, as well as poorly-aerated lagoons and marshes. One important foraminiferal assemblage change was identified from the depth between 650.5 m and 648.3 m, where *Porosononion granosum* highly dominates (morphogroup C/epiphytes, Fig. 8). This, together with miliolids, which is typical in hypersaline conditions (Boltovskoy & Wright, 1976; Murray, 2006), may document strong short-term salinity fluctuation during sedimentation. From 648 m, miliolid foraminifera dominate (*Articulina, Articularia, Cycloforina, Dogielina*) in the samples, what according to Alperin et al., (2011), implies sand sediment of shallow gulf areas with the temperate, hypersaline, and productive conditions. Depending on the spatial diversity distribution (Fig. 9), we interpret them as association from the marginal seas of hypersaline lagoons (Murray, 2006). In Devínska Kobyla (Hyžný et al., 2012; Pivko et al. 2017), shallow water hypersaline foraminiferal association was also observed. Small miliolids were observed only in the topmost sample form the MZ 93 borehole. Based on the correlation of biostratigraphy and sedimentology in the studied area, we can interpret an alternation of salty fens or marshes inhabited by miliolids of the EP-D morphogroup, as well as brackish fens inhabited by the EP-C morphogroup dominated with *Porosononion granosum*. Calcareous nannoplankton associations from depth interval (from 649.2 to 647.2 m) are exclusively represented by *Braarudosphaera bigelowii*, including *B. bigelowii parvula* and abundant ascidian spicules typical for lowered salinity (Stradner & Fuchs, 1979). Similar assemblages were observed in Sarmatian sediments of the Vienna and Danube basins in a marginal environment, with sea level fluctuations and terrestrial draw (Kováč et al., 2005; Kováč et al., 2008a). The sediments with shallow water hyposaline associations end at a depth of 646.1 m, above which sediments are barren of foraminifera tests.

4. CONCLUSIONS

Paleoecological and sedimentological changes of the Vienna Basin sediments were studied in the MZ 102 borehole and correlated with borehole MZ 93, both located near the town of Malacky in the western (Slovak) part of the Vienna Basin.

The Badenian sediments in the MZ 102 borehole are documented based on the foraminifera from the depth of 1059.8 to 1041.6 meters (uppermost Badenian – equivalent of Bulimina/Bolivina Zone). The calcareous nannoplankton confirms the NN6 Zone from the depth of 1041.6 m. The first occurrence of the Sarmatian index species was documented in a depth of 1035.8 m thus we interpret it as the Badenian/Sarmatian boundary. From the depth 646.1 to ~ 620 m, the Sarmatian sediments (Porosononion granosum Zone) were documented based on foraminifera and calcareous nannofossils. Interpretation fits well with the results obtained from the M 93 borehole, in which lower Sarmatian was cored. Badenian sediments originated in the deltaic condition with possible reworking with episodes of deeper open marine waters with lowered oxygen on the sea floor. Major paleoecological change has been identified in samples from the depths of 1038.8 m – 1034.6 m, where the sea floor conditions changed from normal marine to low-oxic.

The Sarmatian sediments studied here generally indicate sedimentation in the distal part of the deltaic lobes, as well as poorly-aerated lagoons and marshes that can explain the variability in proportion of the foraminiferal morphogroups. The shallow water environments with significant changes in salt and oxygen content at the bottom with facultative sea grass cover were found in the studied sediments. Major paleoecological changes have been identified in depths from 659.4 m to 650.5 m, where the lowered oxygen level in the water/sediment interface was identified with the three most pronounced excursions of very low level of oxygen in the interval between 656.9 m to 652.4 m. The predominance of miliolids (family Miliolidea) indicates the shallow water, hypersaline, as well as an aerated lagoonal environment from the depth of 648.3 m up to the 641.1 m.

Comparison of the two methodological approaches to the paleoenvironmental analyses – (1) species analysis or (2) morphogroups analysis shows that the morphogroup approach seems to be a quick and sufficiently effective method for paleoenvironmental reconstructions.

Acknowledgments: This research was supported by the Slovak Research and Development Agency under the contracts APVV-20-0120, APVV-20-0079, APVV 17-0555 and VEGA2/0169/19. Authors express gratitude for fruitful discussion and helpful review to Katarína Holcová Srt and Sorin Filipescu. Our gratitude goes to English native speaker Mike Sabo for formal corrections.

References

Alperin, M.I., Cusminsky, G.C. & Bernasconi, E., 2011: Benthic foraminiferal morphogroups on the Argentine continental shelf. Journal of Foraminiferal Research, 41, 2, 155–166.

Báldi K., 2006: Paleoceanography and climate of the Badenian (Middle Miocene, 16.4–13.0 Ma) in the Central Paratethys based on foraminifera and stable isotope (δ18O and δ13C) evidence. International Journal of Earth Science (Geologische Rundschau), 95, 119–142.

Berkeley, A, Perry, C.T., Smithers, S.G., Horto, B., & Taylor, K.G., 2007: A review of the ecological and taphonomic controls on foraminiferal assemblage development in intertidal environments. Earth Science Reviews, 83, 205–230.

Berkeley, A., Perry, C.T., Smithers, S.G., & Horton, B., 2008: The spatial and vertical distribution of living (stained) benthic foraminifera from a tropical, intertidal environment, north Queensland, Australia. Marine Micropaleontology, 69, 240–261.

Bernhard, J.M., 1986: Characteristic assemblages and morphologies of benthic foraminifera from anoxic, organic-rich deposits; Jurassic through Holocene. Journal of Foraminiferal Research, 16, 3, 207–215.

Boltovskoy, E. & Wright, R., 1976: Recent Foraminifera. Junk, The Hague Price Dutch Guilders 125.00., 515 p.

Bouma, A.H., Normark, W.R. & Barnes, N.E., 1985: Submarine Fans and Related Turbidite System. Springer Verlag, New York, 1–351.

Burone, L. & Pires-Vanin, A.M.S., 2006: Foraminiferal assemblages in the Ubatuba Bay, south-eastern Brazilian Coast. Scientia Marina, 70, 2, 203–217.

Burone, L., Venturini, N., Sprechmann, P., Valente, P., Muniz, P., 2006: Foraminiferal responses to polluted sediments in the Montevideo coastal zone, Uruguay. Marine pollution bulletin, 52, 1, 61–73.

Cicha I., Rögl F., Rupp Ch. & Čtyroká J., 1998: Oligocene – Miocene foraminifera of the Central Paratethys. Kramer, Frankfurt am Main, 325 p.

Cicha, I., Marinescu, F. & Senes, J., 1975: Corrélation du Néogène de la Paratéthys Centrale. GCP IUGS UNESCO project no. 25, Geologic Survey Prague, 33 p.

Ćorić S. & Hohenegger J., 2008: Quantitative analyses of calcareous nannoplankton assemblages from the Baden-Sooss section (Middle Miocene of Vienna Basin, Austria). Geologica Carpathica, 59, 5, 447–460.

Corliss, B.H. & Emerson, S., 1990: Distribution of Rose Bengal-stained benthic foraminifera from the Nova Scotia continental margin and Gulf of Maine. Deep-Sea Research, 37, 381–400.

Csontos L., Nagymarosy A., Horváth F. & Kováč M., 1992: Tertiary evolution of the Intra-Carpathian area: a model. Tectonophysics, 208, 221–241.

Filipescu, S., 2004: Anomalinoides dividens bioevent at the Badenian/Sarmatian boundary – a response to paleogeographic and paleoenvironmental changes. Studia Universitatis Babeş Bolyai, Geologia, 49, 2, 21–26.

Filipescu, S. & Silye, L., 2008: New Paratethyan biozones of planktonic foraminifera described from the Middle Miocene of the Transylvanian Basin (Romania). Geologica Carpathica, 59, 6, 537–544.

Fordinál, K. & Zlinská, A., 1998: Fauna of the upper part of Holíč Formation (Sarmatian) in Skalica (Vienna Basin). Mineralia Slovaca, 30, 137–146.

Galović I. & Bajraktarević Z., 2006: Sarmatian biostratigraphy of the Mountain Medvednica at Zagreb based on siliceous microfossils (North Croatia, Central Paratethys). Geologica Carpathica, 57, 3, 199–210.

Gozhyk P., Semenenko V., Andreeva-Grigorovich A. & Maslun N., 2015: The correlation of the Neogene of Central and Eastern Paratethys segments of Ukraine with the International Stratigraphic Chart based on planktonic microfossils. Geologica Carpathica, 66, 3, 235–244.

Grill R., 1941: Stratigraphische Untersuchungen mit Hilfe von Mikrofaunen im Wiener Becken und den benachbarten Molasse-Anteilen. Oel und Kohle, 37, 595–602.

Grill R., 1943: Über mikropaläontologische Gliederungsmöglichkeiten in Miozän des Wiener Becken. Mitteilungen des Reichsamst für Bodenforschung, 6, 33–44.

Hammer, Ø., Harper, D.A.T. & Ryan, P.D., 2001: Past: Paleontological Statistics Software Package for Education and Data Analysis. Palaeontologia Electronica, 4, 1, 4, 9. http://palaeo-electronica.org/2001_1/past/issue1_01.htm

Handy M.R., Schmid S.M., Bousquet R., Kissling E. & Bernoulli D., 2010: Reconciling plate-tectonic reconstructions of Alpine Tethys with the geological-geophysical record of spreading and subduction in the Alps. Earth Science Reviews, 102, 121–158.

Handy M.R., Ustaszewski K. & Kissling E., 2015: Reconstructing the Alps–Carpathians–Dinarides as a key to understanding switches in subduction polarity, slab gaps and surface motion. International Journal of Earth Sciences, 104, 1–26.

Harzhauser M. & Piller W.E., 2004: The Early Sarmatian – hidden seesaw changes. Courier Forschungsinstitut Senckenberg, 246, 89–112.

Harzhauser, M. & Piller, W.E., 2007: Benchmark data of a changing sea – Palaeogeography, palaeobiogeography and events in the Central Paratethys during the Miocene. Palaeogeography, Palaeoclimatology, Palaeoecology, 253, 8–31.

Hudáčková, N. & Hudáček, J., 2001: Databáza fosílií – technické spracovanie. Mineralia Slovaca, Geovestnik, 33, 2, 24. [in Slovak]

Hudáčková, N., Soták, J., Ruman, A., Rybár, S. & Milovský, R., 2018: Marsh-type agglutinated foraminifera from Upper Miocene sediments of the Danube Basin. Micropaleontology, 64, 5–6, 481–492.

Hudáčková, N., Ruman, A., Plašienková, I., Jamrich, M., Halásová, E., Kiss, P., Kováčová, M., Babejová-Kmecová, J. & Kováč, M., 2019: Badenian/Sarmatian foraminifera shift in the Central Paratethys: Two methods comparison — a morphogroup and species approach. Geologica Carpathica, 70, 144–145.

Hudáčková, N., Babejová-Kmecová, J., Heteš, A., Nesterenko, O., Hupka, R. & Zervanová, J., 2021: Stratigraphic and paleoecological assesment of the foraminiferal association from the HC-4 well (Holíč, Vienna Basin). Geologické práce, Správy, 137, 3–18. [in Slovak with English summary]

Hudeček D. & Šály S., 1995: Malacky - západ - výpočet zásob zemného plynu na výhradnom ložisku, stav k 1. 1. 1995. Manuscript, archív Geofond, 39 p. [in Czech]

Hyžný, M. Hudáčková, N. Biskupič, R. Rybár, S. Fuksi, T. Halásová, E. Zágoršek, K. Jamrich, M. & Ledvák, P., 2012: Devínska Kobyla – a window into the Middle Miocene shallow-water marine environments of the Central Paratethys (Vienna Basin, Slovakia), Acta Geologica Slovaca, 4, 2, 95–111.

Jones, R.W. & Charnock, M.A., 1985: "Morphogroups" of agglutinated foraminifera. Their life positions and feeding habits and potential applicability in (paleo)ecological studies. Revue de Paléobiologie, 4, 2, 311–320.

Jorissen, F.J., de Stigter H.C. & Widmark, J.G.V., 1995: A conceptual model explaining benthic foraminiferal micrihabitats. Marine Micropaleontology, 22, 3–15.

Kaiho, K., 1994: Benthic foraminiferal dissolved-oxygen index and dissolved-oxygen levels in the modern ocean. Geology, 22, 8, 719–722.

Konečný V., Kováč M., Lexa J. & Šefara J., 2002: Neogene evolution of the Carpatho-Pannonian region: an interplay of subduction and back-arc diapiric uprise in the mantle. EGU Stephan Mueller Special Publication Series, 1, 105–123.

Koubová, I. & Hudáčková, N., 2010: Foraminiferal successions in the shallow water Sarmatian sediments from the MZ 93 borehole (Vienna Basin, Slovak part). Acta Geologica Slovaca, 2, 1, 47–58.

Kováč M., Kráľ J., Márton E., Plašienka D. & Uher P., 1994: Alpine uplift history of the Central Western Carpathians: geochronological, paleomagnetic, sedimentary and structural data. Geologica Carpathica, 45, 2, 83–96.

Kováč M., Baráth I. & Nagymarosy A., 1997: The Miocene collapse of the Alpine–Carpathian–Pannonian junction – an overview. Acta Geologica Hungarica, 40, 3, 241–264.

Kováč M., Nagymarosy A., Oszczypko N., Csontos L., Slaczka A., Mărunteanu M., Matenco L. & Márton E., 1998: Palinspastic reconstruction of the Carpathian – Pannonian region during the Miocene. *In:* Rakús M. (Ed.): Geodynamic development of the Western Carpathians. Geological Survey of Slovak Republic, Bratislava, pp. 189–217.

Kováč M., Andreyeva-Grigorovich A.S., Brzobohatý R., Fodor L., Harzhauser M., Oszczypko N., Pavelić D., Rögl F., Saftić B., Sliva Ľ. & Stráník Z., 2003: Karpatian paleogeography, tectonics and eustatic changes. *In:* Brzobohatý R., Cicha I., Kováč M. & Rögl F. (Eds.): The Karpatian – a Lower Miocene stage of the Central Paratethys. Masaryk University, Brno, pp. 49–72.

Kováč, M., Baráth, I., Harzhauser, M., Hlavatý, I. & Hudáčková, N., 2004: Miocene depositional systems and sequence stratigraphy of the Vienna Basin. Courier Forschungsinstitut Senckenberg, 246, 187–212.

Kováč, M., Fordinál K., Andreyeva-Grigorovic, A., Halásová, E., Hudáčková, N., Joniak, P., Pipík, R., Sabol, M., Kováčová M. & Sliva, L., 2005: Západokarpatské fosílne ekosystémy a ich vzťah k paleoprostrediu v kontexte neogénneho vývoja eurázijského kontinentu [The Western Carpathians fossil ecosystems and their relationship to palaeoenvironment in the context of the Neogene development of the Eurasia]. Geologické práce, Správy, 111, 61–121. [in Slovak]

Kováč, M., Hudáčková, N., Hlavatá, J., Sopková B., Andreyeva-Grigorovic, A., Halásová, E., Kováčová, M., Kováčová, P., Sliva, L. & Baráth, I., 2008a: Miocénne usadeniny vo vrtoch regiónu Záhorská nížina: sedimentológia, biostratigrafické zaradenie a prostredie depozície [Miocene sediments in the boreholes from the Záhorská nížina region: sedimentology, biostratigraphy and depositional environment]. Geologické práce, Správy 114, 7–49. [in Slovak]

Kováč M., Sliva Ľ., Sopková B., Hlavatá J. & Škulová A. 2008b: Serravallian sequence stratigraphy of the northern Vienna Basin: high frequency cycles in the Sarmatian sedimentary record. Geologica Carpathica, 59, 6, 545–561.

Kováč M., Plašienka D., Soták J., Vojtko R., Oszczypko N., Less Gy., Ćosović V., Fügenschuh B. & Králiková S., 2016: Paleogene palaeogeography and basin evolution of the Western Carpathians, Northern Pannonian domain and adjoining areas. Global and Planetary Change, 140, 9–27.

Kováč M., Márton E., Oszczypko N., Vojtko R., Hók J., Králiková S., Plašienka D., Klučiar T., Hudáčková N. & Oszczypko-Clowes M., 2017a: Neogene palaeogeography and basin evolution of the Western Carpathians, Northern Pannonian domain and adjoining areas. Global and Planetary Change, 155, 133–154.

Kováč, M., Hudáčková, N., Halásová, E., Kováčová, M., Holcová, K., Oszczypko-Clowes, M., Báldi, K., Less, Gy., Nagymarosy, A., Ruman, A., Klučiar, T. & Jamrich, M., 2017b: The Central Paratethys palaeoceanography: a water circulation model based on microfossil proxies, climate, and changes of depositional environment. Acta Geologica Slovaca, 9, 2, 75–114.

Kováčová P. & Hudáčková N., 2009: Late Badenian foraminifers from the Vienna Basin (Central Paratethys): stable isotope study and paleoecological implications. Geologica Carpathica, 60, 1, 59–70.

Langer, M., 1988: Recent epiphytic foraminifera from Vulcano (Mediterranean Sea). Revue de Paléobiologie, Volume spécial 2, Part 2, 827–832.

Loeblich, A.R. & Tappan, H., 1992: Present status of foraminiferal classification, *In:* Takayanagi Y. & Saito T. (Eds.): Studies in Benthic Foraminifera. Proceedings of the Fourth International Symposium on Benthic Foraminifera, Sendai, 1990 (Benthos '90), Tokai University Press, Tokyo, Japan, pp. 93–102.

Łuczkowska E., 1972: Miliolidae (Foraminifera) from Miocene of Poland. Part 1. Revision of the classification. Acta Palaeontologica Polonica, 17, 341–377.

Łuczkowska, E., 1974: Miliolidae (Foraminiferida) from the Miocene of Poland. Part II. Biostratigraphy, palaeoecology and systematics. Acta Palaeontologica Polonica, 19, 1, 3–176.

Matenco L.C., 1997: Tectonic evolution of the outer Romanian Carpathians. The Netherlands Research School of Sedimentology (NSG) publication, 970, 148, 160 p.

Meulenkamp J.E., Kováč M. & Cicha I., 1996: On Late Oligocene to Pliocene depocentre migrations and the evolution of the Carpathian-Pannonian system. Tectonophysics, 266, 301–317.

Miall, A.D., 2006: The geology of fluvial deposits. Springer, New York, 1–582.

Murray, J.W., 1973: Distribution and ecology of living benthic foraminiferids. Crane Russak & Co., New York, 274 p.

Murray, J.W., 1991: Ecology and Paleoecology of Benthic Foraminifera. John Wiley and Sons, New York, 320 p.

Murray, J.W, 2006: Ecology and Applications of Benthic Foraminifera. Cambridge University Press, New York, 426 p.

Neubauer T.A., Harzhauser M., Kroh A., Georgopoulou E. & Mandic O., 2015: A gastropod-based biogeographic scheme for the European Neogene freshwater systems. Earth-Science Reviews, 143, 98–116.

Nielsen, T., Shew, R.D., Steffens, G.S. & Studlick, J.R.J., 2007: Atlas of Deepwater Outcrops. AAPG Studies in Geology, 56, 1–504.

Orbigny, A.d'., 1846: Die fossilen Foraminiferen des tertiären Beckens von Wien. Foraminifères fossiles du bassin tertiaire de Vienne. Paris, 312 p.

Orpin, A.R., Ridd, P.V. & Stewart, L.K., 1999: Assessment of the relative importance of major sediment transport mechanisms in the central Great Barrier Reef lagoon. Australian journal of Earth sciences, 46, 883–896.

Oszczypko N., 1998: The Western Carpathian Foredeep – development of the foreland basin in front of the accretionary wedge and its burial history (Poland). Geologica Carpathica, 49, 6, 415–431.

Oszczypko N., 1999: The Miocene subsidence of the Polish Carpathian Foredeep. Prace Państwowego Instytutu Geologicznego, 168, 209–230. [in Polish with English summary]

Oszczypko N. & Oszczypko-Clowes M., 2006: Ewolucja basenu magurskiego [Evolution of the Magura Basin]. *In:* Oszczypko N., Uchman A. & Malata E. (Eds.): Paleotectonic evolution of the Outer Carpathian and Pieniny Klippen Belt Basins. Instytut Nauk Geologicznych, UJ, pp. 133–164. [in Polish]

Palcu, V.D., Tulbure, M., Bartol, M., Kouwenhoven, T,N., Krijgsman, W. 2015: The Badenian–Sarmatian Extinction Event in the Carpathian foredeep basin of Romania: Paleogeographic changes in the Paratethys domain. Global and Planetary Change, 133, 346–358.

Patterson, R.T., Scott, D.B. & McKillop, W.B., 1990: Recent marsh-type agglutinated foraminifera from Lake Winnipegosis, Manitoba. Proceedings of the third International Advanced Course on Paleoecology, Biostratigraphy, Palaeoceanography, and Taxonomy of Agglutinated Foraminifera: NATO Advanced Study Institutes Programme Series, Series C, Mathematical and Physical Sciences, 327, 765–781.

Piller W.E., Harzhauser M. & Mandic O., 2007: Miocene Central Paratethys stratigraphy – current status and future directions. Stratigraphy, 4, 2–3, 151–168.

Pivko D., Hudáčková N., Hrabovský J., Sládek I. & Ruman A., 2017: Palaeoecology and sedimentology of the Miocene marine and terrestrial sediments in the "Medieval quarry" on the Devínska Kobyla hill (Vienna Basin). Geological Quarterly, 61, 3, 549–568.

Popov S.V., Rögl F., Rozanov A.Y., Steininger F.F., Shcherba I.G. & Kováč M. (Eds.), 2004: Lithological–Paleogeographic maps of Paratethys. 10 Maps Late Eocene to Pliocene. Courier Forschungsinstitut Senckenberg, 250, 1–46.

Pregnolato, L.A., Viana R., Passos, C.C., Misailidi M.L. & Duleba W., 2018: Ammonia-Elphidium index as a proxy for marine pollution assessment, Northeast Brazil. Journal of Sedimentary Environments, 3, 3, 176–186.

Ratschbacher L., Merle O., Davy P. & Cobbold P., 1991a: Lateral extrusion in the Eastern Alps, Part 1: Boundary conditions and experiments scaled for gravity. Tectonics, 10, 2, 245–256.

Ratschbacher L., Frisch W., Linzer H.G. & Merle O., 1991b: Lateral extrusion in the Eastern Alps, Part 2: Structural analysis. Tectonics, 10, 2, 257–271.

Rider, M. & Kennedy, M., 2011: The geological interpretation of well logs (Third Edition). Bell and Bain, Glasgow, 1–442.

Rossi, V., Perillo, M., Steel, R. & Olariu, C., 2017: Quantifying mixed-process variability in shallow-marine depositional systems: What are sedimentary structures really telling us? Journal of Sedimentary Research, 87, 1060–1074.

Schmid S.M., Bernoulli D., Fügenschuh B., Matenco L., Schefer S., Schuster R., Tischler M. & Ustaszewski K., 2008: The Alpine-Carpathian-Dinaridic orogenic system: correlation and evolution of tectonic units. Swiss Journal of Geosciences, 101, 1, 139–183.

Sen Gupta, B.K., 2003: Modern Foraminifera. Springer Dordrecht, 384 p.

Seneš J., 1961a: Paleogeography of the central part of the Paratethys Sea. *In:* Murgeanu G., Patrulius D., Tocorjescu M., Contescu L., Jipa D., Mihailescu N., Bombita G., Panin N., Butac A., Filipescu M.G., Alexandrescu G., Mutihac V., Sandulescu M., Sandulescu J., Bratu E. & Iliescu G. (Eds.): Ghidul excursiilor B carpatii orientali. Asociatia Carpato fi"Balcanica, Congresulal V-lea, 4.–9. Septembrie, Bucuresti, pp. 51–52. [in Russian]

Seneš J., 1961b: Paläogeographie des westkarpatischen raumes in beziehung zur übrigen Paratethys im Miozän. Geologické Práce, Zošit 60, 159–195.

Stradner H. & Fuchs R., 1979: Über Nannoplanktonvorkommen im Sarmatien (Ober-Miozän) der Zentralen Paratethys in Niederösterreich und im Burgenland. Beiträge zur Paläontologie von Österreich, 7, 251–279.

Studencka B., Popov S.V., Bieńkowska-Wasiluk M. & Wasiluk R., 2016: Oligocene bivalve faunas from Silesian Nappe, Polish Outer Carpathians: evidence of the early history of the Paratethys. Geological Quarterly, 60, 2, 317–340.

Talling, P., Masson, D., Sumner, E. & Malgeseni, G., 2012: Subaqueous sediment density flows: Depositional processes and deposit types. Sedimentology, 59, 1937–2003.

Ustaszewski K., Schmid S.M., Fügenschuh B., Tischler M., Kissling E. & Spakman W., 2008: A map-view restoration of the Alpine-Carpathian-Dinaridic system for the Early Miocene. Swiss Journal of Geosciences, 101, Supplement 1, 273–294.

van der Zwaan G.J., Jorissen, F.J. & De Stiger, H.C., 1990: The depth dependency of planktonic/benthonic foraminiferal ratios: constraints and applications. Marine Geology, 95, 1–16.

Vass, D., 2002: Litostratigrafia Západných Karpát: neogén a budínsky paleogén [Lithostratigraphy of Western Carpathians: Neogene and Buda Paleogene]. Štátny geologický ústav Dionýza Štúra, Bratislava, 202 p. [in Slovak]

Walanus, A. & Nalepka, D., 1999: POLPAL. Program for counting pollen grains, diagrams plotting and numerical analysis. Acta Palaeobotanica, 2, 659–661.

Wallner J., Sliva Ľ., Beňo J., Šefarová B., Šály B., Makruš P., Blahovič L. & Polesňák P., 2014: Rozvoj PZZP Láb 4. stavba. Vrt Malacky Z 102, podrobný a ťažobný ložiskový geologický prieskum. Manuscript, archív Geofond, 51 p. [in Slovak]

Young, J.R., Geisen, M., Cros, L., Kleijne, A., Probert, I. & Ostergaard, J.B., 2003: A guide to extant coccolithophore taxonomy. Journal of Nannoplankton Research, Special Issue, 1, 1–132.

Zlinská, A., Hudáčková, N. & Koubová, I., 2010: Lower Sarmatian foraminifera from marginal marine environments in the Malacky vicinity (Vienna Basin). Geologické výzkumy na Moravě a ve Slezsku, 17, 1–2, 104–106.