

# Shallow-water benthic foraminiferal assemblages and their response to the palaeoenvironmental changes — example from the Middle Miocene of Medvednica Mt. (Croatia, Central Paratethys)

ĐURĐICA PEZELJ, JASENKA SREMAC and VLADIMIR BERMANEC

Department of Geology and Paleontology, Faculty of Science, University of Zagreb, Horvatovac 102a, 10000 Zagreb, Croatia; djurdjica.pezelj@geol.pmf.hr, jsremac@geol.pmf.hr, vberman@public.carnet.hr

(Manuscript received November 26, 2015; accepted in revised form June 7, 2016)

**Abstract:** During the Middle Miocene, the northern Croatian Medvednica Mt. was an island within the Pannonian Basin System, situated on the SW margin of the Central Paratethys Sea. Miocene sedimentary rocks (the Late Badenian *Bulimina–Bolivina* Zone and *Ammonia beccarii* ecozone), from the SW slopes of Medvednica Mt. clearly reflect a transgressive-regressive cycle with emersion during the Badenian/Sarmatian boundary. After the initial phase of transgression, the pioneer *Elphidium–Asterigerinata–Ammonia* benthic foraminiferal assemblage is present in bioclastic limestones, such as those at the Borovnjak locality. This marginal marine assemblage from a highly energetic, normally saline environment is characterized by poor preservation of foraminiferal tests, low diversity and strong domination. Advanced transgression is followed by establishment of the *Elphidium–Asterigerinata* assemblage, which is found in biocalcsiltites from the laterally deeper and more sheltered environment at Gornje Vrapče. This diverse assemblage is typical for inner/middle shelf environment with sufficient oxygen content. A general shallowing upward trend can be recognized at both localities, followed by visible interchange of different sedimentological and biotic features. Successive and oscillatory regression in the marginal marine environment was followed by salinity fluctuations and final brackish conditions with *Ammonia–Elphidium* assemblage. The laterally deeper environment reacted to regressive trends on finer scale with almost regular changes of benthic foraminiferal assemblages in the laminae (*Heterolepa–Bolivina* assemblage/*Bolivina–Cassidulina* assemblage/*Elphidium–Asterigerinata* assemblage). It might reflect sea-level oscillations with periodically increased siliciclastic and nutrient input from land or influence of seasonality on benthic assemblages, which occurred in the advanced phase of the regression near the Badenian/Sarmatian boundary.

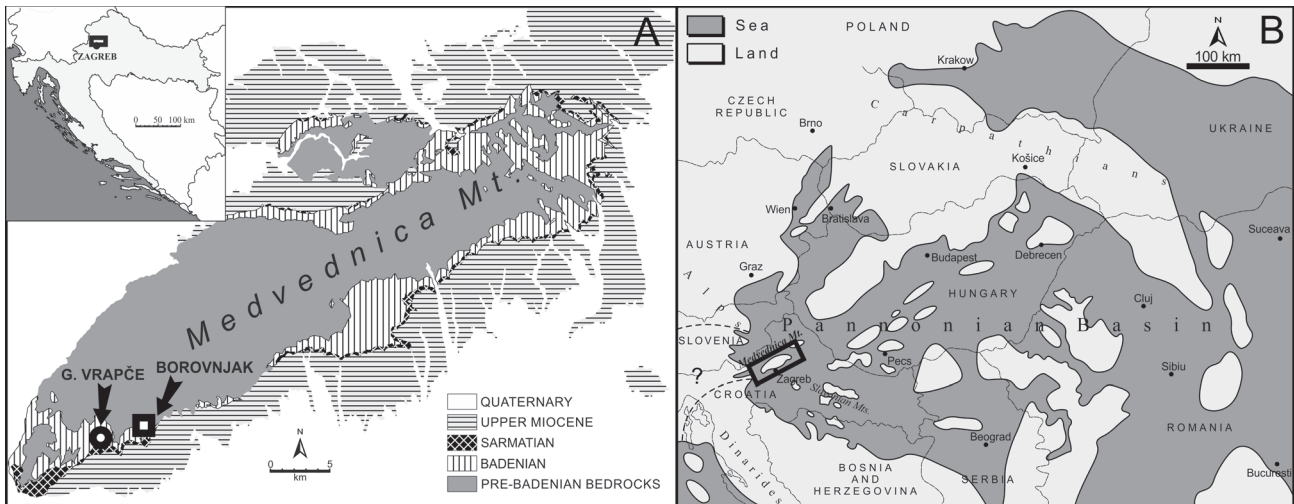
**Key words:** Middle Miocene, Late Badenian, Central Paratethys, palaeoecology, benthic foraminifera.

## Introduction

The north-western part of Croatia during the Middle Miocene belonged to the south-western margin of the Pannonian Basin System (Central Paratethys) flooded by the Paratethys Sea (Fig. 1A, B). Flooding was a consequence of extensional processes between the Alpine-Carpathian and the Dinaride tectonic units (Pavelić 2001; Vrsaljko et al. 2006; Ćorić et al. 2009). The upper part of the Middle Miocene is a particularly interesting period in the development of the Paratethys, because it represents the end of the fully marine regime in the basin, due to the global regression and sea-level fall (Harzhauser & Piller 2007; Hohenegger et al. 2014). During the Late Badenian, equivalent of the lower part of the Middle Serravalian Mediterranean substage (Fig. 2), the Central Paratethys-Mediterranean corridor via Slovenia was probably closed (Rögl 1999; Kováč et al. 2007), although some authors believe that the marine connection was still open (Selmeczi et al. 2012; Bartol et al. 2014). The Badenian/Sarmatian Paratethys substage boundary can be traced through emersion and unconformity at many localities, but the exact

timing of this event and palaeoenvironmental conditions are still the subject of debate of many geologists (Rižnar et al. 2002; Sopková et al. 2007; Radivojević et al. 2010; Gedl & Peryt 2011; Hyžný et al. 2012; Śliwiński et al. 2012).

The Upper Badenian deposits are exposed along the SW slopes of the Medvednica Mt. and have been under research for many years (Kochansky 1944; Šikić 1967; Pezelj & Sremac 2007; Pezelj et al. 2014), but detailed quantitative analyses of foraminiferal assemblages were not yet published. These deposits represent transgressive-regressive trends, with pronounced discontinuity at the Badenian/Sarmatian boundary (Avanić et al. 2005; Vrsaljko et al. 2006). This paper offers detailed analyses of shallow-marine benthic foraminiferal assemblages, particularly sensitive to sea-level oscillations. Triggers of these changes can be of different origin, from eustatic changes, to global and regional tectonic transtension/transpression phases. Special attention was paid to the laminated marls in the upper part of the Gornje Vrapče section. Such occurrence was observed at several localities within the Central Paratethys (Mihajlović & Knežević 1989; Báldi 2006; Crihan & Mărunțeanu 2006; Bartol 2009), but



**Fig. 1. A** — Geographical position of studied area in Croatia and simplified geological map of Medvednica Mt. with geographic range of the Middle Miocene (Badenian and Sarmatian) sediments (modified after Šikić 1995). Analyzed sections are marked with arrows. **B** — Paleogeographical setting showing position of Medvednica Mt. in the southern Pannonian Basin System of Central Paratethys during the Late Badenian (modified after Kováč et al. 2007).

Age (Ma)	Geomagnetic polarity	Chronostratigraphy		Centr. Paratethys Chronostratigraphy		Sea level reconstr.	Central Paratethys biostratigraphy	
	ATNTS04	Epoch	Age	Stage	Subst.	3rd order Sequences	Eco/bio-zones	
12	C5	MIDDLE MIOCENE	Serravallian	Sarmatian		TB2.6	<i>Porosonion granosum</i>	
	C5A					Ser3	<i>Elphidium hauenerum</i> <i>Elphidium reginum</i> <i>Anomalinoidea dividens</i>	
13	C5AA					Kosovian	TB2.5	<i>Ammonia beccarii</i>
	C5AB						Ser2	<i>Bulimina-Bollvina</i>
	C5AC						Wielic.	TB2.4
14	C5AD	Langhian	Badenian	Moravian		Ser1	Upper Lagenidae	
15	C5B					TB2.3	Lower Lagenidae	

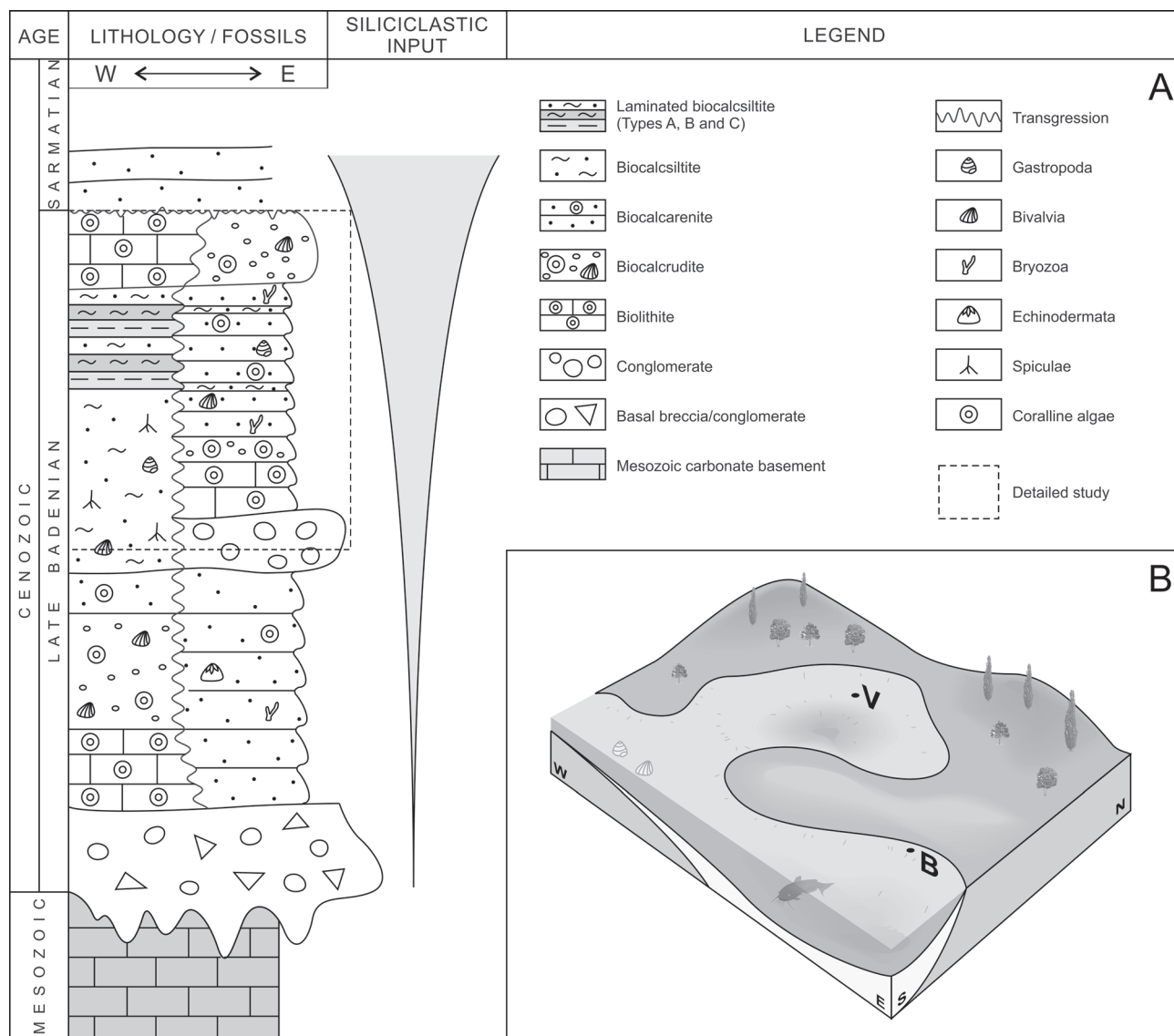
**Fig. 2.** Miocene chronostratigraphic stages of Paratethys and Mediterranean (modified after Lourens et al. 2004; Strauss et al. 2006; Hilgen et al. 2009; Pezelj et al. 2013) with highlighted age of analysed sections.

laminae were sterile or poor in fossils, and their stratigraphic position is uncertain. Some authors regard laminated sections as lithological markers of the Badenian/Sarmatian boundary (Bartol 2009), while others assign them to the Sarmatian (Crihan & Mărușeanu 2006). Laminated deposits at Gornje Vrapče locality are extremely fossiliferous, with clear almost regular exchange of benthic foraminiferal assemblages, enabling both: stratigraphic and palaeoecological interpretation.

The aim of this paper is to apply the results of benthic foraminiferal assemblage analyses to reconstruct the Late Badenian palaeoenvironments present on the south-western slopes of the Mt. Medvednica and explain events and environmental conditions at the Badenian/Sarmatian boundary. We will try to follow the respond of the Late Badenian benthic foraminiferal assemblages to stressful regressive trends, recognize the timing of these changes and establish a model of the Badenian/Sarmatian boundary, which could be applied to the wider Paratethys region.

### Geological settings and description of sections

Medvednica Mt. is a prominent topographical unit in north-western Croatia occupying an area of ca. 300 km<sup>2</sup> (Fig. 1A). Its core is predominantly composed of Palaeozoic and Mesozoic rocks of varied origin, surrounded by younger, Palaeogene, Neogene and Quaternary sedimentary rocks (Šikić 1995). The Middle Miocene shelf deposits represent an elongated ring-shaped belt around the recent Medvednica island within the Paratethys Sea (Fig. 1B). A specific development of the Late Badenian deposition in SW part of the Medvednica Mt. was recognized by Kochansky (1944) who described it as “Dolje sedimentary type”. These deposits represent a transgressive-regressive sequence, with final emersion at the Badenian/Sarmatian boundary (Fig. 3). Basal Upper Badenian deposits in this area are transgressive breccia and conglomerate deposited over the Mesozoic sedimentary rocks. Along the beaches clastic deposition continued in form of sandstones (biocalcrudite and biocalcarenite) but in areas away from the terrestrial input, coralgall biolithites (*Lithothamnium* limestone) are present. Bryozoans are often significant coproducers of



**Fig. 3. A** — Schematic geological column through the Middle Miocene rocks in SW part of the Medvednica Mt. with visible increase of siliciclastic input. **B** — Reconstructed palaeoenvironment of localities Gornje Vrapče (V) and Borovnjak (B). Total thickness of the Late Badenian sequence is estimated to be 65 metres at Gornje Vrapče (West) and 25 meters at Borovnjak (East).

biolithites. Diverse benthic fauna, including bivalves *Lucinoma borealis* (Linnè), *Ostrea* and pectinids lived on and within the coralgall buildups. Echinoids, corals and benthic foraminifera are also common, with taxa typical for the Late Badenian (Vrsaljko et al. 1995, 2006). One short episode of sediment coarsening is visible at the Borovnjak locality (Fig. 3), but a generally transgressive trend is typical for the greater part of the Late Badenian. At the locality Gornje Vrapče deposition of biocalcsiltites indicates further deepening of the sedimentary basin. Global sea level drop in the uppermost Badenian, (Fig. 2) can be recognized from shallowing upward sequences and increase of siliciclastic input in the depositional basin (Vrsaljko et al. 2006). At the locality Gornje Vrapče regression results with deposition of laminated biocalcsiltites, and then biolithites. The sequence from the Borovnjak locality shows a different depositional

pattern, marked by biocalcirudites. The approximate thickness of the Upper Badenian deposits is ca. 65 m at the Gornje Vrapče locality, and 25 m in the Borovnjak sequence. Some shallow marginal areas were finally emerged, and the Sarmatian beds transgressively overlay the Upper Badenian deposits in SW part of the Medvednica Mt. (Fig. 3).

#### Borovnjak section

The Borovnjak section (Lat: 45°50'24.772" Lon: 15°54'52.141"), (also known as Krvarić; Figs. 3, 4) is situated along the forest road Gornja Kustošija–Risnjak, above the Kustošija creek. It was sedimentologically studied by Avanić et al. (1995) and discussed by Vrsaljko et al. (2006). The section's length is 28.5 m, and the following rock types can be recognized: conglomerates, biolithites, biocalcirudites,

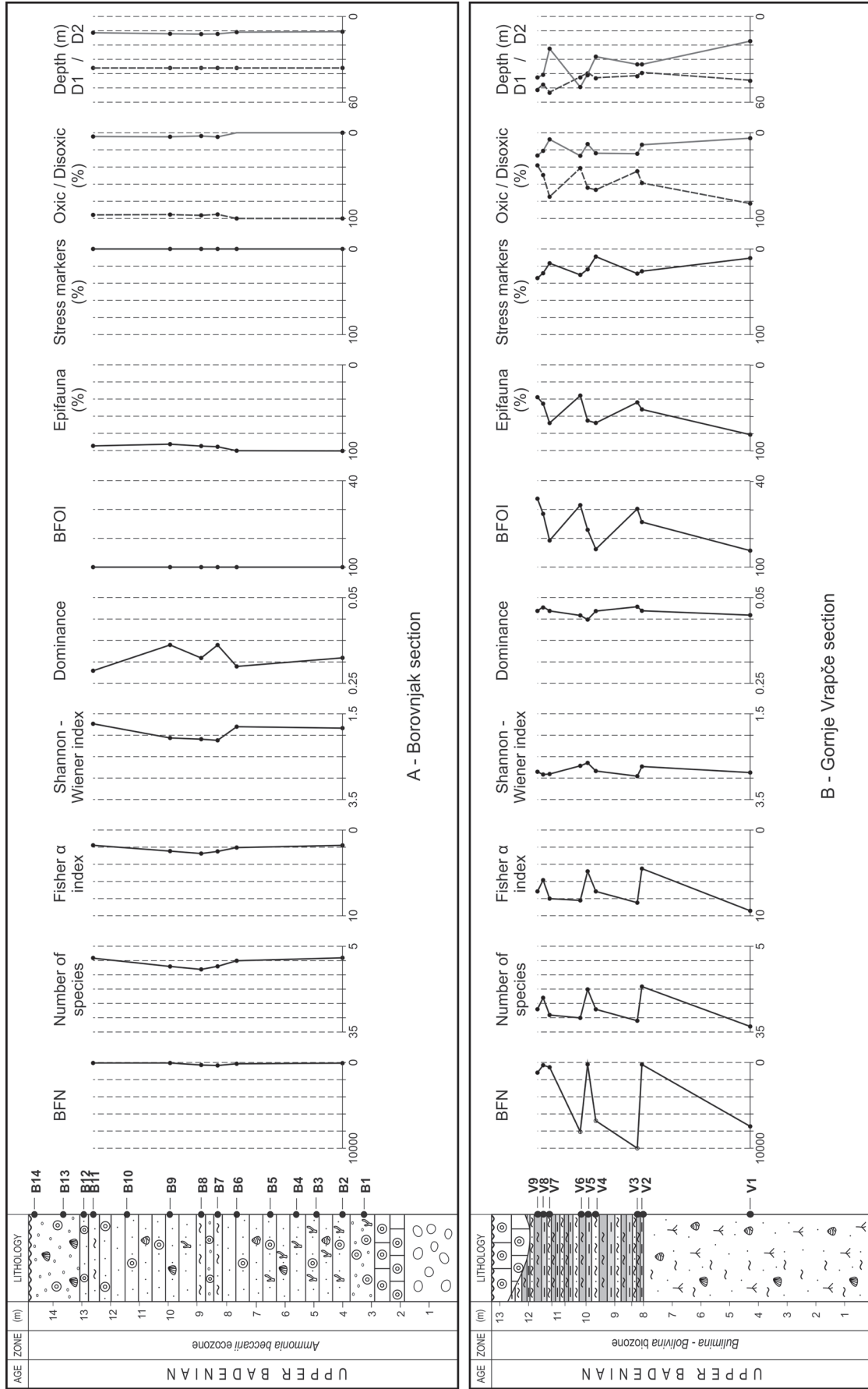


Fig. 4. Detailed sections at the localities Borovnjak (A) and Gornje Vrapče (B) with position of samples, and graphic trends of different palaeoecological proxies.

biocalcarenites and biocalcsiltites within the Upper Badenian part of the section, and sandy oolitic calcarenites within the Sarmatian part of the section. Biocalcrudites and biocalcarenites are coarse-grained to fine-grained deposits, often weathered into sands with destroyed primary textures. Fragments of molluscs, crinoids, corals, coralline algae and echinoids were collected at this locality.

Probe analyses emphasized the potentially interesting central and upper part of the section, while the basal and lower parts of the section were almost sterile. Therefore a more detailed sampling was performed within the upper 15 metres of the section (Figs. 3, 4), dominated by biocalcarenites. The first sample, (B1), was taken within the biocalcrudite, directly above the conglomerate and strongly weathered corallgal biolithite, and the last sample, (B14), was taken in the topmost part of the section, directly below the emersion. Intercalations of biocalcsiltite are also present in the central and upper part of the section.

### *Gornje Vrapče section*

Section with grey fine-grained clastic deposits in Gornje Vrapče (Lat: 45°50'21.12" Lon: 15°54'2.514") was first described by Gorjanović-Kramberger (1882) as "Spongite marl", due to the high content of sponge spicules (from Kochansky 1944). Section is subvertical, ca. 13×10 m large (Figs. 3, 4). Vrsaljko et al. (1995, 2006) proposed the deposition from suspended material in the basal part of the section, and suggested climatic changes as the main trigger for lamination in the upper part of the section. Besides the abundant microfossils (Šikić 1967), numerous macrofossils (molluscs, echinoids, crabs, coralline algae and other fossils) can be found within these siltites (Kochansky 1944).

Greyish-brown siltites in the lower part of the section are variably consolidated, with no visible textures (sample V1). The upper part of the section exhibits clear cyclic alteration of three types of thin laminae (average thickness from 0.5 to 1 cm, some of them are up to 2 cm). Grey-coloured calcitic-siltose laminae (Type A) are sampled as V2, V5 and V8; brownish argillaceous-siltose laminae (Type B) are sampled as V3, V6 and V9, and greyish-brown siltose laminae (Type C) are sampled as V4 and V7 (Fig. 4). In order to reveal the succession of environmental change, laminae are separated into three groups. The first group was collected directly above the basal massive siltite, with no visible textures (samples V2 and V3). The second group (samples V4, V5 and V6) was taken in the central part of the profile, and the third group (samples V7, V8 and V9) was collected from the upper part of the section (Fig. 4).

### **Methods**

All together twenty-three samples were micropalaeontologically analysed and their foraminiferal and ostracod content was studied. For each sample, 300 g of sediment was

soaked, treated with hydrogen peroxide and washed over 0.063 mm sieve. The dried material was repeatedly split by Retsch microsplits, until standard samples with 300 randomly chosen foraminiferal specimens were obtained. After that, the plankton/benthos (P/B) ratio was calculated for each sample. Benthic foraminifera species were identified according to Papp et al. (1978), Papp & Schmid (1985), Loeblich & Tappan (1987a,b) and Cicha et al. (1998), while palaeoecological proxies were co-opted from Kaiho (1994, 1999); Den Dulk et al. (2000), Hohenegger (2005), Van Hinsbergen et al. (2005), Báldi (2006), Pezelj et al. (2007), Holcová & Zágorský (2008), Pippèr & Reichenbacher (2010), De & Gupta (2010), Grunert et al. (2012), Pérez-Asensio et al. (2012) and Pezelj et al. (2013). Each standardized sample was carefully checked (the presence of size-sorting, fragmentation, abrasion, corrosion, and the incongruence of stratigraphic ranges and palaeoecological preferences), in order to exclude redeposited and transported specimens of benthic foraminifera from statistical analysis (Murray 1991; Holcová 1999). The number of species (N) was defined and relative abundance of benthic species within the assemblage was estimated according to Murray (1991). In order to quantify the species diversity of benthic foraminifera, Fisher  $\alpha$ -index ( $\alpha$ ), Shannon-Wiener index (H), and Dominance (D) were determined by means of PAST (PALaeontology STatistic) Program (Hammer et al. 2001). Epifaunal/infaunal ratio and environmental stress markers (Van Hinsbergen et al. 2005) were also calculated. In order to illustrate variations of oxygen content on the sea bottom during the deposition we calculated the Benthic Foraminiferal Oxygen Index (BFOI) for each sample (Kaiho 1999), and determined oxic, suboxic and disoxic indicators (Kaiho 1994). The number of benthic foraminifera in 1 g of dried sediment (Foraminiferal number — NBF) was also determined for each sample. The depth of the depositional basin was estimated through three independent methods: the plankton/benthos ratio (P/B) (Murray 1991); modified plankton/benthos ratio (D1; Van Der Zwaan et al. 1990, 1999), and gradient analysis (D2; Hohenegger 2005; Báldi & Hohenegger 2008).

The Cluster Analysis (Ward's method) and Non-metric Multidimensional Scaling (Bray-Curtis Similarity Index) were conducted by means of PAST (PALaeontology STatistic) Program (Hammer et al. 2001). They were applied to all identified species of benthic foraminifera to determine the differences between benthic foraminiferal assemblages and their distribution in different samples. Such analyses group the samples with homogenous foraminiferal assemblages typical for different palaeoenvironments.

Additionally, the number of ostracod species and their relative abundance within each standardized sample were determined. Ostracod/foraminifera ratio (O/F ratio — number of ostracod specimens/number of foraminifera specimens in 1g of dried sediment) was also calculated. Whole carapaces were calculated as two valves (Danielopol et al. 2002). Ostracoda were determined according to Brestenská & Jiříček (1978), Gross (2006) and Hajek-Tadesse & Prtoljan (2011).

Two different methods of measuring carbonate content were applied to samples V1, V2 and V3 from three lithologically different horizons in the Gornje Vrapče section. Determination of carbonate content in soil by volumetric measuring by Scheibler calcimeter, standard method: HRN ISO: 10693:2004 and Complexometric determination of Calcium and Magnesium. These analyses were done in the Chemical laboratory, Department of Mineralogy and Petrology, University of Zagreb.

Palaeontological samples are stored in the collection of the Department of Geology and Palaeontology (Faculty of Science, University of Zagreb).

## Results

### *Borovnjak locality*

At the Borovnjak locality eight analysed rock samples were palaeontologically sterile or did not contain enough specimens of benthic foraminifera for further statistical analysis. Microfossil assemblages are generally poorly preserved. Foraminiferal tests are often broken into particles, encrusted with calcite crystals and/or abraded or partly dissolved. Diagenetic overprint complicates the process of determination. Besides foraminifera and ostracoda, bryozoan fragments and echinoid spines are present in these samples (Fig 5. A–G). Foraminifera are rather scarce and show low species diversity. The best preserved specimens were recorded in the central part of the section. Planktonic and agglutinated foraminifera were not recorded. A total of 10 genera and 14 species of benthic foraminifera (Table 1) were determined. Benthic foraminifera with perforated tests dominate in all samples, while imperforated foraminifera are slightly more common in the lower part of the profile.

Cluster I unites the samples from the Borovnjak section (Fig. 6). The most important environmental features are high oxygen values at the bottom (BFOI=100), small depth variability (D1=36m; D2=11–12m) and total lack of planktonic foraminifera, disoxic and stress indicators (Table 2). Cluster I is subdivided into two subclusters Ia and Ib.

**Subcluster Ia. *Elphidium*–*Asterigerinata*–*Ammonia* assemblage:** This subcluster includes samples from the lower and the middle part of the Borovnjak section (samples B2, B6 and B9) taken from biocalcarenite. Dominant species are *Elphidium crispum* (23.3–27.6%), *Asterigerinata planorbis* (20.9–28.6%), *Ammonia vienennsis* (16.3–20.3%) and *Elphidium macellum* (11.9–15.6%). This is a low biodiversity assemblage (N=10;  $\alpha$ =2.07; H=1.97) with highly expressed domination (D=0.17). Within the assemblage the most prominent features are oxic indicators (98.5%) and epifaunal taxa (97.4%). The average number of benthic foraminifera individuals (BFN) within the 1g of sediment is 77.

**Subcluster Ib. *Ammonia*–*Elphidium* assemblage:** This subcluster includes the samples from the middle (B7, B8) and the upper part of the Borovnjak section (B11), collected

from biocalcsiltites. It is characterized by pronounced domination of the species *Ammonia vienennsis* (30.2–37.0%). Other dominant species are *Elphidium crispum* (13.8–25.9%) and *Asterigerinata planorbis* (10.8–21.0%). The medium represented species is *Elphidium macellum* (2.6–11.0%). Compared with Subcluster Ia this subcluster shows a higher number of taxa and biodiversity (N=11;  $\alpha$ =2.20; H=1.83), and particularly an increase of the number of individuals BFN=221. Slight increase of suboxic indicators (4.6%) and infaunal taxa (5.8%) within the benthic assemblage are also visible, while the domination (D=0.22) is more prominent than in the previous subcluster.

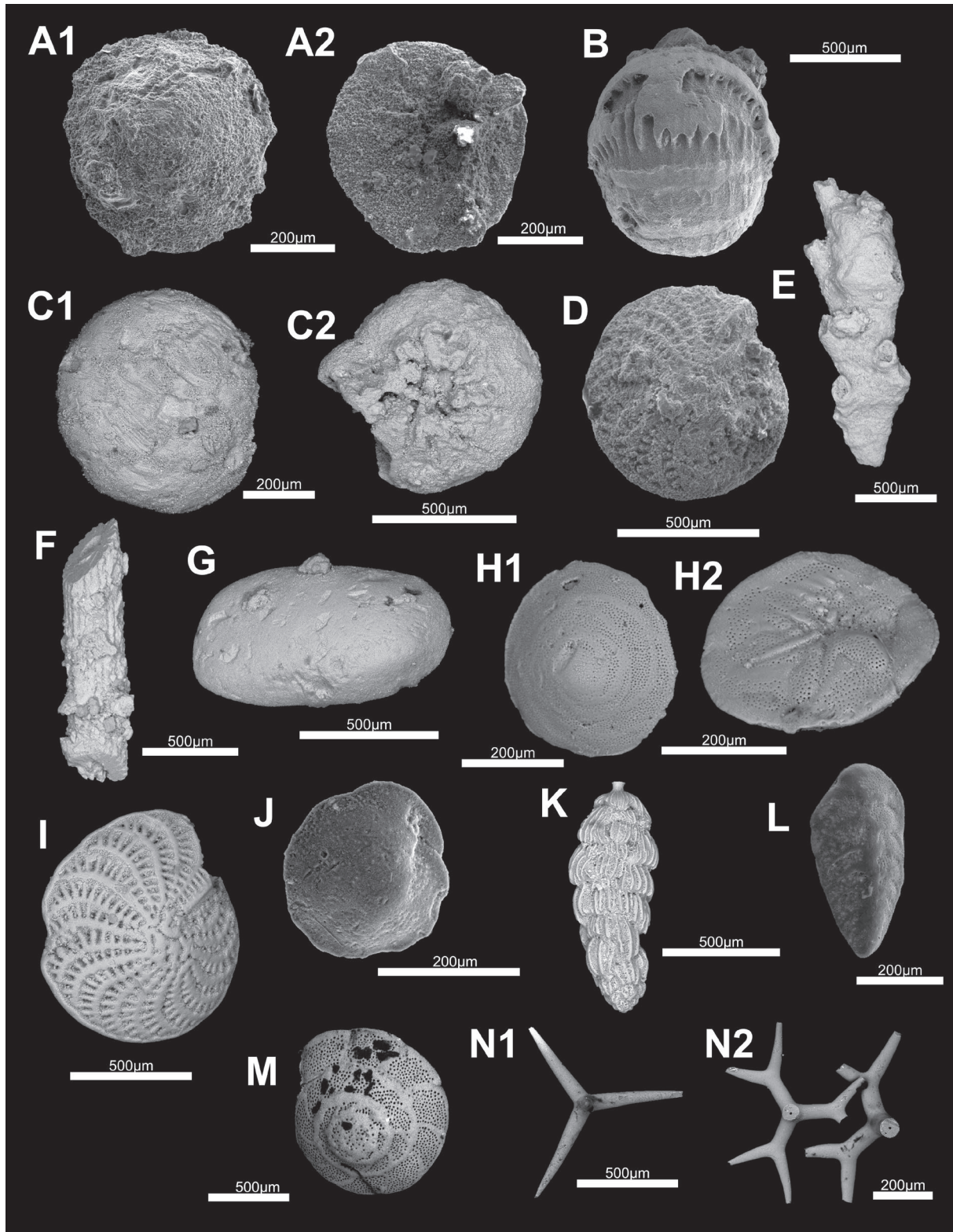
A total of 7 species of ostracoda were determined at the Borovnjak locality. Ostracoda/foraminifera ratio varies from 5.6% (sample B2) to 12.7% (sample B7) (Table 1). In the lower part of the section a few specimens of *Aurila* sp., *Loxococoncha hastata* (Reuss), *Costa edwardsi* (Roemer), *Xestoleberis glabresans* (Brady) and *Cytheridea pernota* Oertly & Key were recorded. Within the central and the upper part of the section the ostracod role in the assemblage becomes more important. Dominant taxa are *Phlyctenophora farkasi* (Zalány), *L. hastata*, *Neocyprideis* (*Miocyprideis*) sp. and *Aurila* sp. The species *C. pernota* and *X. glabresans* are also common. A significant number of specimens was found with closed complete valves (almost 50%), and adult individuals and the last larval stages prevail within the assemblage.

### *Gornje Vrapče locality*

Fine-grained laminated siltites from the section Gornje Vrapče contain rich, diverse and well preserved microfossil assemblage (Fig 5. H–N). This habitat was characterized by an extremely rich assemblage of siliceous sponges. At least eight morphotypes of spicules can be clearly recognized (Fig 5. N1, N2), and deserve further attention. Planktonic foraminifera are scarce, while benthic foraminifera are extremely rich and diverse. A total of 31 genera with 44 species of benthic foraminifera were determined (Table 1). Benthic foraminifera with perforated tests dominate in all samples from this locality. Imperforated foraminifera are less common, while the percentage of agglutinated foraminifera is almost negligible. There are no signs of transportation or redeposition of benthic foraminifera.

Cluster II groups the samples from the locality Gornje Vrapče. Subclusters can be clearly recognized, considering the dominant benthic foraminifera and palaeoecological indicators (Fig. 6; Table 2).

**Subcluster IIa. *Elphidium*–*Asterigerinata* assemblage:** Sample V1 collected from the massive siltite in the base of the section is grouped with siltose laminae (Type C) from the central (V4) and the upper part of the section (V7). The dominant species are *Elphidium crispum* (11.6–19.5%) and *Asterigerinata planorbis* (13.5–17.6%). Medium represented species are *Heterolepa dutemplei*, *Cibicidoides ungerianus* and *E. macellum*. Planktonic foraminifera are present in small numbers (P=6.24%), and the estimated depth of the



**Fig. 5.** Typical microfossils from Borovnjak (A-G) and Gornje Vrapče section (H-N). **A** — *Asterigerinata planorbis* (d'Orbigny), sample B6; A1, spiral side, A2, umbilical side. **B** — *Borelis melo* (Fichtel & Moll), sample B6; apertural view. **C** — *Ammonia viennensis* (d'Orbigny), sample B11; C1, spiral side, C2, umbilical side. **D** — *Elphidium crispum* Linne, sample B2; side view. **E** — Bryozoa, sample B2. **F** — Echinoid radiola, sample B6. **G** — *Neocyprideis* sp., sample B11; left valve, external Lateral view. **H** — *Asterigerinata planorbis* (d'Orbigny), sample V1; H1, spiral side, H2, umbilical side. **I** — *Elphidium crispum* Linne, sample V4; side view. **J** — *Cassidulina laevigata* d'Orbigny, sample V3; apertural side. **K** — *Pappina neudorfensis* (Toula), sample V2; side view. **L** — *Bolivina dilatata* Reuss, sample V6; side view. **M** — *Heterolepa dutemplei* d'Orbigny, sample V5; spiral side. **N1-N2** — Spicule, sample V1.

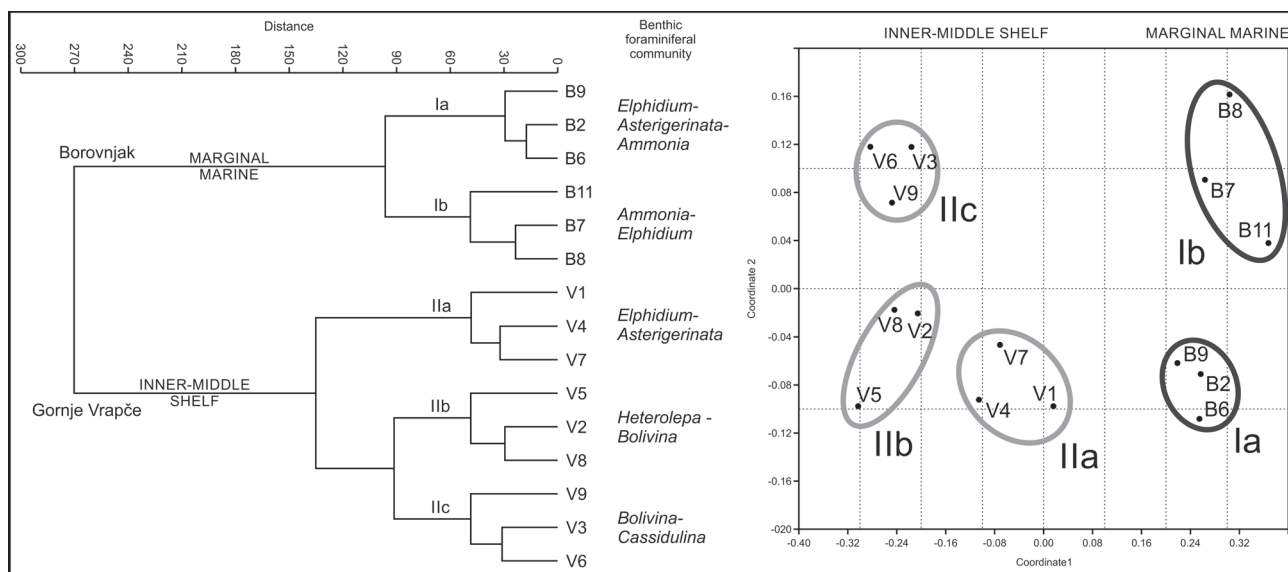
**Table 1. A** — List of determined species of benthic foraminifera from the localities Gornje Vrapče and Borovnjak, their absolute number in samples and ecological/palaeoecological requirements. Bolded taxa were represented with more than 5% in at least one sample. Lower part of the table: Percentage of planktonic taxa, estimated depths of sedimentary basin, number of species and number of individuals (BFN) of benthic foraminifera, diversity indices, BFOI, oxic, suboxic and disoxic indicators, epifauna/ifauna ratio, stress markers and ostracoda/foraminifera ratio. **B** — List of determined species of ostracoda from the localities Gornje Vrapče and Borovnjak.

A. BENTHIC FORAMINIFERA	Oxic preference	Mode of life	Stress marker	V1	V2	V3	V4	V5	V6	V7	V8	V9	B2	B6	B7	B8	B9	B11
<i>Textularia gramen</i> d'Orbigny	S	E/SI		1	0	1	2	0	0	0	0	1	0	0	0	0	0	0
<i>Quinqueloculina aknerianad</i> d'Orbigny	O	E		4	10	2	1	7	1	1	7	0	0	0	0	0	0	0
<i>Quinqueloculina</i> sp.	O	E		1	7	1	0	8	0	2	0	2	0	0	0	0	0	0
<i>Triloculina</i> sp.	O	E		1	3	0	1	0	0	0	0	0	14	14	4	5	12	7
<i>Borelis melo</i> (Fichtell & Moll)	O	E		0	0	0	0	0	0	0	0	0	9	12	2	0	3	0
<i>Lenticulina inornata</i> (d'Orbigny)	O	E/SI		0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
<i>Globulina gibbad</i> d'Orbigny	O	SI		0	0	3	0	0	0	0	0	0	0	0	0	6	10	5
<i>Fissurina</i> sp.	S	E/SI		0	0	0	5	8	1	2	0	2	0	0	0	0	0	0
<b><i>Bolivina dilatata</i> Reuss</b>	D	I	x	11	<b>30</b>	<b>37</b>	4	<b>35</b>	<b>55</b>	8	<b>29</b>	<b>51</b>	0	0	0	0	0	0
<i>Bolivina plicatella</i> (Cushman)	D	I		2	0	4	0	0	0	0	0	0	0	0	0	0	0	0
<i>Bolivina pokorny</i> Cicha & Zapletalova	D	I	x	2	0	7	0	0	0	1	0	2	0	0	0	0	0	0
<i>Cassidulina laevigata</i> d'Orbigny	S	I		5	<b>29</b>	<b>53</b>	<b>21</b>	<b>19</b>	<b>49</b>	6	<b>18</b>	<b>31</b>	0	0	0	0	0	0
<b><i>Globocassidulina oblonga</i> (Reuss)</b>	O	I		1	<b>20</b>	1	3	0	<b>16</b>	<b>15</b>	13	5	0	0	0	0	0	0
<b><i>Bulinina elongata</i> d'Orbigny</b>	D	I	x	7	<b>24</b>	<b>28</b>	14	<b>16</b>	<b>25</b>	<b>21</b>	<b>27</b>	10	0	0	0	0	0	0
<i>Bulinina gusulica</i> Livalent	D	I	x	0	0	0	0	0	1	0	0	7	0	0	0	0	0	0
<i>Bulinina insignis</i> Luczkowska	D	I	x	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0
<b><i>Pragelobulimina pyrala</i> (d'Orbigny)</b>	D	I	x	2	8	1	6	7	7	10	8	<b>28</b>	0	0	0	0	0	0
<i>Pappina neudorfensis</i> (Toula)	S	I		2	14	11	8	0	15	9	7	11	0	0	0	0	0	0
<i>Uvigerina bellocostata</i> Luczkowska	D	I	x	0	0	0	0	0	2	0	0	3	0	0	0	0	0	0
<i>Uvigerina brunneis</i> Karer	D	I	x	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0
<i>Uvigerina semiornata</i> d'Orbigny	D	I		0	0	0	0	0	2	0	0	0	0	0	0	0	0	0
<i>Reusella spinulosa</i> (Reuss)	E	E		4	0	0	8	0	2	0	0	0	0	0	0	0	0	0
<i>Fursenkoina acuta</i> (d'Orbigny)	D	O	x	4	0	1	1	6	1	1	0	1	0	0	0	0	0	0
<i>Caneris auriculatus</i> (Fichtell & Moll)	D	I	x	9	5	12	5	0	4	2	9	4	0	0	0	0	0	0
<i>Valvulineria complanata</i> (d'Orbigny)	O	E		7	0	4	0	0	0	0	0	0	0	0	0	0	0	0
<i>Neoconorbina terquemii</i> (Rzehak)	O	E		6	9	5	1	0	6	5	0	0	0	0	0	0	0	0
<i>Rosalina obtusa</i> d'Orbigny	O	E/SI		15	0	10	<b>30</b>	<b>32</b>	<b>26</b>	10	<b>18</b>	<b>23</b>	0	0	0	0	0	0
<b><i>Cibicides ungerianus</i> (d'Orbigny)</b>	O	E/SI		11	0	3	2	0	2	3	0	0	0	0	0	0	0	0
<i>Cibicides</i> sp.	O	E		3	0	0	0	0	0	0	0	0	0	0	12	0	0	0
<i>Lobatula lobatula</i> (Walker & Jacob)	O	E		13	13	11	8	14	5	7	11	8	0	8	15	4	6	10
<b><i>Asterigerinata planorbis</i> (d'Orbigny)</b>	O	E		<b>53</b>	<b>31</b>	<b>12</b>	<b>45</b>	<b>14</b>	<b>3</b>	<b>39</b>	<b>16</b>	<b>16</b>	<b>75</b>	<b>84</b>	<b>42</b>	<b>32</b>	<b>64</b>	<b>54</b>
<i>Nonion commune</i> (d'Orbigny)	S	I		0	0	13	0	0	1	4	14	8	0	0	15	11	14	13
<i>Melonis pompilioides</i> (Fichtell & Moll)	S	I		10	0	0	21	6	14	2	6	6	0	0	0	0	0	0
<b><i>Pulleania bulloides</i> (d'Orbigny)</b>	S	I		2	0	0	15	6	3	0	<b>17</b>	<b>21</b>	0	0	0	0	0	0
<b><i>Heterolepa duteplei</i> d'Orbigny</b>	O	E		3	<b>42</b>	<b>17</b>	<b>27</b>	<b>69</b>	<b>18</b>	<b>29</b>	<b>42</b>	<b>16</b>	0	0	0	0	0	0
<i>Hanzawaia boueana</i> (d'Orbigny)	O	E		3	0	12	8	8	5	5	9	4	0	0	1	10	9	0
<b><i>Ammonia viennensis</i> (d'Orbigny)</b>	O	E/SI		1	0	1	1	6	2	2	0	0	<b>51</b>	<b>42</b>	<b>93</b>	<b>110</b>	<b>50</b>	<b>117</b>
<i>Porosonion granosum</i> (d'Orbigny)	O	SI		0	0	0	0	0	1	7	0	0	0	0	0	0	0	0
<i>Elphidium aculeatum</i> (d'Orbigny)	O	E/SI		8	0	7	6	0	0	3	5	0	0	0	0	0	0	0
<b><i>Elphidium crispum</i> (Linné)</b>	O	E/SI		<b>59</b>	<b>16</b>	<b>22</b>	<b>35</b>	<b>14</b>	<b>29</b>	<b>45</b>	<b>12</b>	<b>17</b>	<b>70</b>	<b>81</b>	<b>49</b>	<b>41</b>	<b>77</b>	<b>79</b>
<i>Elphidium fichtellianum</i> (d'Orbigny)	O	E/SI		12	8	8	14	8	6	13	7	9	13	10	10	8	13	0
<i>Elphidium flexuosum</i> (d'Orbigny)	O	E/SI		10	5	4	0	0	0	10	0	0	15	8	14	9	7	0
<b><i>Elphidium macellum</i> (Fichtell &amp; Moll)</b>	O	E/SI		<b>25</b>	<b>10</b>	<b>16</b>	9	3	3	<b>19</b>	4	13	<b>47</b>	<b>35</b>	<b>34</b>	<b>27</b>	<b>44</b>	8
<i>Elphidium rugosum</i> (d'Orbigny)	O	E/SI		5	0	2	0	0	0	0	0	1	0	0	0	0	0	0
<i>Elphidium</i> sp.	O	E/SI		0	0	0	0	0	0	0	0	0	11	9	0	11	0	0
				302	298	318	301	295	306	289	292	301	305	303	291	274	309	293



**Table 1 (continuation): A.** List of determined species of benthic foraminifera from the localities Gornje Vrapče and Borovnjak, their absolute number in samples and ecological/palaeoecological requirements. Bolded taxa were represented with more than 5% in at least one sample. Lower part of the table: Percentage of planktonic taxa, estimated depths of sedimentary basin, number of species and number of individuals (BFN) of benthic foraminifera, diversity indices, BFOI, oxic, suboxic and disoxic indicators, epifauna/infrafauna ratio, stress markers and ostracoda/foraminifera ratio. **B.** List of determined species of ostracoda from the localities Gornje Vrapče and Borovnjak.

	V1	V2	V3	V4	V5	V6	V7	V8	V9	B2	B6	B7	B8	B9	B11
P/B ratio (%)	5.22	1.34	2.72	4.38	2.03	3.14	9.12	5.43	6.65	0	0	0	0	0	0
D1 (m)	45	39	41	43	40	42	53	47	51	36	36	36	36	36	36
D2 (m)	17	33	33	28	40	49	23	41	43	11	12	12	12	12	11
BFN	7392	214	9896	6733	192	8007	502	246	1128	53	121	352	269	57	42
Number of species	33	19	31	27	20	30	29	23	27	9	10	12	12	12	8
Fisher $\alpha$ index	9.44	4.52	8.5	7.18	4.85	8.24	8.03	5.85	7.18	1.74	1.99	2.52	2.57	2.48	1.52
Shannon-Wiener index	2.87	2.73	2.95	2.83	2.64	2.71	2.9	2.91	2.85	1.92	1.91	2.01	1.94	2.07	1.54
Dominance	0.09	0.08	0.07	0.08	0.1	0.09	0.08	0.07	0.08	0.17	0.19	0.18	0.22	0.16	0.27
BFOI	88.3	68.3	59.2	87.3	73.8	56.5	81.2	62.6	52	100	100	100	100	100	100
Oxic (%)	82.5	58.4	44.7	66.5	64.1	41.2	74.7	49.3	38.2	100	100	94.8	95.9	95.5	95.6
Suboxic (%)	6.6	14.4	24.5	23.9	13.2	27.1	7.9	21.2	26.6	0	0	5.2	4.1	4.5	4.4
Disoxic (%)	10.9	27.2	30.8	9.6	22.7	31.7	17.3	29.5	35.2	0	0	0	0	0	0
Epifauna (%)	81.1	51.7	43.4	67.4	64.8	35.6	67.5	44.9	37.5	100	100	94.8	93.9	92.2	93.8
Infrauna (%)	18.9	48.3	56.6	32.6	35.2	64.4	32.5	55.1	62.5	0	0	5.2	6.1	7.8	6.2
Stress markers (%)	11.6	27.2	29.9	10	24.8	31.4	17.7	29.5	35.2	0	0	0	0	0	0
O/F ratio (%)	2.6	0	1.9	3.7	0.7	1.3	2.1	0	0.7	5.6	4.6	12.7	9.5	2.9	6.8
<b>B. OSTRACODA</b>															
<i>Phytanophora farkasi</i> (Zalány)			x	x	x	x	x								x
<i>Callistocythere canaliculata</i> (Reuss)	x	x	x	x	x	x	x	x							
<i>Cnestocythere lamellicostata</i> Triebel	x	x	x	x	x	x	x								
<i>Aurila haueri</i> (Reuss)	x	x	x	x	x	x	x								
<i>Aurila</i> sp.															
<i>Carinocythereis carinata</i> (Roemer)				x		x				x					
<i>Costa edwardsi</i> (Roemer)															
<i>Cytheridea permota</i> Oertly & Key															x
<i>Neocytherideis</i> ( <i>Miocytherideis</i> ) sp.															
<i>Semicytherura</i> cf. <i>acuticostata</i> Sars															
<i>Hemicytherura</i> sp.	x		x	x			x								
<i>Loxoconcha hastata</i> (Reuss)															x
<i>Loxoconcha punctanella</i> (Reuss)															x
<i>Aesoleberis glabrescans</i> (Brady)	x			x		x									x



**Fig. 6.** Results of Cluster Analysis (Ward's method, Bray-Curtis Similarity Index) and Non-metric-Multidimensional Scaling analyses (Bray-Curtis Similarity Index) of the Middle Miocene foraminiferal benthic communities from localities Borovnjak and Gornje Vrapče in SW Medvednica Mt.

sedimentary basin ranges from D1=47 m to D2=23 m. Within this assemblage the highest oxygen amount at Gornje Vrapče locality is calculated (BFOI=85.6), the highest number of species (N=30), highest biodiversity ( $\alpha=8.22$ ; H=2.87), and average domination (D=0.08). Within the assemblage oxic indicators prevail (74.6%) as well as epifaunal taxa (72.0%), while the amounts of suboxic and disoxic indicators are equal (around 13%). The amount of stress markers is small (13.1%), and number of individuals of benthic foraminifera (BFN) is 4876.

**Subcluster IIb. *Heterolepa-Bolivina* assemblage:** This subcluster groups the samples taken from the solid grey calcilite laminae (Type A; V2, V5 and V8) laying directly above the base, and above the silty laminae (Subcluster IIa). The dominant species are *Heterolepa dutemplei* (14.1–23.4%) and *Bolivina dilatata* (9.9–11.9%). Medium represented species are *Bulimina elongata*, *Cassidulina laevigata*, *Asterigerinata planorbis* and *Cibicidoides ungerianus*. Within this subcluster, an abrupt decrease in number of species can be observed (N=21) as well as a decrease of the number of individuals (BFN=217). Indices reflect the decrease in diversity of benthic foraminifera ( $\alpha=5.07$ ; H=2.76). Domination is still unchanged and the amount of planktonic foraminifera slightly decreases (P=2.93%). Compared to Subcluster IIa infaunal taxa increase in number (46.2%), as well as suboxic (16.3%) and particularly disoxic (26.5%) indicators. The amount of stress markers is doubled (27.2%). Indices reflect the decrease of oxygenation at the bottom (BFOI=68.2), while the estimated depth of the sedimentary basin remains the same as in the previous subcluster (D1=42m) or slightly increases (D2=38 m).

**Subcluster IIc. *Bolivina-Cassidulina* assemblage:** Samples V3, V6 and V9 collected within the argillaceous-silty laminae (Type B), directly above the grey marly laminae are

grouped within this subcluster. The dominant species are *Bolivina dilatata* (11.6–18.0%) and *Cassidulina laevigata* (10.3–16.7%), while the medium represented species are *Elphidium crispum*, *Bolivina elongata*, *Cibicides ungerianus* and *Heterolepa dutemplei*. Within this assemblage extreme increase of number of individuals is present (BFN=6344), there is restoration of diversity (N=29;  $\alpha=7.94$ ; H=2.84), while the domination remained unchanged. Decrease of oxygenation of the sea bottom is still in progress (BFOI=55.9) and amount of planktonic foraminifera is increasing (P=4.17%). Estimation of depth is almost the same as in the previous subcluster (D1=45m; D2=42m). Within this assemblage infaunal taxa are dominant (61.2%). The amount of suboxic (26.0%), disoxic (32.6%) and stress markers (32.2%) is still increasing.

The number of ostracods (Table 1) within the microfossil assemblages varies from 0% (samples V2, V8) to maximally 3.7% (sample V4). A total of 8 species were recognized, including the most common species *Aurila haueri* (Reuss), *Cnestocythere lamellicostata* Triebel, *Callistocythere canaliculata* (Reuss) and *Semicytherura* cf. *acuticostata* Sars. Ostracod species *Carinocythereis carinata* (Roemer), *Phlyctenophora farkasi* (Zalány), *Loxocochocha punctanella* (Reuss) and *Hemicytherura* sp. occur with small numbers of individuals. The number of complete ostracod carapaces is very low (around 2%), and assemblage comprises adult, as well as larval stages.

Three lithologically different samples from the Gornje Vrapče section were analysed by calcimetric and complexometric methods. The results are very similar (Table 3) and clearly exhibit excursions of calcite content. The calcite content in sample V1 from the basal massive marl is 56.60% (56.38%). Carbonate component increases in the first overlying lamina (Type A) up to 75.00% (73.89%) and again

**Table 2:** Mean values of paleoecological indices for different benthic foraminiferal assemblages at analysed sections Borovnjak and Gornje Vrapče.

Cluster Community	Ia <i>Elphidium–Asterigerinata– Ammonia</i>		Ib <i>Ammonia–Elphidium</i>		IIa <i>Elphidium–Asterigerinata</i>		IIb <i>Heterolepa–Bolivina</i>		IIc <i>Bolivina–Cassidulina</i>	
	range	mean	range	mean	range	mean	range	mean	range	mean
P (%)	0	0	0	0	4.38–9.12	6.24	1.34–5.43	2.93	2.72–6.65	4.17
D1 (m)	36–36	36	36–36	36	43–53	47	39–47	42	41–51	45
D2 (m)	42715	11.5	42715	11.5	17–28	23	33–41	38	33–49	42
BFOI	100	100	100	100	81.2–88.3	85.6	62.6–73.8	68.2	52.0–59.2	55.9
Number of species (N)	42713	10	42712	11	27–33	30	19–23	21	27–31	29
BFN	53–121	77	42–352	221	502–7392	4876	192–246	217	1128–9896	6344
Fisher $\alpha$ index ( $\alpha$ )	1.74–2.48	2.07	1.52–2.57	2.2	7.18–9.44	8.22	4.52–5.85	5.07	7.18–8.50	7.94
Shannon–Wiener index (H)	1.91–2.07	1.97	1.54–2.01	1.83	2.83–2.90	2.87	2.64–2.91	2.76	2.71–2.95	2.84
Dominance (D)	0.16–0.19	0.17	0.18–0.27	0.22	0.08–0.09	0.08	0.07–0.10	0.08	0.07–0.09	0.08
Oxic (%)	95.5–100	98.5	94.8–95.9	95.4	66.5–82.5	74.6	49.3–64.1	57.2	38.2–44.7	41.4
Suboxic (%)	0–4.5	1.5	4.1–5.2	4.6	6.6–23.9	12.8	13.2–21.2	16.3	24.5–27.1	26
Disoxic (%)	0	0	0	0	9.6–13.3	12.6	22.7–29.5	26.5	30.8–35.2	32.6
Epifauna (%)	92.2–100	97.4	93.8–94.8	94.2	67.4–81.1	72	44.9–64.8	53.8	35.6–43.4	38.8
Infauna (%)	0–7.8	2.6	5.2–6.2	5.8	18.9–32.6	28	35.2–55.1	46.2	56.6–64.4	61.2
Stress markers (%)	0	0	0	0	10.0–17.7	13.1	24.8–29.5	27.2	29.9–35.2	32.2
O/F ratio (%)	2.9–5.6	4.4	6.8–12.7	9.7	2.1–3.7	2.8	0–0.7	0.2	0.7–1.9	1.3

decreases in the next overlying lamina (Type B) to 41.98% (41.54%). Such oscillations are probably present up to the top of the laminated portion of the section. Three-valent metal (probably iron) also exhibits variations ( $R_2O_3$ , Table 3).

## Biostratigraphy

Biostratigraphic analysis of the studied sections is based upon standard biozonations for Central Paratethys (Papp et al. 1978; Papp & Schmid 1985; Cicha et al. 1998). Two Late Badenian zones *Bulimina–Bolivina* Zone (biozone) and *Ammonia beccarii* Zone (ecozone) can be recognized on the basis of detailed microfossil study.

Samples from the locality Borovnjak belong to the *Ammonia beccarii* ecozone. Benthic foraminiferal assemblage shows low diversity, with a dominant role for *Ammonia* (*A. viennensis*), *Elphidium* (*E. crispum*, *E. macellum*) and rather common occurrence of miliolids (*Borelis melo*, *Triloculina inflata*). The *Elphidium–Ammonia* assemblage was observed at several localities within the Central Paratethys in different Miocene stratigraphic horizons (Bakrač et al. 2010; Pippèr 2011; Nehyba et al. 2016), and similar shallow-water environments at the Late Badenian/Early Sarmatian boundary were described from Slovakia (Hyžný et al. 2012). The Late Badenian age was proven by ostracods *Phlyctenophora farkasi* (Zalány) and *Neocyprideis* (*Miocyprideis*) sp., which are typical for the uppermost part of the Badenian (Brestenská & Jiříček 1978; Jiříček 1983). Another criterion is superposition — after the short emersion, the Sarmatian clastic sediments were deposited in this area.

Samples from the locality Gornje Vrapče belong to the Late Badenian *Bulimina–Bolivina* Zone. Age is presumed on the basis of benthic foraminifera *Pappina neudorfensis* (Toula), *Bulimina insignis* Luczkowska and *Uvigerina bellucostata* Luczkowska (indicative for the Late Badenian) and *Bulimina gutsulica* Livental and *Uvigerina brunensis* Karrer (Middle to Late Badenian), (Cicha et al. 1998). Additional proofs are the presence of marine ostracod *Carinocythereis carinata* (Roemer), typically present in the Late Badenian of the Paratethys and the Badenian ostracod taxa *Cnestocythere lamellicostata* Triebel, *Aurila haueri* (Reuss) and *Loxococoncha punctanella* (Reuss) (Brestenská & Jiříček 1978; Nascimento & Riha 1996; Hajek-Tadesse & Proljan 2011).

## Discussion

Miocene rocks in both investigated sections reflect three different phases of deposition within TB 2.5 global 3<sup>rd</sup> order sequence (Hilgen et al. 2009; Fig. 2): initial Late Badenian transgression and establishment of shallow marine environments, start of regression and environmental stress in the uppermost Late Badenian and final regression and emersion at the Badenian/Sarmatian boundary. During wet periods marginal shelf deposits of the Paratethys are characterized by coarse clastics, while the carbonate-siliciclastic complexes are known only in some intervals which were dry (Moissette et al. 2007; Holcová et al. 2015). Marginal facies are present at the Borovnjak locality and they are assigned to the *Ammonia beccarii* ecozone. Along with transgression, more

**Table 3:** Results of calcimetric and complexometric analyses of three different samples from Gornje Vrapče section.

Sample	CALCIMETRY				COMPLEXOMETRY		
	CaCO <sub>3</sub> [%]	CaO [%]	CaCO <sub>3</sub> [%]	R <sub>2</sub> O <sub>3</sub> [%]	R <sub>2</sub> O <sub>3</sub> recalculated to carbonate [%]	Undissolved residue [%]	Total [%]
V-1	56.60	31.25	56.38	1.68	3.08	40.00	99.46
V-2	75.00	41.51	73.89	1.41	2.61	23.92	100.42
V-3	41.98	23.34	41.54	3.49	6.38	51.91	99.84

specialized taxa appear, indicative for *Bulimina–Bolivina* Zone such as those present at the Gornje Vrapče locality.

### The Late Badenian transgression

The initial transgression along the SW slopes of Medvednica Mt. took place over the pronounced palaeorelief developed in the Mesozoic carbonate basement (Fig. 3). Encrusting coralline algae were the first sessile inhabitants of clastic shelf, stabilizing the substrate and enabling colonization by other benthic biota. The first additional frame-building metazoans were bryozoa, producing compound reef buildups — suitable habitats for diverse benthic assemblage of thick-shelled taxa (e.g. ostreids, echinoids, corals) (Gorka et al. 2012). Reef buildups, in most cases patch-reefs composed of coralline algae and/or corals, are common in the Badenian deposits of Paratethys (Pisera, 1996; Reuter et al. 2012). Small reef buildups at the locality Borovnjak were produced in shallow, relatively warm, agitated, normally saline environments. Corals and vermetids were not collected during this study, but scarce findings were reported by previous authors in Croatia (Avanić et al., 1995; Vrsaljko et al. 2006).

Laterally, bioherms are replaced with coarse-grained bioclastic limestones (calcrudite/calcarenite) with typical marginal marine *Elphidium–Asterigerinata–Ammonia* assemblage (Subcluster Ia). The depth of this facies estimated by two methods ranges between 11 and 36 metres. Laboratory experiments have shown that foraminifera from *Elphidium–Ammonia* assemblage are active colonizers of sterile substrates, and are in many cases the pioneer biota in marginal marine environments during the initial transgression (Debenay et al. 2009). Poor preservation of specimens with visible traces of destruction, abrasion and corrosion, suggest highly energetic environments. The analysed assemblages exhibit low number of species, low diversity and pronounced domination (Fig. 4, Table 2), which is typical for stress environments, sometimes with brackish or hypersaline water, but also for normal marine habitats with high domination of one or several species (Murray 1991). Lack of planktonic foraminifera, highly oxic conditions (BFOI=100), with dominance of oxic proxies and epifaunal taxa definitely indicate a typical shallow-marine habitat. Such conditions are also favourable for organic carbonate growth, particularly of reef structures and reef-building biota. Typical marine species of *Elphidium* (*E. crispum*, *E. macellum* and *E. fichtelianum*) represent more than 45% of the basal Borovnjak assemblages. Recent keeled elphidia are in most cases herbivorous, epifaunal, preferring sandy substrates and often attached to rhizomes of sea-grasses (Murray 1991, 2006). Together with

other epiphytic foraminifera (*Asterigerinata*, *Triloculina*, *Borelis*) they point to the environment with algal/sea-grass meadows in the Late Badenian of Borovnjak. A particularly indicative genus is *Borelis* (present up to 4%), recently common in the Red Sea and Gulf of Aquaba, with fossil species *B. schlumbergeri* typical for fore-reef assemblages (Parker et al. 2012). It is a shallow-marine genus (up to 40 metres depth), typical for warm seas. The tolerance of benthic foraminifera to clastic influx is variable and it seems that *Borelis* at the Borovnjak locality could tolerate such temporary episodes. Ostracod assemblages comprise scarce stenohaline marine taxa *Aurila* sp., *Loxocochoa hastata*, *Costa edwardsi*, *Xestoleberis* cf. *glabresans* and *Cytheridea pernata* (Table 1, 2) which are typical for littoral and epineritic environment (Smith & Horne 2002). Their carapaces are in most cases strongly calcified and with coarse ornamentation, except the smooth-surfaced epiphytic *Xestoleberis* (Triantaphyllou et al. 2010). A significant amount of carapaces were preserved complete, with closed valves, which is a consequence of selective sorting due to the high-energy conditions. Adult specimens and last larval stadia predominate, which is also typical for agitated shallow marine environments. Minute carapaces in such environments can be disturbed by turbulences and later transported by currents (Danielopol et al. 2002).

The open section at the locality Gornje Vrapče begins with similar marginal marine stressed facies (Fig. 3). Advancing transgression results with a deeper inner shelf, more stable environment and very rich (44 species) and diverse *Elphidium–Asterigerinata* assemblage (Subcluster IIa) and increase of siltose and argillaceous component in marls. Planktonic foraminifera are scarce (<10%), as is typical for the inner shelf (Murray 1991). The values of the Fisher  $\alpha$  index (Table 1) additionally point to the normal salinity shelf environment or marine lagoon. The estimated depth of the basin according to Van der Zwann (1999) (39–53 m), and gradient analysis (17–49 m) confirm the shallow inner/middle shelf environment. Within the assemblage oxic and epifaunal indicators prevail, with dominant shallow water species *Elphidium crispum*, *Asterigerinata planorbis* and *Elphidium macellum*. Compared to the precursor *Elphidium–Asterigerinata–Ammonia* assemblage, this assemblage with average domination lived in a significantly more stable environment with abundant oxygen (BFOI=85.6). The accompanying ostracod taxa *Aurila haueri*, *Cnestocythere lamellcostata* and *Semicytherura acuticostata* are typical for a shallow marine environment (Smith & Horne 2002). The sheltered habitat of Gornje Vrapče was also inhabited with an extremely abundant and diverse siliceous sponge

assemblage. Loose spicules are so numerous that geologists named these deposits “Spongite marls” or “Spongite siltites”. Findings of the Miocene sponges in Paratethys deposits are extremely scarce. A nice sponge assemblage from basinal Karpatian deposits of the Vienna Basin (Pisera & Hladilova 2003; Łukowiak et al. 2014) contain a significant number of transported shallow-marine spicules. Most of the collected spicules from Gornje Vrapče are monaxone, or simple trienes, probably belonging to demosponges, but it is very hard to determine them in detail. Some of the collected amphitriane spicules, short-shafted dichotrienes can be well compared with Karpatian samples. Rich and well preserved spicules deserve further attention.

### ***Shallowing upward trend and environmental stress***

The Borovnjak locality is a good example of a stressed marginal marine environment, particularly in the middle part of the section, which is characterized by cyclic alteration of foraminiferal assemblages (Subcluster Ia and Subcluster Ib) and final establishment of *Ammonia–Elphidium* assemblage (Subcluster Ib) in the upper part of the column. The benthic foraminifera *Ammonia* and *Elphidium* frequently dominate recent foraminiferal assemblages in the lower reaches of estuaries, and in normal marine lagoons and bays (Leckie & Olson 2003). Compared to the previous *Elphidium–Asterigerinata–Ammonia* assemblage, decrease in abundance of stenohaline elphidiids and species *Asterigerinata planorbis*, and pronounced domination of the species *A. viennensis* (more than 30%) can indicate temporary fresh-water influence in the sedimentary basin and seasonal oscillation between normal and decreased salinity. The genus *Ammonia* is common in both, brackish (Amarossi et al. 2013; Reymond et al. 2013) and marine assemblages, as it can quickly adapt to variable salinity, oxygen and temperature oscillations (Donnici & Serandreo Barbero 2002). They are also common in deposits with highly variable organic component (TOC) and they can become facultative anaerobes (Murray 2006). Reduction in abundance of imperforate foraminifera and complete lack of *Borelis* in the upper part of the section supports the theory of fresh-water input. These foraminifera diminish in brackish lagoons and estuaries and completely vanish in brackish marshes (Murray 1991). A higher number of specimens, slightly higher amount of infaunal taxa and suboxic proxies (Table 2), and somewhat better preservation, indicate the environment with increased mud support. At the same time, the number of ostracods increases (average rate 9.7%) within the microfossil assemblage and brackish genus *Neocyprideis* (*Miocyprideis*) sp. appears (Brestenská and Jiříček 1978; Olteanu 1997). Common taxa are *Cytheridea pernata* and *Xestoleberis glabresans*. Some species within the genera *Cytheridea*, *Xestoleberis* and *Loxococoncha* can be well adapted to low-salinity habitats (Ruiz et al. 2000; Pipik 2007). We can presume that *Ammonia–Elphidium* assemblage reflects a phase of increased siliciclastic and nutrient input from land, which can be caused by local regression. On

the other hand, seasonal or periodical fresh-water influx could cause the oscillations of salinity in the habitat.

Almost regular exchange of three different types of laminae in the upper part of the profile from the laterally deeper and more sheltered environment at Gornje Vrapče also indicates temporary instabilities. Laminae differ in colour and are characterized by almost regular interchanges of benthic foraminiferal assemblages, carbonate content, and high-valent metal content. Evident increase of environmental stress can be recognized at the beginning of the upper part of the section (Type A lamina) with abruptly decreased diversity and number of specimens of benthic foraminifera, while amount of stress markers is doubled (Table 1, 2). The amount of oxygen in bottom waters decreases (BFOI=68.2) and the *Heterolepa–Bolivina* assemblage (Subcluster IIB) is typical for this lamina. Oxygen depletion in bottom waters generally influences the quantity and quality of available food for benthic foraminifera, and is usually followed by increase of organic particles within the substrate (Duijnsteet et al. 2004). At the Gornje Vrapče locality this leads to the diminishing of oxic and epifaunal taxa, while suboxic, disoxic and infaunal taxa flourish, additionally supported by ample food supply. Environmental needs of the abundant species *Heterolepa dutemplei* dominantly depend on the food supply, and this foraminifera preferably lives on organic-rich substrates (Debenay & Redois 1997). The opportunistic species *Bolivina dilatata* also positively responds to the increased input of fresh phytodetritus and is extremely tolerant to oxygen depleted environments (Bartels-Jonsdotir 2006; Diz & Francès 2008). A further trend of oxygen depletion in bottom waters (BFOI=55.9) can be observed in an argillaceous lamina (Type B) with *Bolivina–Cassidulina* assemblage (Subcluster IIC). Infaunal biota predominate, and suboxic, disoxic and stress proxies further increased in number. Compared to the previous *Heterolepa–Bolivina* assemblage, the number of species and diversity increase, while the dominance remains unchanged. Some opportunistic species (especially *Cassidulina laevigata* and *Bolivina dilatata*) very quickly adapted to the new conditions and increased their number of specimens more than 29 times, due to their rapid reproduction. The genus *Cassidulina* is well adapted to oxygen depletion (suboxic proxy) and abundance of the species *Cassidulina laevigata* is strongly dependent on high nutrient influx (De Stigter et al. 1999). Amount of high-valent metal (probably iron) is twice as high in this type of lamina than in types A and C, which points to the available source of metal (possible bacterial activity). The overlying siltite lamina (Type C) with *Elphidium–Asterigerinata* assemblage repeats environmental conditions from the basal part of the section and indicates reoxidization of bottom waters. Alteration of all three types of laminae and associated benthic foraminiferal assemblages occurs regularly up to the top of the laminated sequence. Similar values of domination in all three types of laminae point to abrupt changes of environmental conditions, and particular taxa did not have enough time to take the dominant role within the benthic assemblage.

Ostracods are very scarce in the laminated section of the Gornje Vrapče profile (average rate 1.3%). Slightly more abundant are the taxa *Cnestocythere lamellicostata*, *Aurila haueri*, *Hemicytherura* sp. and *Callistocythere canaliculata*. Like the Borovnjak locality, the analysed section at Gornje Vrapče fits into the generally proven regressive trend. In newly established nearshore environments the influence of sea level oscillations can be much better observed. In the same time periodical (seasonal) input of detritus and nutrients from land strongly influences the biota and mode of deposition. In most inner and middle shelf environments (enclosed systems), seasonal hypoxia (decrease in oxygen content in bottom water) during the summer season is very common (Jorissen 1999; Čosović et al. 2002). If bottom water oxygen concentration fluctuates on a shorter seasonal or interannual timescale, the composition of the benthic foraminiferal assemblage may be highly variable depending on the duration and intensity of successive oxygen minima and maxima, and reproductive rate of certain foraminiferal groups under the variable environmental conditions (Den Dulk et al. 2000). Although microfossil assemblages of Gornje Vrapče show similarities with seasonally controlled recent assemblages, direct comparisons are not fully possible. We must take into consideration taphonomic processes and known fact that fossil assemblage only partly reflects the composition of ancient biocoenosis. Nevertheless, the *Heterolepa–Bolivina* assemblage (Subcluster IIb) can be assigned to the period spring–early summer, with pronounced freshwater discharge, which influences the start of the spring phytoplankton bloom, and, consequently, oxygen depletion at sea-bottom. Opportunistic foraminiferal taxa increase in number responding to the newly available nutrients. The *Bolivina–Cassidulina* assemblage (Subcluster IIc) can be assigned to the summer–early autumn period. The summer phytoplankton bloom, increased temperature, high organic matter degradation and maximal stratification of the water-column cause the disoxic/anoxic conditions at the sea-bottom. The *Elphidium–Asterigerinata* assemblage (Subcluster IIa) reflects the late autumn–early spring period. Re-established vertical water circulation again supplies the bottom waters and benthic assemblage with oxygen.

#### ***End-Badenian regression and emersion***

Sedimentary features, deposition of massive biocalcrudites with visible coarsening-upwards in the upper part of the Borovnjak locality, undoubtedly indicate a regressive trend. These deposits, unfortunately, do not comprise microfossils and therefore we cannot reach any conclusions on eventually full freshwater conditions before the final emersion. During the emersion the Upper Badenian biocalcrudites were intensively weathered and karstified, producing a pronounced palaeorelief as the base for the Sarmatian transgression (Vrsaljko et al. 2006).

The End-Badenian regression is also evident in the upper part of the Gornje Vrapče section. The laminated portion of

the section is overlain by biolithites, and, finally, emersion occurs before the deposition of the Sarmatian clastic sedimentary rocks.

#### **Conclusions**

The Upper Badenian shallow marine sediments on the SW slopes of the Medvednica Mt. were transgressively deposited over the Mesozoic carbonate basement. The marginal marine highly oxygenated environment of normal salinity is represented by the pioneer *Elphidium–Asterigerinata–Ammonia* benthic foraminiferal assemblage, with low diversity and strong domination. The relatively rich and diverse *Elphidium–Asterigerinata* assemblage appears with an advanced transgression, visible in the Gornje Vrapče section. This assemblage is typical for high-oxygenated inner/middle shelf environments. Shallowing upward sequences with increase of siliciclastic and nutrient input in a depositional basin are present in the middle and upper part of the studied sections. In the marginal shoal area (Borovnjak locality) fluctuations in salinity appear, finishing with brackish conditions and an *Ammonia–Elphidium* assemblage. The deeper and more sheltered inner/middle shelf environment (locality Gornje Vrapče) bears evidence of environmental changes in lamination. Laminae differ in colour, calcium content and benthic foraminiferal assemblages. The dominant controlling factors in this part of the section were fluctuations in bottom oxygen content and changes in quantity and quality of food supply. In the *Heterolepa–Bolivina* assemblage opportunistic taxa increase in number responding to the newly available nutrients and oxygen depletion. The *Bolivina–Cassidulina* assemblage is typical for periods of minimal oxygen concentrations, while the *Elphidium–Asterigerinata* assemblage reflects the period of recovery of vertical water circulation and oxygenation of bottom waters. Similar almost regular changes and distribution of foraminiferal assemblages is known from modern seasonally controlled shelf environments. The uppermost part of both sections is represented by massive biocalcrudite or coralgal biolithite, and, finally, emersion between the Upper Badenian and the Sarmatian deposits. Ostracod assemblages generally comprise scarce taxa which are typical for shallow marine environments while in the middle and upper part of Borovnjak section, amount of ostracods increases within the microfossil assemblage. The occurrence of the brackish ostracod *Neocyprideis* (*Miocyprideis*) sp. indicates fresh water inflows into a marine environment.

**Acknowledgements:** Our thanks go to reviewers Katarina Holcova and Stjepan Čorić for critical suggestions that helped to improve the manuscript. Financial support for this study was provided by scientific project (119-1951293-1162) of the Croatian Ministry of Science, Education and Sports.

## References

- Amorosi A., Rossi V. & Vella C. 2013: Stepwise post-glacial transgression in the Rhône Delta area as revealed by high-resolution core data. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 374, 314–326.
- Avanić R., Brkić M., Miknić M., Šimunić A. & Pavelić D. 1995: Late Badenian and Sarmatian deposits of Gornja Kustošija locality. In: Šikić K. (Ed.): Medvednica Mt. Geological Field Guide. *Inst. geol. Istraž.*, Zagreb, 71–73 (in Croatian).
- Bakrač K., Hajek-Tadesse V., Miknić M., Grizelj A., Hećimović I. & Kovačić M. 2010: Evidence for Badenian local sea level changes in the proximal area of the North Croatian Basin. *Geol. Croatica* 63, 3, 259–269.
- Báldi K. 2006: Paleocyanography and climate of the Badenian (Middle Miocene, 16.4–13.0 Ma) in the Central Paratethys based on foraminifera and stable isotope ( $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$ ) evidence. *Int. J. Earth Sci.* 95, 119–142.
- Báldi K. & Hohenegger J. 2008: Paleocology of benthic foraminifera of the Baden–Sooss section (Badenian, Middle Miocene, Vienna Basin, Austria). *Geol. Carpath.* 59, 5, 411–424.
- Bartels-Jónsdóttir H.B., Knudsen K.L., Abrantes F., Lebreiro S. & Eiriksson J. 2006: Climate variability during the last 2000 years in the Targus Prodelta, western Iberian Margin: Benthic foraminifera and stable isotopes. *Mar. Micropaleontol.* 59, 83–103.
- Bartol M. 2009: Middle Miocene calcareous nannoplankton of NE Slovenia (western Central Paratethys). *Založba ZRC, Ljubljana*, 1–136.
- Bartol M., Mikuž V. & Horvat A. 2014: Palaeontological evidence of communication between the Central Paratethys and the Mediterranean in the Late Badenian/Early Serravallian. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 394, 144–157.
- Brestenská E. & Jiříček R. 1978: Badenian ostracoda of the Central Paratethys. In: Papp A., Cicha I., Seneš J. & Steininger F. (Eds.): Chronostratigraphie und Neostatotypen Miozän der Zentralen Paratethys. Badenian. *Verlag der Slowak. Akad. der Wissen.*, Bratislava, 405–439.
- Cicha I., Rögl F., Rupp C. & Čtyroká J. 1998: Oligocene–Miocene foraminifera of the Central Paratethys. *Abh. Senckenberg. Naturforsch. Gessell.* 549, 1–325.
- Crihan I.M. & Mărunțeanu M. 2006: The Badenian–Sarmatian transition in the Melicesti Synclyne (Subcarpathians of Muntenia, Romania). In: Sudar M., Ercegovac M. & Grubić A. (Eds.): Proceeding of the XVIIIth Congress of the Carpathian–Balkans Geological Association, Special Volume, September 3–9. *Serbian Geol. Soc.*, Belgrade, 83–86.
- Čorić S., Pavelić D., Rögl F., Mandić O., Vrabac S., Avanić R., Jerković L. & Vranjković A. 2009: Revised Middle Miocene datum for initial marine flooding of North Croatian Basins (Pannonian Basin System, Central Paratethys). *Geol. Croatica* 62, 1, 31–43.
- Ćosović V., Juračić M., Bajraktarević Z. & Vaniček V. 2002: Benthic foraminifera of the Mljet Lakes (Croatia)-potential for (paleo)environmental interpretation. *Mem. Soc. Geol. It.* 57, 533–541.
- Danielopol D.L., Ito E., Wansard G., Kanya T., Cronin T.M. & Baltanas A. 2002: Techniques for collection and study of Ostracoda. In: Holmes J.A. & Chivas A.R. (Eds.): Ostracoda. Applications in Quaternary research. The Geophysical Monograph 131. *American Geoph. Union*, Washington, DC, 65–98.
- De S. & Gupta A.K. 2010: Deep-sea faunal provinces and their inferred environments in the Indian Ocean based on distribution of recent benthic foraminifera. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 291, 3–4, 429–442.
- De Stigter H.C., Van der Zwaan G.J. & Langone L. 1999: Differential rates of benthic foraminiferal test production in the surface and subsurface sediment habitats in the southern Adriatic Sea. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 149, 67–88.
- Debenay J. P. & Redois F. 1997: Distribution of the twenty seven dominant species of shelf benthic foraminifera on the continental shelf, north of Dakar (Senegal). *Mar. Micropaleontol.* 29, 3, 237–255.
- Debenay J. P., Della Patrona L. & Goguenheim H. 2009: Colonization of coastal environments by foraminifera: insight from shrimp ponds in New Caledonia (SW Pacific). *J. Foram. Res.* 39, 4, 249–266.
- Den Dulk M., Reichart G.J., Van Heyst S., Zahariasse W.J. & Van der Zwaan G.J. 2000: Benthic foraminifera as proxies of organic matter flux and bottom water oxygenation? A case history from the northern Arabian sea. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 161, 337–359.
- Diz P. & Francés G. 2008: Distribution of live benthic foraminifera in the Ría de Vigo (NW Spain). *Mar. Micropaleontol.* 66, 3, 165–191.
- Donnici S. & Serandreo Barbero R. S. 2002: The benthic foraminiferal communities of the northern Adriatic continental shelf. *Mar. Micropaleontol.* 44, 93–123.
- Duijnste I.A.P., De Lugt I., Vonk Noordegraaf H. & Van der Zwaan B. 2004: Temporal variability of foraminiferal densities in the northern Adriatic Sea. *Mar. Micropaleontol.* 50, 125–148.
- Gedl P. & Peryt D. 2011: Dinoflagellate cyst, palynofacies and foraminiferal records of environmental changes related to the Late Badenian (Middle Miocene) transgression at Kudryntsi (western Ukraine). *Ann. Soc. Geol. Pol.* 81, 331–349.
- Gorjanović-Kramberger D. 1882: The Lower Tertiary fish fauna from Croatia. Part I. *Beitrag. Pal. Österr. Ungar. Or.* 2, 1–26 (in German).
- Górka M., Studencka B., Jasionowski M., Hara U., Wysocka A. & Poberezhskyy A. 2012: The Medobory Hills (Ukraine). Middle Miocene reef systems in the Paratethys: Their biological diversity and lithofacies. *Biul. Państw. Inst. Geol.* 449, 147–174.
- Gross M. 2006: Mittelmiozäne Ostracoden aus dem Wiener Becken (Badenium/Sarmatium, Österreich). *Verlag der Österr. Akad. der Wissen.*, Wien, 1–224.
- Grunert P., Soliman A., Čorić S., Roetzel R., Harzhauser M. & Piller W.E. 2012: Facies development along the tide-influenced shelf of the Burdigalian Seaway: An example from the Ottnangian stratotype (Early Miocene, middle Burdigalian). *Mar. Micropaleontol.* 84, 85, 14–36.
- Hajek-Tadesse V. & Prtoljan B. 2011: Badenian Ostracoda from the Pokupsko area (Banovina, Croatia). *Geol. Carpath.* 62, 5, 447–461.
- Hammer O., Harper D.A.T. & Ryan P.D. 2001: PAST: paleontological statistics software package for education and data analysis. *Paleont. Electronica* 4, 1, 1–9.
- Harzhauser M. & Piller W.E. 2007: Benchmark data of a changing sea — palaeogeography, palaeobiogeography and events in the Central Paratethys during the Miocene. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 253, 8–31.
- Hilgen F.J., Abels H.A., Iaccarino S., Krijgsman W., Raffi I., Sprovieri R., Turco E. & Zachariasse W.J. 2009: The Global Stratotype Section and Point (GSSP) of the Serravallian Stage (Middle Miocene). *Episodes* 32, 3, 152–166.
- Hohenegger J. 2005: Estimation of environmental paleogradient values based on presence/absence data: a case study using benthic foraminifera for paleodepth estimation. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 217, 115–130.
- Hohenegger J., Čorić S. & Wagreich M., 2014: Timing of the Middle Miocene Badenian Stage of the Central Paratethys. *Geol.*

- Carpath.* 65, 1, 55–66.
- Holcová K. 1999: Postmortem transport and resedimentation of foraminiferal tests: relations to cyclical changes of foraminiferal assemblages. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 145, 1–3, 157–182.
- Holcová K. & Zágorský K. 2008: Bryozoa, foraminifera and calcareous nannoplankton as environmental proxies of the “bryozoan event” in the Middle Miocene of the Central Paratethys (Czech Republic). *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 267, 216–234.
- Holcová K., Hrabovský J., Nehyba S., Hladilová Š., Doláková N. & Demény A. 2015: The Langhian (Middle Badenian) carbonate production event in the Moravian part of the Carpathian Foredeep (Central Paratethys): a multiproxy record. *Facies* 61, 1, 1–26.
- Hyžný M., Hudáčková N., Biskupič R., Rybár S., Fuksi T., Halásová E. & Ledvák P. 2012: Devínska Kobyla — a window into the Middle Miocene shallow-water marine environments of the Central Paratethys (Vienna Basin, Slovakia). *Acta Geol. Slovaca* 4, 2, 95–111.
- Jiríček R. 1983: Redefinition of the Oligocene and Neogene ostracod zonation of the Paratethys. *Knihov. Zem. Plyn Nafta* 4, 195–236.
- Jorissen F.J. 1999: Benthic foraminiferal successions across Late Quaternary Mediterranean sapropels. *Mar. Geol.* 153, 91–101.
- Kaiho K. 1994: Benthic foraminiferal dissolved-oxygen index and dissolved-oxygen levels in the modern ocean. *Geology* 22, 719–722.
- Kaiho K. 1999: Effect of organic carbon flux and dissolved oxygen on the benthic foraminiferal oxygen index (BFOI). *Mar. Micropaleontol.* 37, 67–76.
- Kochansky V. 1944: Miocene marine fauna of the south part of Medvednica Mt. (Zagrebačka gora Mt.). *Vjest. Hrv. Drž. Geol. Zav. Hrv. Drž. Geol. Muž.* 2–3, 171–280 (in Croatian).
- Kováč M., Andreyeva-Grigorovich A., Bajraktarević Z., Brzobohatý R., Filipescu S., Fodor L., Harzhauser M., Nagymarosy A., Oszczytko N., Pavelić D., Rögl F., Saftić B., Sliva L. & Studencka B. 2007: Badenian evolution of the Central Paratethys Sea: paleogeography, climate and eustatic sea-level changes. *Geol. Carpath.* 58, 6, 579–606.
- Leckie R.M. & Olson H.C. 2003: Foraminifera as proxies of sea-level change on siliciclastic margins. In: Olson H.C. & Leckie R.M. (Eds.): *Micropaleontologic Proxies of Sea-Level Change and Stratigraphic Discontinuities. Special Publication 75. Society for Sedimentary Geology*, Tulsa, 5–19.
- Loeblich A.R. & Tappan H. 1987a: Foraminiferal genera and their classification. *Van Nostrand Reinhold*, New York, 1–970.
- Loeblich A.R. & Tappan H. 1987b: Foraminiferal genera and their classification. Plates. *Van Nostrand Reinhold*, New York, 1–1059.
- Lourens L., Hilgen F., Shackleton N.J., Laskar J. & Wilson D. 2004: The Neogene Period. In: Gradstein F.M., Ogg J.G. & Smith A.G. (Eds.): *A Geologic Time Scale 2004. Cambridge University Press*, Cambridge, 409–440.
- Lukowiak M., Pisera A. & Schlögl J. 2014: Bathyal sponges from the Late Early Miocene of the Vienna Basin (central Paratethys, Slovakia). *Paläont. Z.* 88, 3, 263–277.
- Mihajlović Đ. & Knežević S. 1989: Calcareous nannoplankton from Badenian and Sarmatian deposits at Višnjica and Karaburma in Belgrade. *Geol. An. Balk. Poluos.* 53, 343–366.
- Moissette P., Dulai A., Escarguel G., Kázmér M., Müller P. & Saint Martin J.P. 2007: Mosaic of environments recorded by bryozoan faunas from the Middle Miocene of Hungary. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 252, 3, 530–556.
- Murray J.W. 1991: Ecology and paleoecology of benthic foraminifera. *Longmann Scientific and Technical*, Harlow, Essex, 1–397.
- Murray J.W. 2006: Ecology and applications of benthic foraminifera. *Cambridge University Press*, Cambridge, 1–438.
- Nascimento A. & Riha J. 1996: Ostracod species common to the Neogene of Portugal and Central Paratethys. In: Keen M.C. (Ed.): *Proceedings of the 2<sup>nd</sup> European Ostracodologists Meeting*, Glasgow. *Brit. Micropal. Soc.*, London, 107–112.
- Nehyba S., Holcová K., Gedl P. & Doláková N. 2016: The Lower Badenian transgressive-regressive cycles — a case study from Oslavany (Carpathian Foredeep, Czech Republic). *Neu Jb. Geol. Paläont. Abh.* 279, 2, 209–238.
- Olteanu R. 1997: The hinge changes within Cytherideinae group taxonomic and systematic significances. *Acta Pal. Rom.*, 1, 211–217.
- Papp A. & Schmid M.E. 1985: The fossil foraminifera of the Tertiary basin of Vienna. (Die fossilen foraminiferen des Tertiären Bekens von Wien). *Abh. Geol. Bundesanst.* 37, 1–311.
- Papp A., Cicha I. & Čtyroká J. 1978: Foraminifera. In: Papp A., Cicha I., Seneš J. & Steininger F. (Eds.): *Chronostratigraphie und Neostatotypen im Miozän der Zentralen Paratethys. Badenian. Verlag der Slowak. Akad. der Wissen.*, Bratislava, 263–325.
- Parker J.H., Gischler E. & Eisenhauer A. 2012: Biodiversity of foraminifera from Late Pleistocene to Holocene coral reefs, South Sinai, Egypt. *Mar. Micropaleontol.* 86, 59–75.
- Pavelić D. 2001: Tectonostratigraphic model for the North Croatian and North Bosnian sector of the Miocene Pannonian Basin System. *Basin Res.* 13, 359–376.
- Pérez-Asensio J.N., Aguirre J., Schmiedl G. & Civis J. 2012: Mesinian paleoenvironmental evolution in the lower Guadalquivir Basin (SW Spain) based on benthic foraminifera. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 326, 135–151.
- Pezelj Đ. & Sremac J. 2007: Badenian Marginal Marine environment in the Medvednica Mt. (Croatia). *Joannea Geol. Paläontol.* 9, 83–84.
- Pezelj Đ., Sremac J. & Sokač A. 2007: Palaeoecology of the Late Badenian foraminifera and ostracoda from the SW Central Paratethys (Medvednica Mt., Croatia). *Geol. Croatica* 60, 2, 139–150.
- Pezelj Đ., Mandić O. & Čorić S. 2013: Paleoenvironmental dynamics in the southern Pannonian basin during initial middle Miocene marine flooding. *Geol. Carpath.* 64, 1, 81–100.
- Pezelj Đ., Sremac J. & Bermanec V. 2014: Middle Miocene benthic foraminiferal communities and their response to shallowing-upward trends — example from Croatia. In: Marchant M. & Hromic T. (Eds.): *Abstract Volume, International Symposium on Foraminifera FORAMS 2014, Chile. Grzybow. Found. Spec. Publ.* 20, 115–116.
- Pipík R. 2007: Phylogeny, palaeoecology, and invasion of non-marine waters by the Late Miocene hemicytherid ostracod *Tyrrhenocythere* from Lake Pannon. *Acta Palaeontol. Pol.* 52, 2, 351–368.
- Pippèr M. 2011: Characterisation of Ottangian (middle Burdigalian) palaeoenvironments in the North Alpine Foreland Basin using benthic foraminifera — a review of the Late Marine Molasse of southern Germany. *Mar. Micropaleontol.* 79, 3, 80–99.
- Pippèr M. & Reichenbacher B. 2010: Foraminifera from the borehole Altdorf (SE Germany): Proxies for Ottangian (early Miocene) palaeoenvironments of the Central Paratethys. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 289, 1–4, 62–80.
- Pisera A. 1996: Miocene reefs of the Paratethys: a review. *SEPM Concepts Sedimentol. Paleontol.* 5, 97–104.
- Pisera A. & Hladilová S. 2003: Siliceous sponge spicules from the Karpatian of the Carpathian Foredeep in Moravia. In: Brzobohatý R., Cicha I., Kováč M. & Rögl F. (Eds.): *The Karpatian, a Lower Miocene stage of the Central Paratethys. Masaryk*



- University, Brno, 189–192.
- Radičević D., Rundić L. & Knežević S. 2010: Geology of the Čoka structure in northern Banat (central Paratethys, Serbia). *Geol. Carpath.* 61, 4, 341–352.
- Reuter M., Piller W.E. & Erhart C. 2012: A Middle Miocene carbonate platform under silici-volcaniclastic sedimentation stress (Leitha Limestone, Styrian Basin, Austria) — depositional environments, sedimentary evolution and palaeoecology. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 350, 198–211.
- Reymond C. E., Roff G., Chivas A. R., Zhao J. X. & Pandolfi J.M. 2013: Millennium-scale records of benthic foraminiferal communities from the central Great Barrier Reef reveal spatial differences and temporal consistency. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 374, 52–61.
- Rižnar I., Miletić D., Verbič T. & Horvat A. 2002: Middle Miocene sediments on the northern part of Gorjanci between Čatež and Kostanjevica (SE Slovenia). *Geologija* 45, 531–536.
- Rögl F. 1999. Mediterranean and Paratethys. Facts and hypotheses of an Oligocene to Miocene paleogeography (short overview). *Geol. Carpath.* 50, 4, 339–349.
- Ruiz F., Gonzales-Regalado M.L., Baceta J.I. & Munoz J.M. 2000: Comparative ecological analysis of the ostracod faunas from low and high polluted southwestern Spanish estuaries: a multivariate approach. *Mar. Micropaleontol.* 40, 345–376.
- Selmeczi I., Lantos M., Bohn-Havas M., Nagymarosy A. & Szegő É. 2012: Correlation of bio- and magnetostratigraphy of Badenian sequences from western and northern Hungary. *Geol. Carpath.* 63, 4, 219–232.
- Śliwiński M., Bąbel M., Nejbert K., Olszewska-Nejbert D., Gąsiewicz A., Schreiber B.C., Benowitz J.A. & Layer P. 2012: Badenian–Sarmatian chronostratigraphy in the Polish Carpathian Foredeep. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 326, 12–29.
- Smith A.J. & Horne D.J. 2002: Ecology of marine, marginal marine and nonmarine ostracodae. In: Holmes J.A. & Chivas A.R. (Eds.): Ostracoda. Applications in Quaternary research. The Geophysical Monograph 131. *American Geoph. Union*, Washington, DC, 37–64.
- Sopková B., Škulová A., Hlavatá J. & Kováč M. 2007: Sequence stratigraphy of the Late Badenian & Sarmatian (Serravallian) of the eastern part of the Vienna Basin — deltaic to tidal flats environments. *Joannea Geol. Paläontol.* 9, 101–103.
- Strauss P., Harzhauser M., Hinsch R. & Wägreich 2006: Sequence stratigraphy in a classic pull-apart basin (Neogene, Vienna Basin). A 3D seismic based integrated approach. *Geol. Carpath.* 57, 185–197.
- Šikić L. 1967: Tortonian and Sarmatian foraminifera from southwest part of the Medvednica Mt. *Geol. vjesnik* 20, 127–135 (in Croatian).
- Šikić K. 1995: Geological composition of the Medvednica Mt. In: Šikić K. (Ed.): Medvednica Mt. Geological Field Guide. *Inst. geol. Istraž.*, Zagreb, 7–30 (in Croatian).
- Triantaphyllou M.V., Kouli K., Tsourou T., Koukousioura O., Pavlopoulos K. & Dermizakis M.D. 2010: Paleoenvironmental changes since 3000 BC in the coastal marsh of Vravron (Attica, SE Greece). *Quat. Int.* 216, 14–22.
- Van Hinsbergen D.J.J., Kouwenhoven T.J. & Van der Zwaan G.J. 2005: Paleobathymetry in the backstripping procedure: Correction for oxygenation effects on depth estimates. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 221, 245–265.
- Van Der Zwaan G.J., Jorissen F.J. & De Stigter H.C. 1990: The depth dependency of planktonic/benthic foraminiferal ratios: constrains and applications. *Mar. Geol.* 95, 1–16.
- Van der Zwaan G.J., Dujinstee I.A.P., Den Dulk M., Ernst S.R., Janink N.T. & Kouwenhoven T.J. 1999: Benthic foraminifera: proxies or problems? A review of paleoecological concepts. *Earth Sci. Rev.* 46, 213–236.
- Vrsaljko D., Šikić K., Pikija M., Glovacki Jernej Ž. & Miknić M. 1995: Miocene deposits from locality Gornje Vrapče. In: Šikić K. (Ed.): Medvednica Mt. Geological Field Guide. *Inst. geol. Istraž.*, Zagreb, 61–66 (in Croatian).
- Vrsaljko D., Pavelić D., Miknić M., Brkić M., Kovačić M., Hećimović I., Hajek-Tadesse V., Avanić R. & Kurtanjek N. 2006: Middle Miocene (Late Badenian/Sarmatian) palaeoecology and evolution of the environments in the area of Medvednica Mt. (North Croatia). *Geol. Croatica* 59, 1, 51–63.