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Foraminifera-based estimation of water depth in epicontinental seas: Badenian deposits from Glavnica Gornja (Medvednica Mt., Croatia), Central Paratethys

Đurđica Pezelj* and Lucija Drobnjak

University of Zagreb, Faculty of Science, Department of Geology, Division of Geology and Paleontology, Horvatovac 102a, 10000 Zagreb, Croatia;
(*corresponding author: djurdjica.pezelj@geol.pmf.hr)

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Abstract

This study presents the first attempt to estimate the palaeo-depth, and to assess the environmental conditions at the sea bottom, by means of foraminifers during the deposition of earlier Badenian deposits in the North Croatian Basin. The studied stratigraphic record, the Glavnica Gornja section is located in Mt. Medvednica, in the southwestern part of the Pannonian Basin System, and it belongs to the Upper Lagenidae Zone (Moravian substage of the Badenian). Three methods were tested to estimate the palaeo-depth; the plankton/benthos (P/B) ratio indicated the lower to upper bathyal zone, the modified P/B ratio indicated 886-987 m depth for the bathyal zone, whereas the Hohenegger method indicated 142-204 m depth for the outer shelf. Of the three estimates, the last is considered as best fitting the general environmental demands of the dominant and common small benthic forams. The well oxygenated sea bottom was temporarily replaced by more stressful conditions in the middle part of the studied interval, pointing to occasional variations in the organic flux.

1. INTRODUCTION

Paratethys, an intracontinental sea, covered a vast proportion of present-day Europe and Asia during the Miocene (RÖGL, 1998, 1999; KOVÁČ et al., 2017). The North Croatian Basin (including Medvednica Mt.; Fig. 1), as part of the Pannonian Basin System, was located in the southwestern part of the Central Paratethys (PAVELIĆ, 2001, 2005; PAVELIĆ & KOVAČIĆ, 2018). This area had a complex geological history, because connections to the Mediterranean Sea or Neotethys and to the Eastern Paratethys realm were interrupted several times provoking changes in the sedimentary settings. The middle Miocene marine transgressive phases, especially the Badenian (Langhian, Lower Serravallian) ones, could be easily traced in sediments due to their diverse and abundant fossil content (foraminifera in particular; KOVÁČ et al., 2007; PILLER et al., 2007). The chronostratigraphic interpretation of the Badenian stage is the subject of many debates, with numerous controversies and disagreements. Differences include two- or three-part biostratigraphic subdivision of the stage and correlation with sedimentary cycles (KOVÁČ et al., 2007, 2018; RÖGL, 1998; PILLER et al., 2007; HOHENEGGER et al., 2014; SANT et al., 2017). In the North Croatian Basin, a "layer cake" stratigraphic model was adopted and the classical small benthic foraminifera (SBF) ecozones were applied (Fig. 2): Lower and Upper Lagenidae (Moravian), *Spirorutilus* (Wielician) and *Bulimina-Bolivina* / *Ammonia beccarii* (Kosovian) Zones (GRILL, 1943; PAPP & TURNOWSKY, 1953; PAPP et al., 1978; HARZHAUSER & PILLER, 2007). These ecozones mainly represent

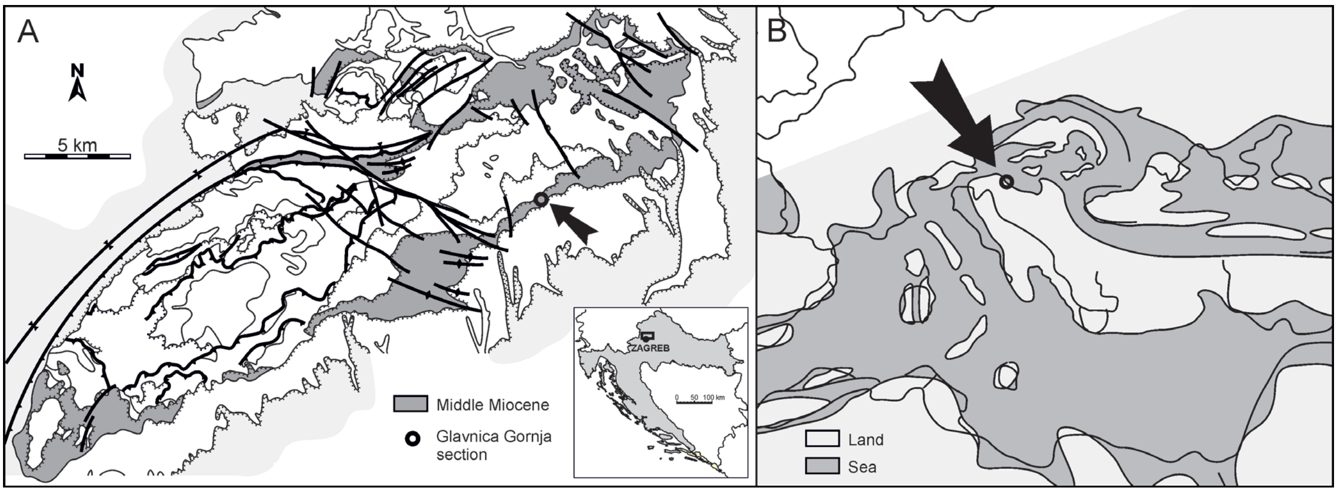

Figure 1. A. Sampling locality - Glavnica Gornja, Medvednica Mt. (ŠIKIĆ, 1995 – modified). B. Location of Medvednica Mt. within the Central Parathetys during the early Badenian (RÖGL, 1999-modified).

the lateral shift of the sedimentary facies (ecological habitats, KOVÁČ et al., 2018).

The aim of this study is to contribute to the knowledge of environmental conditions during the Badenian (Lagenidae Biochron) in the Central Paratethys, and to describe the abundance, diversity, composition, and vertical distribution of benthic foraminiferal assemblages across different productivity phases. In this paper, special attention is paid to estimation of water depth of the depositional environment. Three independent methods were used in order to decide which provides the most realistic estimate. The discrepancies in estimated palaeo-depths obtained using P/B ratio (MURRAY, 1991) or modified P/B ratio (VAN DER ZWAAN et al., 1990, 1999) method/s and the transfer functional method – Hohenegger method – based on known depth ranges of identified benthic foraminifera (HOHENEGGER, 2005) are known for middle Miocene deposits of the Central Paratethys (SPEZZAFERRI et al., 2002; HOHENEGGER, 2005; BÁLDI & HOHENEGGER, 2008) and lower Miocene Karpatian (SCHLÖGL et al. 2011). Until now, only a few papers dealing with quantified data of Badenian SBF from the North Croatian Basin have been available, and those are mostly focused on the Upper Badenian (PEZELJ, 2006, 2007, 2013, 2017, 2018). At the Glavnica Gornja locality, analysis of the abundance and diversity of SBF assemblages from the Upper Lagenidae Zone along with foraminiferal life-habitats preferences resulted in the reconstruction of sub-environments. Thus, our present study, except for some preliminary research (PEZELJ, 2015; KOVAČIĆ et al., 2015), presents the first attempt to estimate the palaeo-depths based on quantified data and to describe the sea bottom conditions during the deposition of earlier Badenian deposits in the North Croatian basin.

2. GEOLOGICAL SETTING AND DESCRIPTION OF THE STUDIED SECTION

Medvednica Mt. is a 40 km long, southwest to the northeast trending „island mountain“ in the North Croatian Basin in northwestern Croatia (Fig. 1.A). The Palaeozoic, Mesozoic, and Palaeogene rocks of the mountain are surrounded by Neogene and Quaternary sediments (ŠIKIĆ K., 1995; TOMLJENOVIĆ, 2008). Two concepts are known regarding the date of the initial Miocene transgression in the North Croatian Basin. The older view holds that it occurred during the Karpatian (corresponding to the TB 2.2, 3rd order sequence) because Ottnangian freshwater deposits directly overlie Palaeozoic rocks and are overlain by Karpatian marine sediments (ŠIKIĆ et al., 1979; BASCH, 1983; ŠIKIĆ, 1995: HAJEK-TADESSE, 2009). This view is supported by some recent planktonic foraminiferal data that confirm the Karpatian age of the oldest Miocene marine sediments (PREMEC-FUČEK et al., 2017; HERNITZ KUČENJAK et al., 2018). According to the second concept (ĆORIĆ et al., 2009; PAVELIĆ & KOVAČIĆ, 2018; MARTINUŠ et al., 2013; BRLEK et al., 2016, 2018) however, the beginning of initial marine transgression coincided with the early middle Badenian (corresponding to the TB 2.4, 3 rd order sequence), as proved by dating of the Čučerje tuffs (14.8 Ma; MARKOVIĆ, 2017). In this scenario, the continental phase lasted from the Ottnangian to the early Badenian, and in the early Badenian the North Croatian Basin was characterized by long-lived fresh-water lacustrine deposition (Fig. 2). In either case, during the initial marine transgression the entire area of Medvednica Mt. was flooded and only the highest peak was emerged (an island surrounded by the sea). Today, the middle Miocene (Badenian and overlying Sarmatian), which forms a more or less continuous sedimentary belt around the mountain core (Fig. 1A),

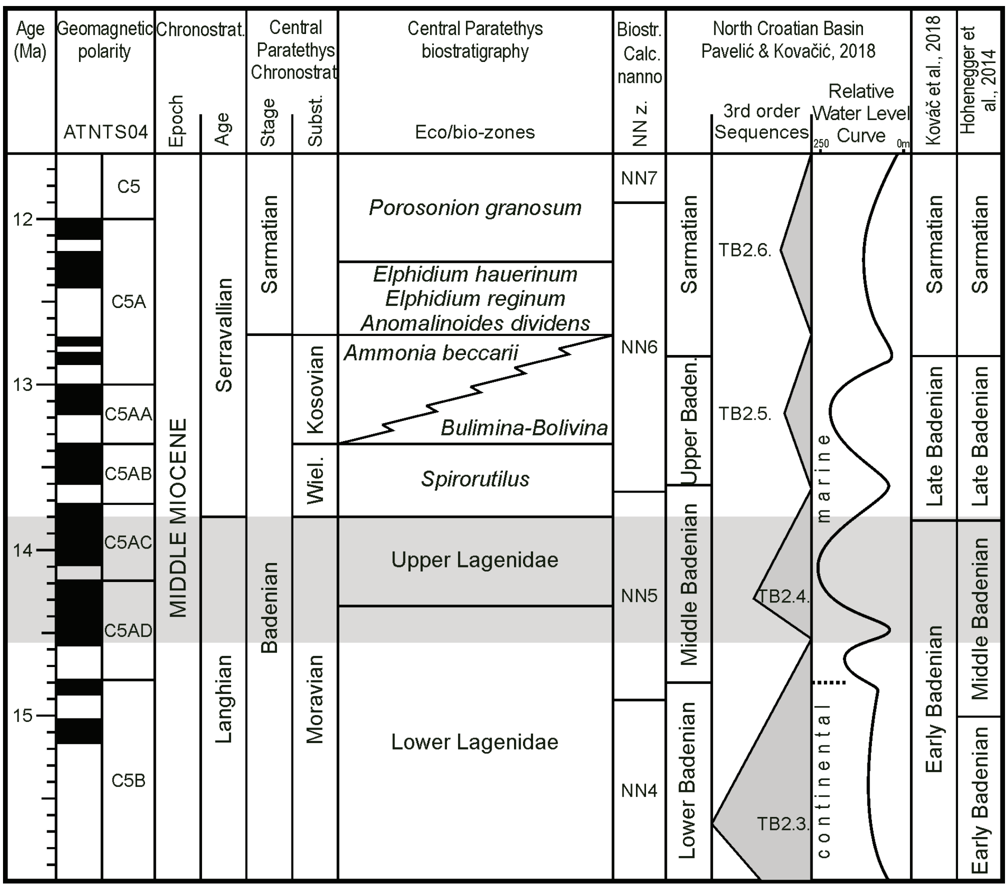

Figure 2. Middle Miocene local/regional small benthic foraminifera ecozones correlated to the regional and standard stages (modified after PEZELJ et al., 2013).

is characterized by recognizable transgressive contact, abundance of fossils and great facies diversity due to sea-level oscillations (BASCH, 1983; ŠIKIĆ, 1995). The beginning of the late Badenian coincided with a widespread transgression over older rocks, including the pre-Neogene basement, while the Badenian-Sarmatian boundary coincided with partial isolation of the Paratethys Sea, causing a decrease in salinity and changes in the palaeoenvironment from marine-brackish to brackish (HARZHAUSER & PILLER, 2007; PAVELIĆ & KOVAČIĆ, 2018).

The Gornja Glavica section is located on the southeast slopes of the central part of Medvednica Mt. (Fig. 1A), and belongs to the so-called „Čučerje deposits" ("Čučerje development" after KOCHANSKY, 1944; KOCHANSKY-DEVIDÉ, 1957). These deposits were considered the oldest and deepest marine sediments of the Badenian stratigraphic record in Medvednica Mt. (AVANIĆ, 1997, ĆORIĆ et al., 2009, BOŠNJAK et al., 2017). The sedimentary record at Glavnica Gornja (Lat: 45° 56′ 21″ Lon: 16° 08′ 23.943″) outcrops along the narrow macadam road leading from Glavnica Donja village to Glavnica Gornja village, with a total thickness of 26 m (Fig. 3). Massive grayish to green marls with scarce fragments of bivalves and echinoids dominate the lower and upper parts of the section. In the central part, structureless massive marls and clay marls are present. Occasionally, up to 1 m thick marl layers occur. Six samples were taken from the section G1 to G6), from places where lithological changes were observed.

3. METHODS

Sediment samples (about 300g each) were soaked in diluted H_2O_2 for a few hours, and then washed through a sieve system of 0.063, 0.125, 0.25 and 0.5 mm size. The selected fraction for this study was > 0.063 mm. The dried material was repeatedly split with the Reich microsplitter until a standard sample of about 300 foraminiferal tests was obtained. After determining the P/B ratio, each sample was split again in order to obtain approximately 300 benthic foraminiferal tests for further quantitative and qualitative analysis.

Taxonomic identification of foraminifera is in accordance with PAPP et al. (1978), AGIP (1982), PAPP & SCHMID (1985), LOEBLICH & TAPPAN (1988 a,b), CIMERMAN & LANGER (1991), CICHA et al. (1998), and BÁLDI (1999). Determination was corrected according to the up-to-date WORMS database (World Register of Marine Species, 2019) to exclude invalid names and synonyms. The ecological/palaeoecological preference of each benthic species was taken from MURRAY (1991, 2006), BÁLDI (2006); PEZELJ et al. (2013, 2016, including all references therein), and others referred to later in the text.

Species richness, dominant and common species were determined in each sample according to MURRAY (1991). Four diversity indices were computed using the PAST (Palaeontology Statistic) program (HAMMER et al., 2001): Fisher α index, Shannon-Wiener index, Dominance, and Equitability. Prior to all analyses and statistical data processing, the benthic foraminiferal assemblages were thoroughly studied to determine their autochtonity (autochtonous vs. allochtonous foraminiferal tests) and the degree of taphonomic alterations on the tests. Taphonomic analysis of foraminiferal assemblages was completed using the concept of HOLCOVÁ (1999). For this purpose, size sorting of tests, degree of test fragmentation, abrasion and corrosion were recorded. This procedure also included the recording of stratigraphic ranges and palaeoecological requirements for the identified species.

Three different methods were used to calculate the palaeodepth: the plankton/benthos ratio, the modified plankton/benthos ratio, and the Hohenegger method.

The plankton/benthos (P/B) ratio. With the increased distance from the coast, the turbidity decreases, which enables the primary production to increase and consequently leads to an increased amount of the planktonic foraminifera in the system. P/B ratio is expressed as a percentage of planktonic foraminifera in the total foraminiferal community (MURRAY, 1991).

The modified plankton/benthos (P/B) ratio (VAN DER ZWAAN et al., 1990, 1999) is based on the fact that the availability of nutrients at the seafloor usually depends on the water depth. Deep infaunal species are excluded from the analysis because they are not directly dependent on the influx of organic matter and food on the sea floor. Based on recent research in stressful environments, VAN HINSBERGEN et al. (2005) modified the original VAN DER ZWAAN et al. (1999) formula so that the following taxa are excluded: *Bolivina* (except *B. plicatella*, *B. pseudoplicata*); *Bulimina* without ribs, *Uvigerina* spp. (except *U. semiornata*), *Rectuvigerina*, *Valvulineria*, *Cancris*, *Fursenkoina*, *Stainfortia*, *Globobulimina*, and *Chilostomella*.

The Hohenegger method. HOHENEGGER (2005) and BÁLDI & HOHENEGGER (2008) followed a two-step procedure for estimating palaeo-depth based on the presence/absence of species: (a) information about the distributions of recent species along the depth, and (b) a transfer equation.

The bottom water oxygen content was estimated using the BFOI developed by KAIHO (1994, 1999). The palaeo productivity was assessed using infaunal/epifaunal ratio.

Cluster Analysis (Ward's method) and Non-metric Multidimensional Scaling (Euclidean distance dissimilarity measure) were used for the representation of relationships between samples and species. They were undertaken using the PAST (PAlaeontology STatiatic) program (HAMMER et al., 2001), and applied to all identified species of benthic foraminifera.

Foraminiferal samples are stored at the University of Zagreb, Faculty of Science, Department of Geology, Division of Geology and Paleontology.

4. RESULTS

The recovered microfossil assemblages are dominated by foraminifera, while rare ostracod shells and sponge spicules are present, too. Foraminiferal assemblages are characterized by well-preserved tests, considerable species diversity, and abundance of particular species. Planktonic foraminiferal tests dominate in all studied samples, comprising more than 85% of the foraminiferal assemblages. The benthic foraminifera are in-situ, their tests are pristine, without corrosion, scraping marks or sorting by test size. Altogether, 44 benthic species were identified (Table 1): two species belong to sub-order Textulariina, one species to the sub-order Milioliina, 19 species are affiliated to the sub-order Lageniina, and 22 species belong to the Rotaliina.

Species richness ranges from 24 to 30 per sample (Fig. 3). Samples from the central part of the section (samples G3 and G4) show slightly lower values. Toward the central part of the section, values of Fisher α index (6.20 - 8.38), as well as the Shannon-Wiener index (2.50 - 2.93), decrease, and the same trend is observed with the Equitability (0.76 - 0.87) values. In contrast, Dominance (0.07 - 0.14) reaches the highest values in the samples from the middle of the section (Fig. 3).

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Table 1. List of identified species of benthic foraminifera, their abundance in samples and ecological/palaeoecological interpretation (O-oxic, S-suboxic, D-disoxic; E-epifauna. SI-shallow infauna, I-infauna).

SPECIES / SAMPLE	G1	G2	G3	G4	G5	G6	
Amphicoryna badenensis (D´ORBIGNY)	0	4	0	0	0	1	S/I
Amphicoryna hispida (D´ORBIGNY)	1	0	0	0	0	1	S/I
Anomalinoides sp.	10	4	11	12	9	7	O/E
Bolivina antiqua D´ORBIGNY	0	0	0	2	0	0	D/I
Bolivina dilatata REUSS	41	31	93	81	42	32	D/I
Bolivina viennensis MARKS	26	18	35	54	30	41	D/I
Bulimina elongata D´ORBIGNY	0	3	0	10	5	3	D/I
Bulimina striata D´ORBIGNY	2	12	3	0	10	9	D/I
Cassidulina laevigata D´ORBIGNY	0	3	7	0	9	12	S/I
Caveastomella adolphina (D´ORBIGNY)	9	5	6	7	1	0	S/I
Ceratocancris hauerii (D´ORBIGNY)	10	11	0	0	0	0	S/I
Cibicidoides austriacus (D´ORBIGNY)	21	32	16	14	31	28	O/E-SI
Cibicidoides ungerianus (D´ORBIGNY)	52	43	35	21	45	30	O/E-SI
Chilostomella ovoidea REUSS	7	0	0	8	1	0	D/I
Dentalina acuta D´ORBIGNY	1	0	0	0	0	2	S/I
Fursenkoina subacuta (D´ORBIGNY)	6	6	0	0	1	3	D/I
Glandulina ovula D´ORBIGNY	0	0	0	0	2	0	S/I
Globocassidulina crassa (D'ORBIGNY)	0	5	4	0	8	10	O/I
Grigelis pyrulus (D´ORBIGNY)	0	1	0	0	1	0	S/I
Hansenisca soldanii D´ORBIGNY	4	0	6	5	8	8	S/E
Heterolepa dutemplei D´ORBIGNY	6	0	1	0	3	0	O/E
Hoeglundina elegans (D´ORBIGNY)	3	0	0	0	0	0	S/E
Laevidentalina communis (D´ORBIGNY)	0	0	0	3	2	1	S/I
Laevidentalina elegans D´ORBIGNY	0	3	5	2	7	0	S/I
Lenticulina inornata (D´ORBIGNY)	15	21	10	11	12	15	O/SI
Lenticulina vortex (FICHTELL & MOLL)	0	2	1	0	0	2	O/E
Marginulina hirsuta D´ORBIGNY	2	0	4	5	3	0	S/I
Martinottiella communis (D´ORBIGNY)	2	0	1	0	0	1	O/E
Melonis pompilioides (FICHTELL & MOLL)	11	8	14	16	14	18	S/I
Neugeborina longiscata (D´ORBIGNY)	9	5	10	6	0	0	S/I
Nonion commune (D´ORBIGNY)	0	5	9	0	2	0	S/I
Planularia casis (FICHTELL & MOLL)	0	0	0	0	1	3	S/I
Planularia dentata (KARRER)	0	13	0	0	0	1	S/I
Planularia lanceolata (D´ORBIGNY)	0	1	0	0	0	2	S/I
Planulina sp.	3	4	2	0	1	3	O/E
Pseudonodosaria brevis D´ORBIGNY	3	4	2	0	0	4	S/I
Pullenia bulloides (D´ORBIGNY)	15	21	3	15	4	15	S/I
Saracenaria arcuata (D´ORBIGNY)	0	6	0	4	0	0	S/I
Spirosigmoilina tenuis (CŽJŽEK)	2	7	0	1	4	8	O/E
Textularia gramen D´ORBIGNY	8	5	2	1	0	2	S/I
Trifarina angulosa (WILLIAMSON)	14	22	5	9	15	17	O/I
Uvigerina grilli SCHMID	2	0	0	2	1	0	D/I
Uvigerina macrocarinata PAPP & TURNOVSKI	1	0	0	1	0	0	D/I
Vaginulinopsis pedum (D´ORBIGNY)	1	0	3	2	1	0	S/I
summ	308	293	301	303	299	304	

The depth estimation based on P/B ratio suggests an upper bathyal environment (85.2 to 92.2 % of planktonic foraminifera). Based on the modified P/B ratio the water depth was between 886 and 987 m. According to the third applied model, the Hohhenneger method, sedimentation took place at depths ranging from 142 down to 204 m.

Cluster analysis (Ward's method) and Non-metric Multidimensional Scaling (Euclidean distance dissimilarity measure, comparing the composition and abundances of all identified benthic foraminifera species) revealed three clusters, separated into two major groups, Group I or the *Cibicidoides–Bolivina* assemblage and Group II, the *Bolivina* assemblage, respectively (Fig. 4). Cluster 1, ***Cibicidoides–Bolivina assemblage***, contains foraminiferal assemblages from the lower and upper parts of the section (lower samples G1 and G2 and upper samples G5 and G6) and includes 28 - 30 species. Dominant species are *Cibicidoides ungerianus* (average 14.9%), *Bolivina dilatata* (average 12.8%) and *B. viennensis* (average 10.2%), whereas species *C. austriacus* (average 9.8%) and *L. inornata* (average 5.5%), while still common, are less abundant. Cluster 2, ***Bolivina assemblage***, comprises samples from the central part of the section and consists of 24 - 27 species. It is characterized by the greater abundance of *Bolivina dilatata* (average 29.9%) and *B. viennensis* (average 15.3%). Still prominent, but less abundant within this cluster are *C. ungerianus* (average 9.7%), *C. austriacus* (average 5.2%) and *Melonis pompilioides* (average 5.2%).

Benthic foraminiferal oxygen index values from 19.89 to 65.00 (BFOI, Fig. 3) suggest that a shift in oxygen content took place during deposition. Sediments from the lower and upper parts of the section originated during high oxic conditions. Moderate oxic conditions prevailed during sedimentation of the central part of the section, and the lowest concentration of oxygen occurred during sedimentation of sample G4, approaching lowoxic conditions. Suboxic species (comprising 35.7 to 51.1% of the total benthic assemblage) and oxic indicators (varying from 12.3 to 31.8%) prevail in the lower and upper parts of the section, while in the middle part of the section an increase in the proportion of disoxic indicators (17.2 - 49.7%) was observed. Within the benthic community, infaunal forms (53.4 - 77.7%) dominate, especially in the central part of the section.

5. STRATIGRAPHY

In this paper, the standard biozonation scheme (Fig. 2) for the Miocene of the Central Paratethys was applied (PAPP et al., 1978; PAPP & SCHMID, 1985; CICHA et al., 1998; PILLER et al., 2007) along with the Badenian stratigraphic correlation table proposed by HOHENEGGER, 2014; KOVÁČ, 2018 and PAVELIĆ & KOVAČIĆ, 2018 (for North Croatian Basin). It has to be stressed that recently, for dating of the Miocene deposits of the North Croatian basin, the sub-division model by HOHENEGGER et al. (2014) was used, in which the Moravian sub-stage is correlated with the lower and middle Badenian (Fig. 2). However, this proposal is still subject to numerous discussions and is not unanimously accepted (HOLCOVÁ, 2018).

The early Badenian age of the studied samples was confirmed by the presence of *Uvigerina macrocarinata* PAPP & TURNOVSKI as well as by various lageniids (Fig. 5; Table 1), some of which are index fossils for this sub-age (*sensu* CICHA et al., 1998), such as *Planularia dentata* (KARRER) and *P. lanceolata* (D'ORBIGNY). The occurrence of *Uvigerina grilli* SCHMID, *Dentalina acuta* D'ORBIGNY, and *Pseudonodosaria brevis* D'ORBIGNY is typi-

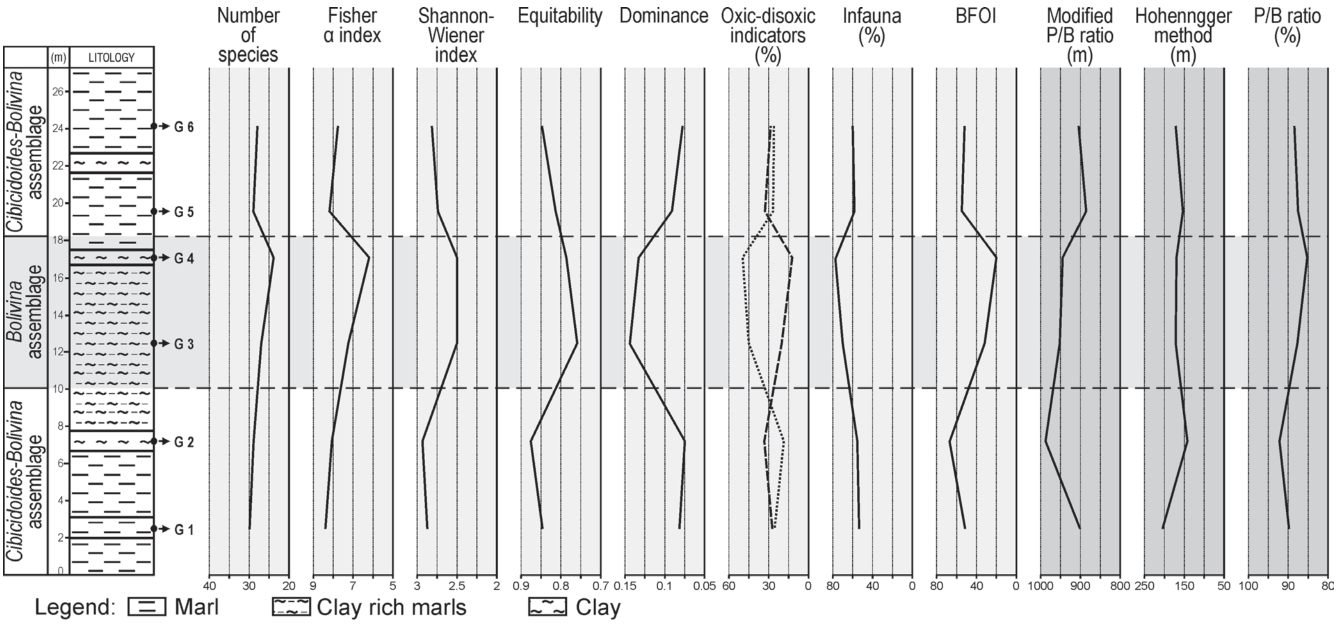

Figure 3. Glavnica Gornja section with sampling points (G), number of benthic foraminifera species, Diversity indices (Fisher α index, Shannon-Wiener index, Equitability, Dominance), oxic - disoxic indicators, epifauna/infauna ratio, BFOI, estimated depths of sedimentary basin after Hohenegger method and modified P/B ratio, and percentage of planktonic taxa.

cal for the early and middle Badenian, and *Vaginulinopsis pedum* (D'ORBIGNY) is typical for the Karpatian and early Badenian.

According to the standard small benthic ecobiozonation scheme (Fig. 2), our samples belong to the Lagenidae zone (Moravian, lower Badenian). Presence of the planktonic foraminifera species *Orbulina suturalis* BRÖNNIMANN indicate a maximum depositional age of 14.56 Ma (the FO datum of *Orbulina suturalis* in the Mediterranean; IACCARINO et al., 2012). Therefore, the studied stratigraphic interval certainly correlates with the Upper Lagenidae Zone, of the middle Badenian (*sensu* HOHENEGGER et al., 2014; *sensu* PAVELIĆ & KOVAČIĆ, 2018 for North Croatian Basin), and can be correlated with the middle Miocene sea level cycle TB 2.4 (Fig. 2).

6. DISCUSSION

The middle part of the Glavnica Gornja section reflects environmental changes, as the *Cibicidoides-Bolivina* assemblage is replaced by the *Bolivina* assemblage. Changes in the foraminiferal composition and species richness correspond to a decrease of diversity indices (Fisher α index, Shannon-Wiener index, Equitability) in the central part of the section, and a consequent increase in Dominance (Fig. 3). These changes could be related to more stressful conditions at the sea-bed. It would be reasonable to assume that they were triggered by changes in water depth.

The abundance of planktonic foraminifera in the samples varies from 85.2% to 92.2%, and undoubtedly points to a good connections to the open sea. These very high values are indicative of the upper bathyal zone (MURRAY, 1991), and the highest values, above 90%, for the lower bathyal zone (VALCHEV, 2003). The ratio of P/B is a good proxy for water depth estimation, because the number of planktonic foraminifera increases with distance from the coast (GRIMSDALE & MORKHOVEN, 1955, MURRAY, 1991). Thus, the percentage of planktonic foraminifera within the fossil assemblages should indicate the water depth, but this is not a linear function (VAN HINSBERGEN et al., 2005). Sometimes a high percentage of planktonic foraminifera can be present in shallow water environments as a consquence of predominating onshore winds (VELLA, 1962). The P/B ratio is not affected solely by the water depths; selective dissolution of planktonic tests and changes in the amount of dissolved oxygen at the sea-bed may also control the P/B ratio (SEN-GUPTA & MACHAN-CASTILLO, 1993; JORISSEN et al., 1995,

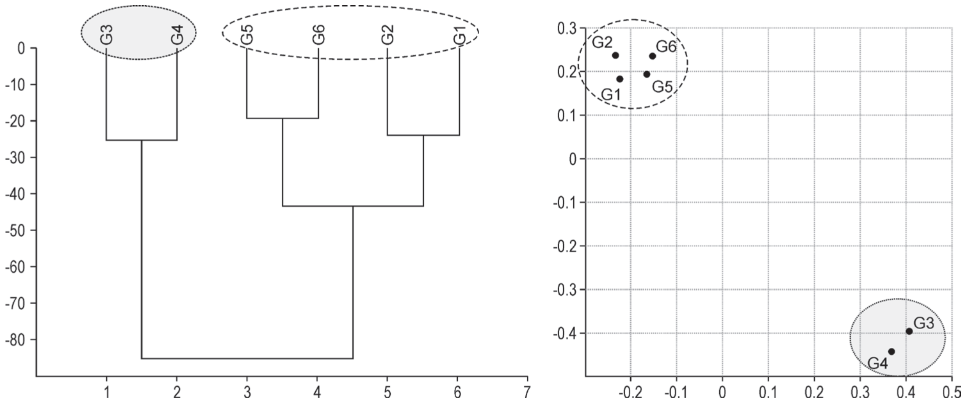

Figure 4. Cluster Analysis (Ward's method) and Non-metric Multidimensional Scaling (Euclidean).

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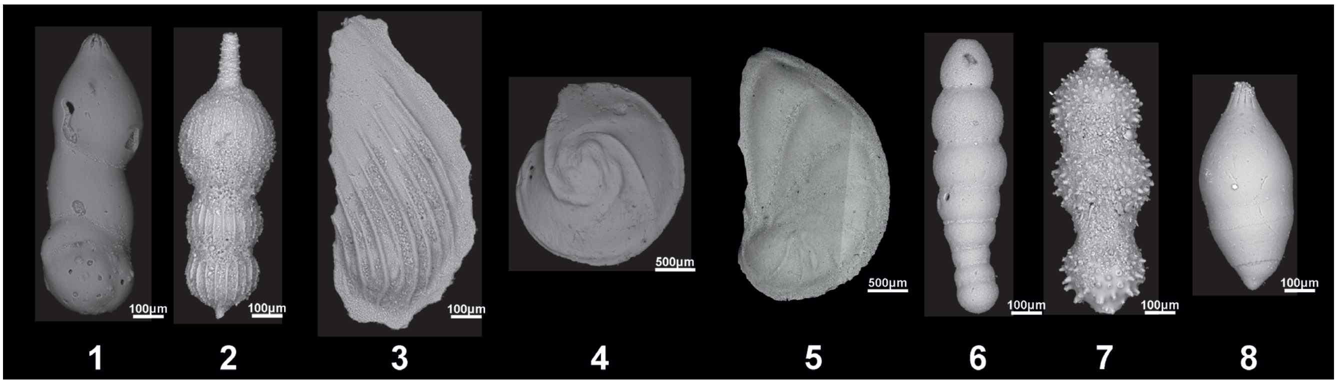

Figure 5. Selected benthic foraminiferal species from Glavnica Gornja. 1. *Vaginulinopsis pedum* (D'ORBIGNY), sample G3: 2. *Amphicoryna badenensis* (D'ORBIGNY). Sample G2; 3. *Planularia lanceolata* (D'ORBIGNY), sample G6; 4. *Lenticulina vortex* (FICHTELL & MOLL), sample G6; 5. *Planularia dentata* (KARRER), sample G2; 6. *Pseudonodosaria brevis* D´ORBIGNY, sample G2; 7. *Marginulina hirsuta* D´ORBIGNY, sample G5; 8. *Glandulina ovula* D´ORBIGNY, sample G5.

KOUWENOVEN et al., 2003). It is known how reduced oxygenation at the seabed affects the quantity and quality of available food (nutrient composition) and causes an increase in the proportion of organic matter in the sediment (GOODAY et al., 2000). This leads to a drop in the abundance of less tolerant species, especially those that are epifaunal (DE STIGTER et al., 1996). In contrast, species adapted to oxygen deficiency thrive because of an increase in nutrients (JORISSEN, 1999; DUIJNSTEE et al., 2004). Under oxygen-deficient (unfavourable) conditions, deep infaunal species may dominate and for this reason the modified P/B ratio (VAN DER ZWAAN et al., 1990, 1999) method excludes them. The calculated water depth for Glavnica Gornja samples, based on the modified P/B ratio, is between 886 to 987m, which corresponds to the middle bathyal zone of the Mediterranean continental slope (EINIG, 1997). Such great depths, however, do not fit with the depth range distribution of the identified benthic foraminifera, because their depth ranges coincide (overlap) with the outer shelf range. The absence or low abundance of typical bathyal and deeper water taxa (in particular *Uvigerina* and agglutinated forms) certainly indicates shallower conditions than those suggested by the modified P/B ratio.

The Hohenegger method for estimation of palaeo-depth (HOHENEGGER, 2005, BÁLDI & HOHENEGGER, 2008) is based on the depth range of recent species of benthic foraminifera. In any case, it should be emphasized that it is impossible to construct a general scheme of depth zoning that would be applicable to all areas of the world, because the species depth range depends on local physico-chemical and biological conditions. Any particular species will be most abundant where the optimum ecological conditions are developed for them (MURRAY, 2006). Therefore, in the palaeoecological reconstruction, the ecological demand of the dominant and common species should be consiedered in the first place. At the Glavnica Gornja locality, palaeo-depths obtained by the Hohenegger method range from 142 to 204 m and indicate the outer shelf, which is far more realistic than the results of the P/B and modified P/B methods. We can speculate that the high percentage of planktonic foraminifera in our samples suggests the predominance of onshore winds or increased primary production.

Regardless of the differences in the obtained water depth values (Fig. 3) it is evident that all three methods show only minor oscillations in the depth of the depositional environment. The change in foraminiferal assemblages in the central part of the section thus cannot be attributed to changes in the palaeo-depth.

What does the small benthic foraminifera of the Glavnica Gornja section suggest about the amount of oxygen at the sea bed? The values of BFOI (Fig. 3) indicate that highly oxic conditions prevailed during sedimentation of the upper and lower parts of the section. Good water circulation throughout the water column ensured oxygenation of sea-bottom water, and suggests that the local climate could be certainly warm (increased evaporation over precipitation and river influx to the basin). Oxic indicative species, such as *C. ungerianus*, *C. austriacus* and *L. inornata* (Table 1) were common within the *Cibicidoides-Bolivina* assemblage. In the central part of the section (*Bolivina* assemblage) a reduction in oxygen content occurred. Moderate to almost low oxic conditions (sample G 4) are defined based on BFOI indices. Also, the apparent increase in the proportion of disoxic species and infaunal forms (Fig. 3) (*B. dilatata*, *B. viennensis* and *B. elongata*) suggests that there could be a change in the quantity and quality of available food. It is possible to assume that organic matter and nutrients were brought into the sedimentation system either due to increased primary production or to increased terrigenous influx.

The results of analysis of small benthic foraminiferal assemblages from this study generally coincide with the results obtained from other Badenian sites of the Central Parathetys (KOVÁČOVÁ & HUDÁČKOVÁ, 2005; BÁLDI & HOHENEGGER, 2008; BÁLDI 2006; KOPECKA 2012; PERYT 2013; PEZELJ 2013; DOLÁKOVÁ et al., 2014, 2015; RYBAR et al., 2015; NEHYBA et al., 2016). In the early Badenian, an antiestuarine circulation pattern with a weakly stratified or non-stratified water column and well-ventilated sea bottom developed, supporting a relatively diverse assemblage of benthic foraminifera (BÁLDI, 2006; KOVÁČ et al., 2007, KOVÁČ et al., 2017, 2018). At the Glavnica Gornja locality, a more stable, deep water environment (ca. 200 m) was established after the TB 2.4 transgression. It was characterized by occasional episodes of minor oscillations in water depth and fluctuations in the intensity of primary production or terrigenous influx.

7. CONCLUSIONS

Diverse and abundant assemblages of small benthic foraminifera (44 species) thrived during the Badenian (Upper Lagenidae biochron) in the area of the Glavnica Gornja section (Medvednica Mt.). The calculation of water depth by different methods highlighted that the Hohenegger method produced the most plausible results (outer shelf) and thus it can be considered a reliable method for estimating water depth in epicontinental seas such as the Central Paratethys. High oxic conditions (*Cibicidoides-Bolivina* assemblage) prevailed at the sea-bed, whereas the central part of the section (*Bolivina* assemblage) reflects moderate to nearly low oxic conditions. The succession of foraminiferal assemblages illustrates the interplay between oxygen and food availability, where a decrease of oxygen correlates to an increase in organic matter and nutrients. Stressed conditions in the central part of the section were also confirmed by the decrease in diversity and increasing importance of dominance within the benthic foraminiferal assemblage as well as a significant increase in the proportion of disoxic and infaunal forms. The most important factors influencing the distribution of benthic foraminifera in the studied section are fluctuations in the amount of oxygen available at the sea bottom and/or flux of organic matter and nutrients into the environment, while minor oscillations in water depth are not reflected in the changes of the foraminiferal assemblages.

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