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Late Badenian foraminifers from the Vienna Basin (Central Paratethys): stable isotope study and paleoecological implications

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Abstract: Paleoecological interpretations based on stable isotope study of benthic (*Uvigerina semiornata*) and planktonic (*Globigerina bulloides, Globigerinoides trilobus*) foraminiferal shells from the Paratethys Vienna Basin (southwestern Slovakia) are presented. The study was performed on sediments of the Devínska Nová Ves-clay pit deposited during the Middle and Late Badenian (Middle Miocene). Our $\delta^{13}C$ data show an enhanced nutrient input to the water column and the organic matter accumulation at the bottom of the Vienna Basin. The remineralization of accumulated organic matter on the sea floor resulted in the formation of oxygen-depleted zones, where no oxic indicators but the oxygen-deficiency tolerant species were found. Positive benthic $\delta^{18}O$ signal can be attributed to the influence of the global cooling recognized in the world-ocean during the Middle Miocene. At the same time, variations observed in the water column are interpreted as reflecting the local temperature and salinity changes resulting from the fluvial and rain inflow. The differences between surface and bottom water temperature reflect the stratification of the water column. Such stratification might be related to the isolation process of Central Paratethys in the Badenian. This study confirms that $\delta^{13}C$ and $\delta^{18}O$ are not always in isotopic equilibrium with the ambient water but are also influenced by vital effects (respiration, symbiont photosynthesis ...). The vital effects led to the incorporation of isotopically light metabolic CO_2 into *Globigerina bulloides* resulting in high similarity between $\delta^{13}C$ values of *Uvigerina* and *Globigerina*. It has been shown that the extremely high $\delta^{13}C$ and very low $\delta^{18}O$ of *Globigerinoides trilobus* clearly imply the influence of algal photosymbionts.

Key words: Middle Miocene, Central Paratethys, Vienna Basin, paleoecology, stable isotopes, planktonic and benthic foraminifers.

Introduction

The development of the Vienna Basin (part of the epicontinental sea, called Central Paratethys) was mainly influenced by local geotectonic movements and global sea-level fluctuations (Hudáčková & Kováč 1997; Kováč 2000; Kováč et al. 2007). The most distinctive changes occurred in the Middle Miocene. These processes caused the formation of marine and terrestrial phases in the Paratethys area with occasional connections with the Mediterranean and Eastern Paratethys. The closing and reactivating of seaways, especially during the Miocene, produced changes of environmental conditions (see Rögl 1998). A significant global change affecting the Paratethys was the gradual temperature decline, which followed the warm period of Miocene Climatic Optimum occurring between 17 and 15 Ma (Gonera et al. 2000; Ivanov et al. 2002; Böhme 2003; Bicchi et al. 2003; Hudáčková et al. 2003a; Báldi 2006). A cooling event in the Central Paratethys was observed first in the Late Badenian (Early Serravallian) marine microfauna assemblages (Hudáčková & Spezzaferri 2002; Spezzaferri et al. 2004). Usually, this cooling step reflects the formation of a permanent ice cap on Antarctica around ~14 Ma (late Middle Badenian, Upper Langhian) and is well documented from the deep-sea records (e.g. Shackleton & Kennett 1975a; Berger et al. 1981; Savin et al. 1985; Miller et al. 1991; Pagani et al. 2000; Zachos et al. 2001; Billups & Schrag 2002). During the time span considered in the present work (Badenian, 16.3–12.7 Ma; Kováč et al. 2007) the Paratethys region became more and more isolated due to tectonic movements in the Carpathian Arc. The Late Badenian (13.6–12.7 Ma) is regarded as the last period of marine connection between the Paratethys and Mediterranean Tethys.

Stable oxygen and carbon isotope records of foraminifers are essential proxies for the paleoceanographic and paleoclimatic evaluation of the sedimentary record. The interpretation of paleoecological conditions from isotope analyses of shells is based on the assumption that the isotopic signal of foraminiferal tests should reflect the isotopic composition of ambient water where the organism was growing. In general, $\delta^{13}C$ and $\delta^{18}O$ are independent of each other and reflect rather different environmental conditions. The oxygen isotope ratio mainly reflects fluctuations of global ice volume and sea-surface and deep-water temperature changes (e.g. Shackleton 1967, 1987; Shackleton & Opdyke 1973; Shackleton & Kennett 1975b). The ^{13}C signal of foraminifers provides information on the carbon cycling and the origin of organic matter in the oceans and is widely used to reconstruct past changes of marine-water properties and organic matter fluxes (e.g. Emrich et al. 1970; Kroopnick et al. 1970; Duplessy 1972; Renard 1986; Zahn et al. 1986; McConnaughey et al. 1997; Corliss et al. 2002). There are several isotope studies that were performed on Miocene foraminifers in the Paratethys region (Šutovská & Kantor 1992; Durankiewicz et al. 1997; Hladilová et al. 1998; Gonera et al. 2000; Hudáčková & Kráľ 2002; Báldi 2006). Some other isotope studies in the Paratethys area were oriented towards gastropod (Latal et al. 2004, 2006a,b), pectinid and brachiopod (Bojar et al. 2004) research.

In the present work, we focus on the stable isotope ($\delta^{13}C$, $\delta^{18}O$) composition of planktonic and benthic foraminiferal shells from Devínska Nová Ves-clay pit (DNV) because it has the most complete profile of Badenian age outcrops in the Vienna Basin. A few stable isotope measurements on foraminiferal shells from this area were performed first in the work of Hudáčková et al. (2003a). In our previous study (Kováčová et al. 2008), we did geochemical research on foraminifers from several localities in the Vienna Basin, including DNV. The present study focuses on confirming paleoecological and paleoclimatological trends indicated on the basis of the previous data from the profile. For the more detailed stable isotope analyses on foraminiferal tests more than 60 new samples were evaluated from the uppermost part of the DNV profile, using the most modern measuring technology.

Geological setting

The Vienna Basin (Fig. 1) represents a typical pull-apart basin situated within the Alpine-Carpathian mountain belt, between the Eastern Alps and Western Carpathians. The basin Neogene fill comprises Early to Late Miocene, and Pliocene-Quaternary deposits. The Early and Middle Miocene sediments were mostly deposited in marine environments. The uppermost Middle Miocene and Upper Miocene sediments were deposited in brackish water conditions and the youngest ones in the freshwater, limnic to fluvial environments (Kováč 2000).

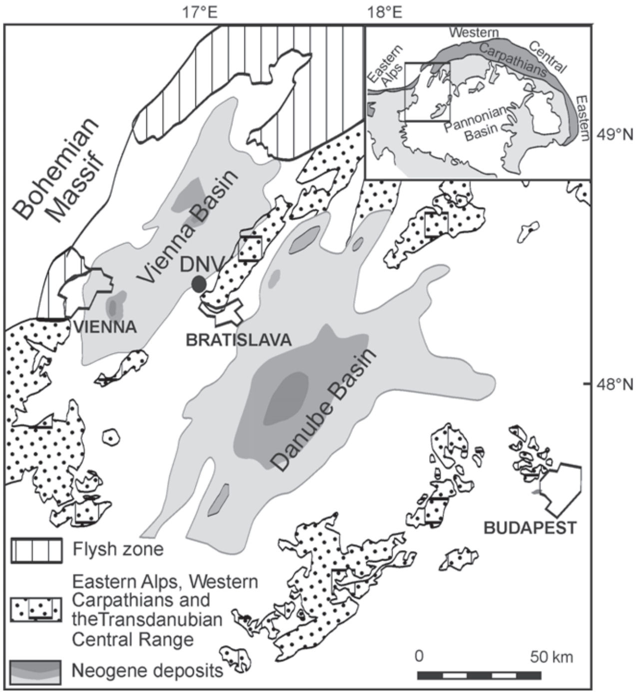

Fig. 1. Location of the Vienna Basin and the investigated Devínska Nová Ves-clay pit (DNV) in the Central Paratethys.

The studied area near the Devínska Nová Ves (DNV, Fig. 1) represents the Slovak part of the Vienna Basin, situated at the foothills of the Devínske Karpaty (subunit of the Malé Karpaty Mts). DNV profile uncovers several stages of the late Middle/Late Badenian sedimentary sequence. The studied interval consists of over 15 meters thick sequence of laminated grey clays to claystones and green-grey marls to marlstones rich in fossil remnants: calcareous nannoplankton, planktonic and benthic foraminifers, molluscs, fish skeletons and otholites as well as a rare flora fragments. The lower part of section (15 m–12.2 m) belongs to the Middle Badenian CPN8 *Globoturborotalita druryi-Globoturborotalita decoraperta* Zone (Cicha et al. 1975). The Late Badenian age of the Studienka Formation was determined in the middle and upper part (from 12.2 m up to top) by the foraminiferal assemblages belonging to the *Bulimina/Bolivina* Zone (Grill 1941) and nannofossils of NN6 Zone (Hudáčková & Kováč 1997; Hudáčková et al. 2003a). The Upper Badenian (13.54 Ma) in the upper part of the transect at 7 m has been documented by $^{87}Sr/^{86}Sr$ age based on *Pappina neudorfensis* (Toula) shells (Hudáčková & Kráľ 2000; Hudáčková et al. 2003b). The fauna support sedimentation in middle-outer neritic environment (Hudáčková et al. 2003a).

Materials and methods

For the paleoecological and paleoclimatological interpretation 108 samples were taken from the DNV profile, in general every 10 cm in the upper 9 m. In the lower part, the interval used was 40 cm. In sample preparation we followed the standard laboratory methods adopted at the Department of Geology and Paleontology at Comenius University in Bratislava to separate foraminiferal shells from the sediment. About two hundred grams of sediment for each sample were soaked in water and diluted hydrogen peroxide (3 %) for several hours to desegregate the sediments without damaging the specimens and to retain the original faunal composition. Samples were then washed under running water through 200 μm, 125 μm and 71 μm mesh sieves. Approximatelly 200–300 specimens for each sample were picked, identified with a binocular microscope and counted. The raw data were transformed into percentages over the total abundance and percent abundance curves were plotted (Fig. 2 for planktonic taxa, Fig. 3 for benthic taxa). Species with phylogenetic affinities and similar environmental significance were grouped to better interpret their distribution patterns.

The best-preserved planktonic and benthic foraminiferal shells were picked for stable isotope measurements. The benthic stable isotope data were obtained from individuals of *Uvigerina semiornata* (Fig. 4.21). In some cases, several species of uvigerinids (e.g. *U. semiornata*, *U. aculeata*) occupying the same environment were used for analyses. In general, the representatives of these taxa inhabit the upper 0–2 cm in the sediment and are believed to precipitate their tests in oxygen isotopic equilibrium with the ambient water (Woodruff et al. 1980). The planktonic stable isotope data were

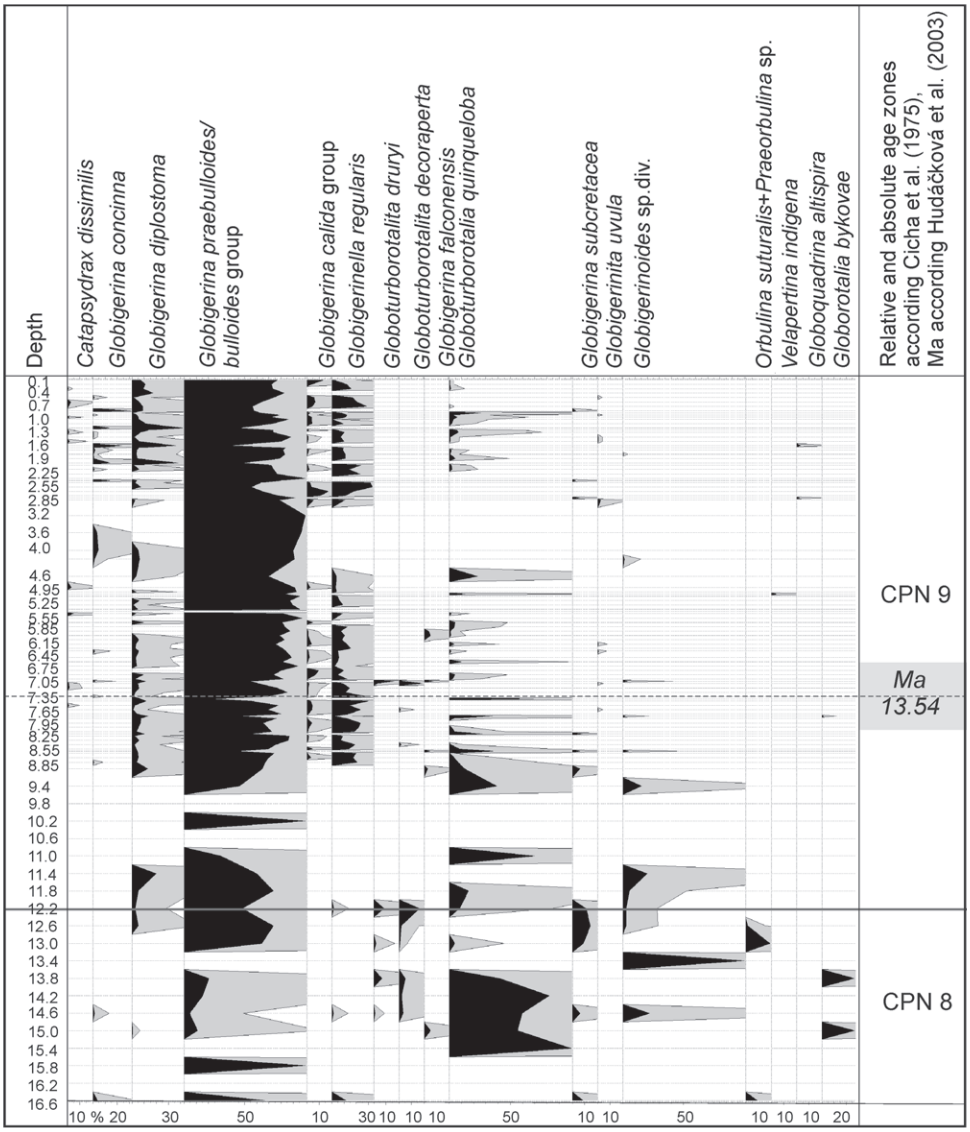

Fig. 2. Relative abundance (percent value) of planktonic foraminifers with estimation of the CPN8/CPN9 planktonic Zones (according to Cicha et al. 1975) boundary. Absolute age according to Hudáčková & Kráľ (2002).

achieved from analysis of the intermediate-water dweller *Globigerina bulloides* (Fig. 4.1,2), in some samples mixed with *G. diplostoma* (Fig. 4.4) or *G. praebulloides*. In two samples (65 and 71) the isotope ratio were measured on prevailing tests of *Globigerinoides trilobus* (Fig. 4.10). This species occupies predominantly the surface-water layers. *G. trilobus* hosts photosymbionts whereas *G. bulloides* is an algal symbiont-barren species (Bé & Tolderlund 1971). In the uppermost two meters of profile, only the planktonic foraminifers have been analysed because of scarcity of benthic specimens.

The use of stable oxygen isotopic measurements as a proxy for past paleothermometry began with Urey's (1947) theoretical prediction that the $^{18}O/^{16}O$ ratio in calcite varies as a function of the temperature in which the mineral precipitated. Since that time, various forms of the paleotemperature equation have been generated (e.g. Erez & Luz 1983) but all generally follow Epstein et al.'s (1953) original determination. In the present work, we used the adapted version of paleotemperature equation as modified by Shackleton (1974) for calculation of the surface and bottom water temperature:

$$T = 16.9 - 4.38\,(\delta^{18}O_c - \delta^{18}O_w) + 0.10\,(\delta^{18}O_c - \delta^{18}O_w)^2$$

where T is the paleotemperature (°C), $\delta^{18}O_c = \delta^{18}O$ of the carbonate and $\delta^{18}O_w$ is the isotopic composition of the seawater where the carbonate was precipitated.

The first one is relative to the Vienna-PDB (VPDB — Vienna PeeDee Belemnite) standard, while the water value in which the carbonate precipitated is on Standard Mean Ocean Water (SMOW) scale. The later must be further corrected by -0.27 ‰ (see in Hut 1987 or Bemis et al. 1998). If $\delta^{18}O_w$ of -0.24 ‰ is applied for Middle Miocene seawater (Lear et al. 2000) the above equation can be rewritten as follows:

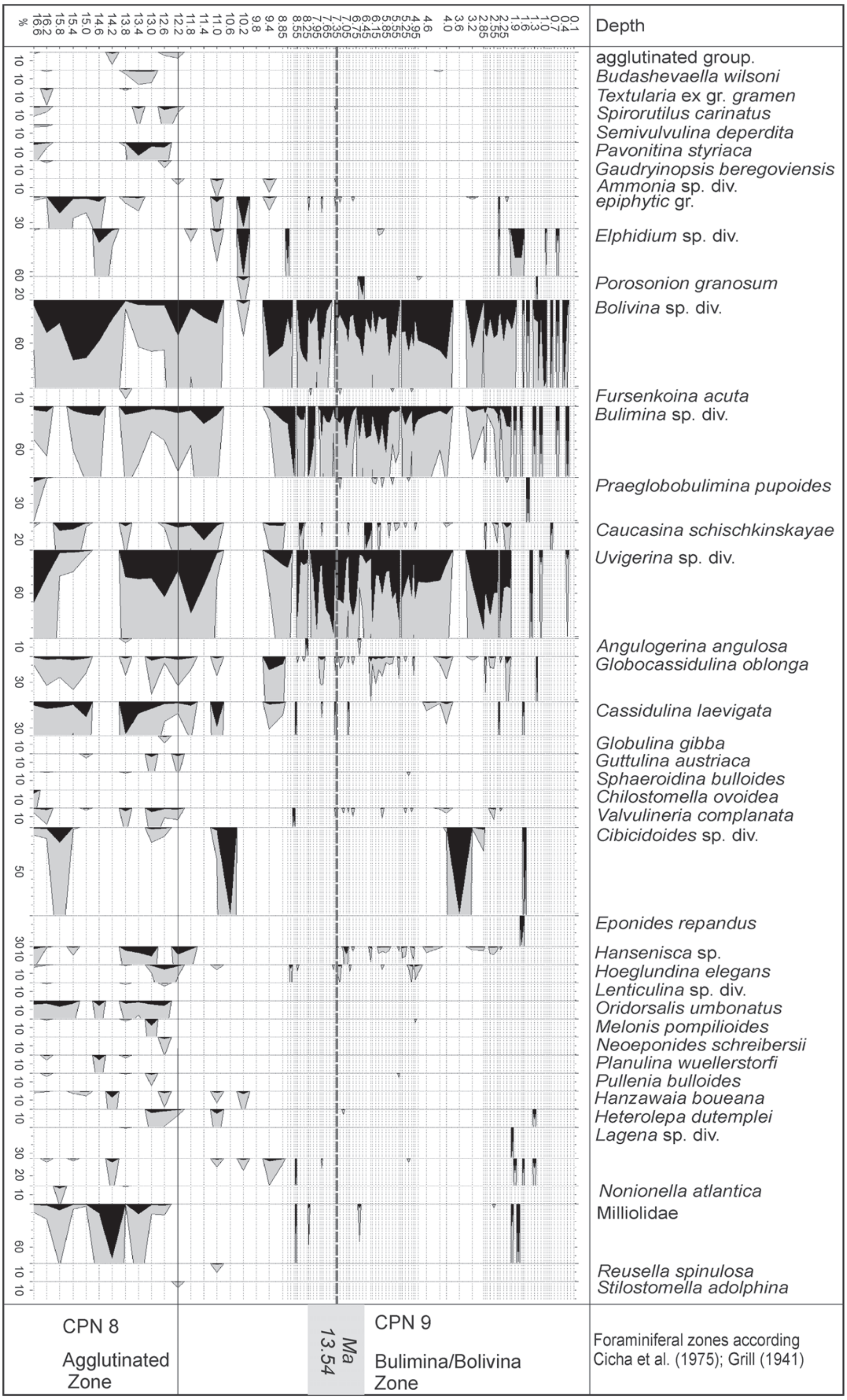

Fig. 3. Relative abundance (percent value) of benthic foraminifers with estimation of the CPN8/CPN9 planktonic Zones (according to Cicha et al. 1975) boundary.

$$T = 16.9 - 4.38\,[\delta^{18}O_c - (-0.51)] + 0.10\,[\delta^{18}O_c - (-0.51)]^2$$

The VPDB standard replaced after intercalibration the older, no longer available standard PDB, which refers to the Cretaceous belemnite formation at PeeDee in South Carolina, USA.

When using Shackleton's equation with the above mentioned corrections, the final temperature values are about 2.2 °C lower than the results without any corrections.

The isotope measurements were performed on a Finnigan MAT 251 mass spectrometer at the GSM laboratory of Bergen University, Norway, adapting the standard method used in that laboratory. The number of specimens analysed at a single measurement varied between 1 and 3 for benthic shells (~85 μg) and between 6 and 10 for planktonic individuals (~70 μg). Foraminiferal tests were ultrasonically cleaned in ethanol for 10 s. Gas for isotope measurements was produced by reaction with orthophosphoric acid at 70 °C in an automated on-line system, where the acid was added to the sample in individual reaction chambers. Results are reported with respect to the VPDB standard through calibration against CM03 standards. The reproducibility of the system is ±0.06 ‰ for $\delta^{13}C$ and ±0.07 ‰ for $\delta^{18}O$, based on replicate measurements of an internal carbonate standard.

Results

On the basis of the 89 identified foraminiferal taxa — (39 planktonic ones) from 108 samples we suggest that water depth during the sedimentation fluctuated from the inner to outer shelf.

The planktonic assemblages indicate a paleoclimatic trend from warm to more temperate conditions from the bottom to the top of the section, based on lower abundance of the *Globigerinoides* and *Orbulina-Praeorbulina* group (Fig. 2).

The benthic foraminiferal assemblages suggest, indeed, that the sea floor was characterized by suboxic episodes, as indicated by positive excursions in the abundance of the *Uvigerina* group (Fig. 3). Suboxic and dysoxic episodes also occurred, documented by drastic decrease in the abundance of benthic foraminifers.

105 stable isotope measurements on benthic and planktonic foraminiferal shells from DNV profile have been produced. The stable isotope results are shown in Table 1. Changes in the isotope ratios of planktonic and benthic foraminiferal tests along the profile are shown in Fig. 5 for both carbon and oxygen stable isotopes.

The benthic $\delta^{18}O$ values are between +1.7 ‰ and +2.3 ‰ with an average of +1.9 ‰. The curve records a slight increasing trend towards the upper part of the studied section. The $\delta^{13}C$ values demonstrate a narrow range of values from -1.06 ‰ to -0.05 ‰ (averaging -0.64 ‰). The record is well balanced and no distinct variances were observed.

Table 1: Stable isotope results of oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) of analysed planktonic and benthic foraminiferal shells in the DNV section. ***G.b.*** — *Globigerina bulloides*, ***G.tr.*** — *Globigerinoides trilobus*, ***U*** — *Uvigerina semiornata*.

Sample number	DNV Depth (m)	$\delta^{18}O$ *U*	$\delta^{13}C$ *U*	$\delta^{18}O$ *G. b.*	$\delta^{13}C$ *G. b.*	$\delta^{18}O$ *G. tr.*	$\delta^{13}C$ *G. tr.*
1	0.1			−0.26	−0.55		
2	0.2			−0.29	−0.30		
3	0.3			0.14	−0.69		
4	0.4			0.11	−0.25		
5	0.5			0.08	−0.53		
6	0.6			−0.06	−0.18		
7	0.7			−0.10	−0.78		
8	0.8			0.26	−0.54		
9	1.1			0.29	−0.77		
10	1.2			0.24	−0.6		
11	1.3			0.28	−0.53		
12	1.5			0.01	−0.78		
13	1.6			1	−1.07		
14	1.7			−0.43	−0.81		
15	1.8			−0.36	−0.81		
16	2	2.10	−0.97	1	−0.87		
17	2.1	1.93	−0.77	***−1.11***	−0.90		
18	2.3	1.91	−0.82				
19	2.4	2.02	−0.92	0.34	−1.33		
20	2.5	1.96	−0.35	0.06	−1.11		
21	2.6	1.97	−0.71				
22	2.7	2.09	−0.87				
23	2.8	1.88	−0.72	0.2	−0.82		
24	3.2	2.02	−0.87	−0.28	−1		
25	3.6	2.24	−0.41	0.66	−1.08		
26	4	2.06	−0.63	0.47	−1.09		
27	4.4	2	−0.5	0.43	−0.59		
28	4.8	1.91	−0.45	−0.28	−0.59		
29	5.2	1.83	−0.40	0.46	−0.92		
30	5.3	1.78	−0.96				
31	5.4	1.74	−0.77	−0.30	−0.30		
32	5.5	1.68	−0.95	−0.41	−0.63		
33	5.6			0.33	−0.46		
34	5.7	1.81	−0.74	−0.72	−0.31		
35	5.8	1.78	−0.63				
36	5.9	***1.70***	−0.87				
37	6	1.76	−0.66	0.04	−0.77		
38	6.1	1.77	−0.41				
39	6.6	1.75	−0.94				
40	6.8			−0.55	−0.79		
41	7	2.03	−0.26	0.68	−0.52		
42	7.1	1.71	−0.48	0.07	−0.69		
43	7.2	1.71	−0.90				
44	7.3	1.76	−0.75				
45	7.4	1.93	−0.67	0.63	−0.65		
46	7.6	1.75	−0.89				
47	7.7	1.76	−0.83	0.79			
48	7.8	1.79	−0.97		−0.73		
49	7.9	1.89	−0.83				
50	8	1.85	−0.62				
51	8.1	1.94	−0.49	0.51	−0.94		
52	8.2	1.81	−1.02	0.41	−0.75		
53	8.3			0.07	−0.94		
54	8.4			0.46	−0.91		
55	8.6	1.99	−0.64	0.69	−0.65		
56	8.8	1.86	−0.83				
57	8.9	1.83	***−1.06***				
58	9	1.92	−0.76	0.56	−0.55		
59	9.1			0.48	−0.42		
60	9.2	2.1	−0.52	1.31	−0.46		
61	11	2.1	−0.22	**1.39**	−0.07		
62	11.2	2.07	−0.19	1.14	−0.06		
63	11.4	1.96	−0.26	0.76	−0.19		
64	11.8	1.84	−0.2	1.08	−0.18		
65	12	1.7	−0.45			***−1.63***	***0.78***
66	12.4	1.95	−0.06				
67	12.8	1.76	−0.56				
68	13.2	**2.3**	**−0.05**	0.02	***−1.37***		
69	13.6	1.,82	−0.69				
70	14	2.01	−0.58	0.57	−1.02		
71	14.2			−0.53	**0.2**	**−1.18**	**1.37**
72	15	1.88	−0.38	0.74	−0.3		

The $\delta^{18}O$ values measured in the shells of planktonic *Globigerina* taxa range from -1.11 ‰ to +1.39 ‰ (mean value +0.25 ‰) and the $\delta^{13}C$ values range from -1.37 ‰ to +0.20 ‰ (mean value -0.65 ‰). The $\delta^{18}O$ values show larger variations with a negative trend towards the top in contrast to $\delta^{13}C$ data, which tend to have positive values, most visible in

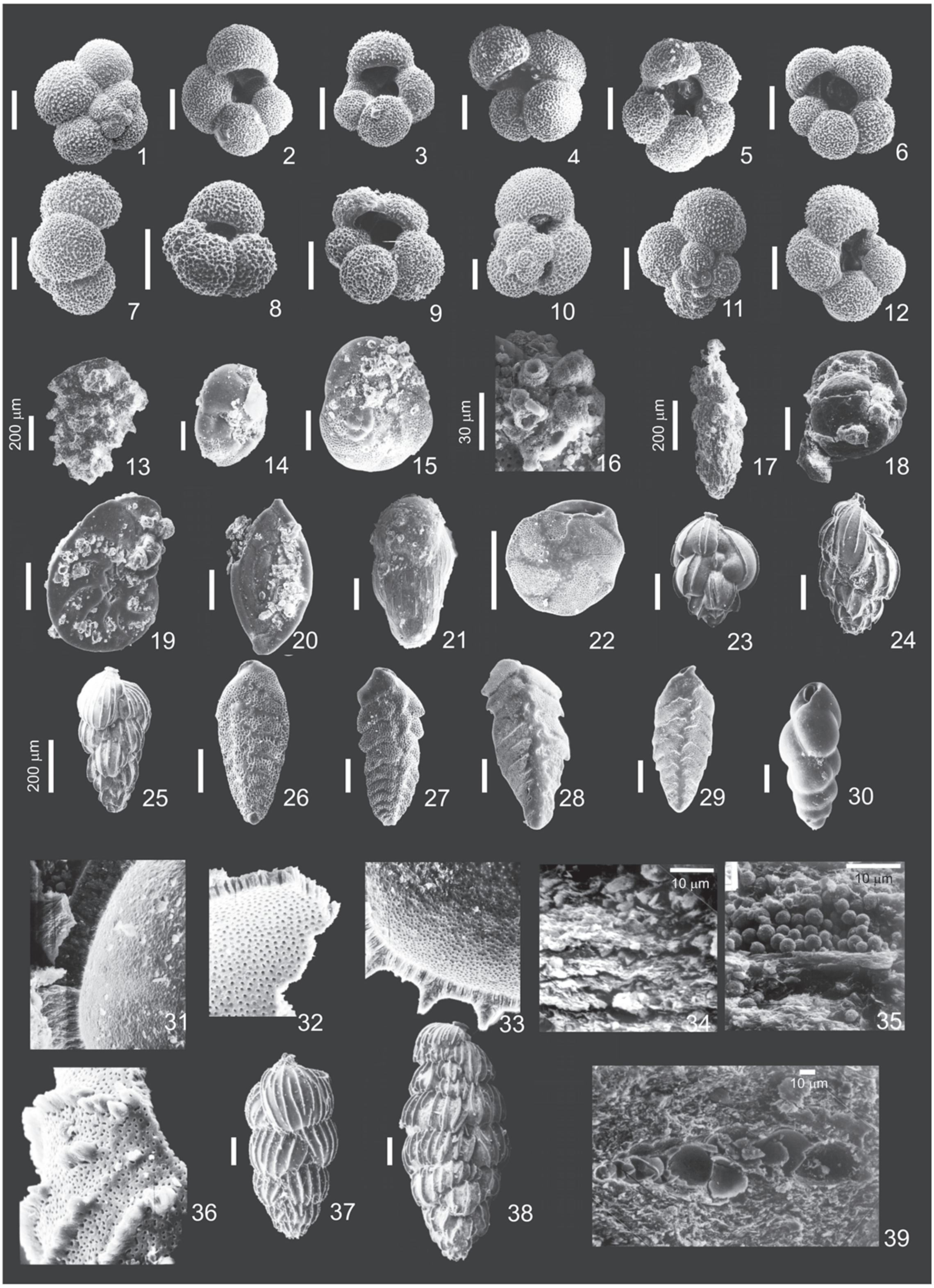

Fig. 4. SEM pictures of the most frequent species in DNV. **1** — *Globigerina bulloides* d'Orbigny, spiral side, 70×, 80 cm. **2** — *Globigerina bulloides* d'Orbigny, apertural side, 72×, 80 cm. **3** — *Globigerina* ex. gr. *bulloides* d'Orbigny, apertural side, 75×, 40 cm. **4** — *Globigerina diplostoma* Reuss, 62×, 120 cm. **5** — *Globigerina concinna* Reuss, 75×, 80 cm. **6, 7** — *Globigerina concinna* Reuss, 77.5×, 95×, 40 cm. **8** — *Globigerinoides* cf. *bulloideus* Crescenti, 110×, 1420 cm. **9** — *Globigerina concinna* Reuss, 87×, 80 cm. **10** — *Globigerinoides trilobus* (Reuss), 55×, 1520 cm. **11** — *Globigerinella obesa* (Bolli), 75×, 120 cm. **12** — *Globigerinella* cf. *obesa* (Bolli), 77.5×, 120 cm. **13** — *Pavonitina styriaca* Schubert, 31×, 1125 cm. **14** — *Valvulineria complanata* (d'Orbigny), 52.5×, 1125 cm. **15** — *Valvulineria complanata* (d'Orbigny) with microbial cover, 72.5×, 1125 cm. **16** — Detail of microbial cover on the *V. complanata* test, 350×, 1125 cm.

the middle and upper part of the section. On samples 65 and 71, planktonic isotope measurements were carried out on the predominant species *Globigerinoides trilobus*. The measured values of this taxon reached ~+1.10 ‰ for $\delta^{13}C$ and ~−1.41 ‰ for $\delta^{18}O$. Considering the $\delta^{18}O$ differences between *Globigerina* and *Globigerinoides* taxa, it was observed that the deeper-water dweller *Globigerina* gives a more positive $\delta^{18}O$ signal than the shallow living *Globigerinoides*. Towards the top of the section increasing differences between the $\delta^{18}O$ data of planktonic and benthic taxa are recorded.

The calculated paleotemperature (Fig. 6) of bottom waters (benthic *Uvigerina*) ranges from 5.2 °C to 7.7 °C (averaging at 6.8 °C). Planktonic *Globigerina bulloides* indicate quite a large temperature range from a minimal value of 9 °C to a maximal value of 19.4 °C (average 13.7 °C). The near-surface living *Globigerinoides trilobus* has been analysed in two samples where the values of 19.7 °C and 21.6 °C (average 20.6 °C) were obtained.

Discussion

Carbon isotopes

The $\delta^{13}C$ values recorded in foraminiferal tests reflect the $\delta^{13}C$ values of dissolved inorganic carbon (DIC) of ambient water masses in the ocean. Foraminiferal $\delta^{13}C$ values, therefore, are usually used as the major tracer for nutrients (Sarnthein et al. 1994). The $\delta^{13}C$ in the ocean is inversely correlated to nutrient concentration; the higher nutrient concentration in seawater produces more depleted $\delta^{13}C$ of calcareous shells. When the ^{12}C-rich organic matter is transported to the sea floor, its remineralization causes release of ^{12}C and depletion of ^{13}C in water. Consequently, the ambient water exhibits nutrient enriched values and causes low $\delta^{13}C$ values in foraminiferal shells. However, the carbon isotopic composition often deviates from equilibrium (Mulitza et al. 1999). These offsets have been attributed to "vital effects" involving biologically, physically and chemically controlled processes, which cause disequilibrium between the $\delta^{13}C_{DIC}$ and $\delta^{13}C$ of foraminiferal shells (Peters 2000).

Our benthic and planktonic $\delta^{13}C$ data indicate that the nutrient-rich water conditions occurred in the investigated Vienna Basin during the late Middle/Late Badenian (Late Langhian/Early Serravallian). The $\delta^{13}C$ measurements on foraminifers show that the subsurface species of *Globigerina* recorded lighter values of ~1.73 ‰ than the near-surface *Globigerinoides* (Fig. 5, Table 1). In many cases it is also lighter than benthic $\delta^{13}C$, even if the mean values are very close (−0.65 ‰ for *Globigerina*, −0.64 ‰ for *Uvigerina*). *G. bulloides* is a typical high biological productivity indicator (Naidu & Niitsuma 2004). When the specimens of *G. bulloides* calcify in fertile waters, their $\delta^{13}C$ signal should be lower resulting from the fractionation pattern of carbon isotopes. The negative $\delta^{13}C$ values of *Globigerina*, thus, imply an increasing nutrient input to the water column of the Vienna Basin.

An accessible reservoir of light carbon ^{12}C is represented mainly by continental organic matter (Berger et al. 1981). Therefore, the most probably nutrient source bringing the organic matter to the water column of the Vienna Basin was provided by terrestrial input. During the Middle Miocene, an important paleogeographical change in the Vienna Basin was the formation of a new drainage pattern resulting in a wide deltaic system of the paleo-Danube on the northern edge of the basin (Jiříček 1990). Thus, we suppose that the paleo-Danube river inflow might have increased the productivity in the surface waters of the Vienna Basin and have caused the $\delta^{13}C$-depleted values in planktonic shells (Kováčová et al. 2008). At this time, the marine connection of Central Paratethys was closing and the river input was probably the only possible source providing the nutrient supply to the water column.

The negative carbon isotopic ratio (−0.64 ‰) extracted from benthic *Uvigerina* shells indicates an increased organic carbon supply to the sea floor. The benthic $\delta^{13}C$ curve exhibits a negative trend towards the top (Fig. 5), which is probably related to enhanced benthic eutrophication, especially pronounced in the Late Badenian, first recognized by Báldi (2006). Such conditions can arise when the remaining organic matter, not consumed by the microorganisms or bigger faunal elements in the water column, falls down to the bottom. Accumulated organic matter, rich in ^{12}C, on the sea floor and within the sediment is subject to decomposition, which depletes the carbon isotope ratio of ambient water (McCorkle et al. 1990).

The *Uvigerina* species analysed in the DNV are considered to be shallow-infaunal and so are influenced by the isotopic composition of pore water (Schmiedl et al. 2004). Under the nutrient-rich conditions, the pore water DIC, even in the upper millimeter, may be depleted in ^{13}C relative to that of the bottom water. Thus, the negative $\delta^{13}C$ of *Uvigerina* analysed in DNV might reflect the nutrient-rich and ^{13}C depleted pore water conditions in the Vienna Basin. At the same time, the remineralization of accumulated organic matter at the bottom can produce oxygen-depleted zones. In the Vienna Basin, an insufficient oxygenation of the sea floor is indicated by abundance of low-oxygen benthic foraminiferal indicators, dominated by the following taxa: *Uvigerina* (*U. ve-*

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Continued from previous page: **17** — *Uvigerina venusta* Franzenau with microbial cover, 45×, 1125 cm. **18** — *Budashevaella wilsoni* (Smith), 77.5×, 1125 cm. **19** — *Hanzawaia crassiseptata* (Łuczkowska) umbilical side, with microbial cover, 85×, 1125 cm. **20** — *Spiroloculina badenensis* d'Orbigny, 72.5×, 1125 cm. **21** — *Uvigerina semiornata* d'Orbigny, 57×, 1125 cm. **22** — *Cassidulina carinata* Silvestri, 142×, 320 cm. **23** — *Uvigerina bellicostata* Łuczkowska, 65×, 420 cm. **24** — *Uvigerina accuminata* Hosius, 62.5×, 420 cm. **25** — *Uvigerina venusta* Franzenau, 47×, 380 cm. **26** — *Bolivina viennensis* Marks, 77×, 740 cm. **27** — *Bolivina pokornyi* Cicha et Zapletalova, 60×, 740 cm. **28** — *Bolivina dilatata maxima* Cicha et Zapletalova, 60×, 740 cm. **29** — *Bolivina dilatata maxima* Cicha et Zapletalova, 57.5×, 720 cm. **30** — *Bulimina elongata* d'Orbigny, 50×, 980 cm. **31** — *Uvigerina venusta* Franzenau, wall detail, 450 cm. **32** — *Uvigerina venusta* Franzenau, wall detail, 450 cm. **33** — *Pappina neudorfensis* (Toula), wall detail, 450 cm. **34** — Sediment microlayer structure, 520 cm. **35** — Sediment microlayer structure, 535 cm. **36** — *Uvigerina venusta* Franzenau, wall detail, 450 cm. **37** — *Uvigerina venusta* Franzenau, 50×, 450 cm. **38** — *Pappina neudorfensis* (Toula), 50×, 450 cm. **39** — Sediment microlayer structure, 740 cm. The scale bars = 100 μm.

nusta, Fig. 4.31,32,36,37; *U. bellicostata*, Fig. 4.23; *U. semiornata*, Fig. 4.21), *Bolivina* (*B. dilatata maxima*, Fig. 4.28, 29; *B. pokornyi*, Fig. 4.27) and *Bulimina* (*B. elongata*, Fig. 4.30; *B. subulata*). The sub/dysoxic conditions are also reflected by absence of oxic indicators reported in previous studies (Fig. 3; Kováč & Hudáčková 1993; Hudáčková & Kováč 1997). Our benthic $\delta^{13}C$ data correspond to the observations, based on benthic foraminiferal species distribution, and support the high nutrient and low oxygen concentrations at the bottom of the Vienna Basin during the late Middle/Late Badenian.

Multi-species measurements of fossil and recent foraminifers revealed that the stable isotope composition of calcareous tests of many species exhibits deviations from the calcite precipitated in equilibrium with the ambient water (Grossman 1987; Spero & Lea 1996; Peeters et al. 2002; Naidu & Niitsuma 2004; Schmiedl et al. 2004). These deviations are most expressed in the $\delta^{13}C$ signal and are called vital effects. Vital effects include the incorporation of metabolic CO_2 into the shells during calcification, calcification rate rising, physiological changes during ontogenesis, kinetic effects and the photosynthetic activity of symbionts (Erez 1987; McConnaughey 1989; McConnaughey et al. 1997). The high similarity between the $\delta^{13}C$ values of *Uvigerina* and *Globigerina* from DNV can be regarded as a vital effects implication for *G. bulloides*. The increased productivity in surface water evocates a higher calcification rate and consequently higher respiration of CO_2 (Berger et al. 1978) in the eutrophic species *G. bulloides*. CO_2 comprises the light carbon isotope ^{12}C. Under the favourable conditions, which apparently occurred in the Vienna Basin, *G. bulloides* could involve more CO_2 enriched in ^{12}C (Naidu & Niitsuma 2004). Consequently, this process led to slightly more negative $\delta^{13}C$ compared to benthic *Uvigerina* from the same area.

Another process affecting foraminifer $\delta^{13}C$ is algal photosymbiosis. Planktonic foraminifers with photosymbionts display higher $\delta^{13}C$ values than nonsymbiotic species (e.g. Spero & Williams 1988; McConnaughey 1989). This could be the case of the analysed symbiont-bearing species *Globigerinoides trilobus*, whose carbon isotope results are surprisingly positive (~+1.10 ‰). The difference between *Globigerina* and *Globigerinoides* is about 1.5 ‰. During photosynthesis, the algal symbionts preferentially use the lighter version of carbon isotope (^{12}C) and so elevate the $^{13}C/^{12}C$ ratio in the ambient water. The production rate of symbionts and the degree of $\delta^{13}C$ increase in foraminifers vary directly as a function of light intensity (see Spero et al. 1991). Consequently, the near-surface dweller *G. trilobus* with photosymbionts should yield the heaviest carbon isotope values. The results from DNV show a distinctive symbiotic influence on the $\delta^{13}C$ signal of *G. trilobus*. The analysed foraminiferal taxa *Uvigerina* and *Globigerina* do not host any symbiotic algae in the cytoplasm and their stable isotope carbon signal is not changed by photosynthetic activity.

Oxygen isotopes

The ratio of the stable oxygen isotopes ^{18}O and ^{16}O is one of the most important tools in paleoceanography and paleoclimatology. In marine sediments, the oxygen isotopic composition of foraminiferal shells is used as a proxy for the temperature (e.g. Emiliani 1954; Erez & Luz 1983; McConnaughey 1989; Bemis et al. 1998). In addition to temperature, sea surface salinity changes also affect foraminiferal $\delta^{18}O$ distribution. The benthic foraminifer $\delta^{18}O$ is controlled by water temperature because salinity seems to be constant in deeper parts of the oceans (Cheng et al. 2004). On the other hand, the planktonic $\delta^{18}O$ appears to have been controlled by both, temperature of surface waters and salinity (Kennett 1986).

Water temperature decreases with increasing water depth and this trend is observed by the foraminiferal $\delta^{18}O$ data in this work (Fig. 5, Table 1). As expected, the most positive oxygen isotope values have been recorded from benthic *Uvigerina* (average +1.9 ‰). It has been shown that the oxygen isotopic composition of *Uvigerina* is in equilibrium with the surrounding seawater (Shackleton 1973). Thus, we can assume that the oxygen isotope signal of shallow-infaunal *Uvigerina* reflects the $\delta^{18}O$ conditions of pore water in the Vienna Basin during the late Middle to Late Badenian. The benthic $\delta^{18}O$ from DNV is comparable to results of many cores from the Pacific and Atlantic oceans during 14–13 Ma (e.g. Shackleton & Kennett 1975b; Woodruff et al. 1981; Savin et al. 1981; Kennett 1986; Boersma 1986). The mean values from those studies range approximately between +1.9 ‰ and +2.6 ‰. Our benthic data from DNV are also positive ranging between +1.7 ‰ and +2.3 ‰ and are apparently very close to the open ocean signal.

An increase in $\delta^{18}O$ values of benthic foraminifers may reflect several processes: a cooling of ocean water temperature, an increase in global ice volume, an increase in salinity, or some combination. The Middle Miocene $\delta^{18}O$ increase between 16.5 and 13.2 Ma (Kennett 1986) has generally been accepted as representing a major permanent buildup of the East Antarctic ice sheet (Savin et al. 1975; Shackleton & Kennett 1975a). Our positive benthic $\delta^{18}O$ record, suggesting colder bottom-water temperature, might be interpreted as result of global cooling influence recognized in world ocean and also affecting the Central Paratethys. Benthic $\delta^{18}O$ values between approximately +1.9 ‰ and +3 ‰ are interpreted as ice periods (see Williams et al. 1988) and we believe that our results of +1.7 ‰–+2.3 ‰ represent the influence of ice-buildup. Because the Vienna Basin was an intramountain shallow (neritic) basin, the bottom-water environment was evidently warmer than in the open ocean. Therefore the benthic oxygen isotope data from DNV are lower and do not show strong variations. However, in the DNV oxygen isotope profile we cannot see the distinct positive trend. We suppose that this is caused by the fact that the investigated profile from DNV represents only a small part of cooling phase.

The oxygen isotope results of *Globigerina* from DNV show a wide range between −1.11 ‰ and +1.39 ‰ (Fig. 5, Table 1). In general, we observe two directions of oxygen isotope signal: a tendency to more positive data (averaging +0.6 ‰) in the lower part of the profile up to 7 m; and a trend to more negative values (average +0.04 ‰) from 7 m to the top of DNV. The planktonic $\delta^{18}O$ data obtained from the Middle Miocene show that the most positive/coolest values between +0.6 ‰ and +1.9 ‰ were observed in the Pacific (Shackleton & Kennett 1975a; Kennett 1986); slightly

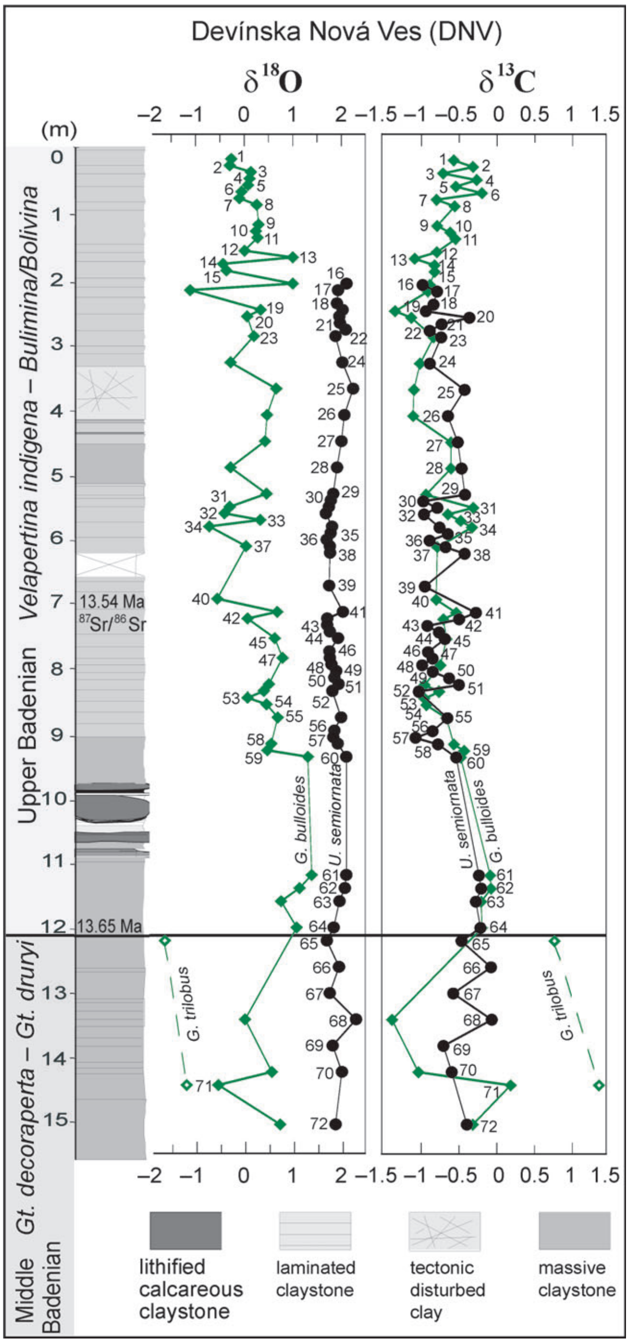

Fig. 5. The Badenian oxygen and carbon stable isotope record of planktonic and benthic foraminifers from the Vienna Basin. Ma ages agree with: 13.54 Ma (radiometric dating $^{87}Sr/^{86}Sr$, Hudáčková & Kráľ 2002), 13.65 Ma (Middle/Late Badenian boundary according to Kováč et al. 2007).

less positive data of −0.2 ‰ to +1.5 ‰ were observed in the Atlantic (Keigwin 1983; Vergnaud-Grazzini 1985) and the most negative/warmest values ranging between −1 ‰ and +0.6 ‰ were obtained in the Mediterranean Sea (Van der Zwaan & Gudjonsson 1986).

Our values from DNV are close to the Mediterranean level and show a slight negative trend. This trend could imply warming of surface water or slight decreasing of salinity or a combination of both. Since the Vienna Basin represents a shallow environment, the water temperature, in general, is expected to be higher than in the open ocean area. On the other hand, the surface water in the basin was affected by isotopically depleted meltwater arriving from the paleo-Danube delta. The frequent variations shown by $\delta^{18}O$ signal of planktonic taxa might thus reflect the temperature and salinity changes caused by both, river and rain inflow. We suggest that in the case of the Vienna Basin, the local effects played an important role and the $\delta^{18}O$ signal recorded by planktonic foraminifer *Globigerina* is influenced by both, the local temperature and salinity changes.

The use of stable isotope ratios is limited by a number of problems. $\delta^{18}O$ measurements on living and laboratory cultured foraminifers show distinct deviations with respect to the isotopic equilibrium (e.g. Grossman 1987). These deviations are presumably influenced by life processes including the vital effects. A perfect example of taxa displaying a deviation due to vital effect in this work is *Globigerinoides trilobus* (as already shown from the carbon isotope signal). This species exhibits the most negative $\delta^{18}O$ values (average −1.41 ‰) and is associated with dinoflagellate symbionts that are distributed between and on spines in a halo around the calcitic shell (Wolf-Gladrow et al. 1999). The photosynthetic activity of algal symbionts affects shell $\delta^{18}O$ values; an increase in symbiont photosynthetic activity results in a decrease in shell $\delta^{18}O$ values (e.g. Bemis et al. 1998). Species exhibiting vital effects generally have compositions 0.5–1.5 ‰ depleted in ^{18}O relative to equilibrium (Grossman 1987). *G. trilobus* from DNV displays a strong deviation of ~1.7 ‰ compared to *G. bulloides*. Such difference between two planktonic species inhabiting roughly the same environment, regarding the shallow water environment of the Vienna Basin, clearly implies the influence of symbionts in the case of *G. trilobus*. We suppose that the depleted oxygen isotope ratio and enriched $\delta^{13}C$ signal observed at the same time in *G. trilobus* do not reflect the isotopic composition of ambient water but represent the deviation due to vital effects.

We calculated paleotemperature from our benthic and planktonic $\delta^{18}O$ values using the equation of Shackleton (1974) described in the methodology part (Fig. 6). The bottom water temperature records variations of about 2 °C and represents relatively cold conditions averaging ~6.8 °C. The temperature of the water column calculated from $\delta^{18}O$ values of *G. bulloides* recorded bigger variations than in the sea floor. In general, we recognize two tendencies: a distinctive trend to cooler temperature (shift of ~6 °C) in the lower part of the profile up to 11 m and the tendency to warmer temperatures (shift of ~7 °C) from 11 m towards the top. However, the temperature in the water column (mean value ~13.7 °C) was very variable and we observe a lot of small shifts towards cooler or warmer conditions. According to our assumptions, the surface water was more influenced by the temperature changes, related to the warmer fluvial and rainwater input, than the sea bottom. Furthermore, the seasonal temperature changes affecting only the near-surface layers could play a role. In the Vienna Basin, temperature stratification has been reported in previous paleoecological works (e.g. Kováč & Hudáčková 1993; Hudáčková & Kováč

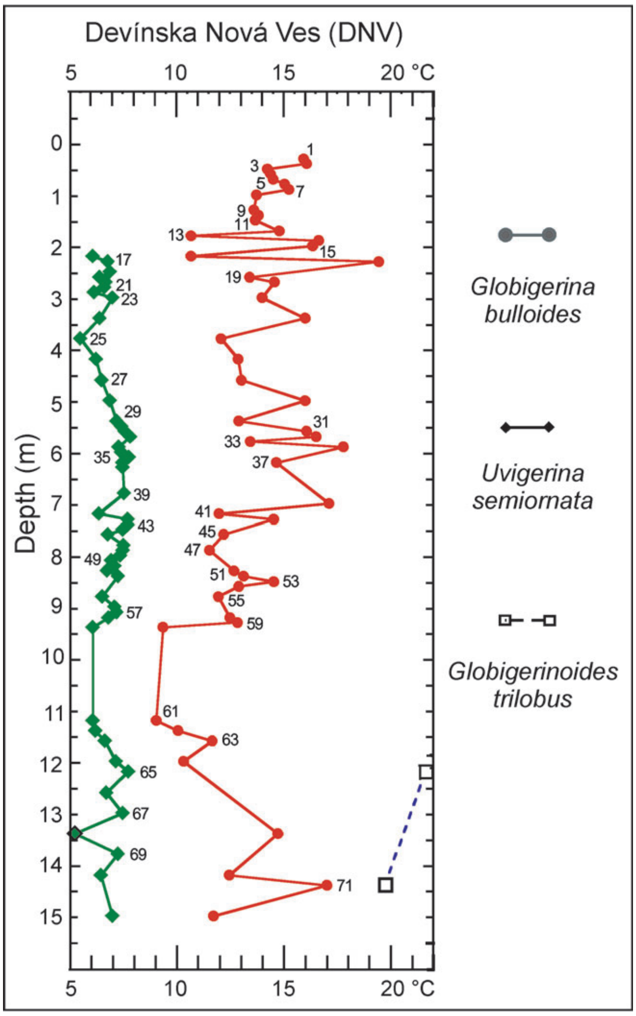

Fig. 6. Paleotemperature (°C) curves calculated from $\delta^{18}O$ data of bottom (*Uvigerina semiornata*), intermediate (*Globigerina bulloides*) and surface water (*Globigerinoides trilobus*) foraminifers in the Vienna Basin (DNV). The equation of Shackleton (1974) was used, assuming the $\delta^{18}O$ of ambient water was −0.24 ‰ according to Lear et al. (2000). The correction of −0.27 ‰ (Hut 1987) from the SMOW to PDB scale was used for $\delta^{18}O_{water}$.

1997). This stratification trend is probably related to the closing of the Central Paratethys Sea, which culminated in the Late Badenian. The difference of ~7 °C between the bottom and surface water temperature shown in this study agrees with previous observations.

The paleotemperature obtained from the oxygen isotope ratio of symbiont-bearing *G. trilobus* is evidently the highest (average at 20.6 °C), as we expected, since it is a near-surface dwelling species. However, as has been previously reported, in consideration of the assumed paleodepth of Vienna Basin (150–200 m), a difference of ~7.5 °C between the *G. bulloides* and *G. trilobus* is enormous. In the shallow basin, these two genera are supposed to have roughly the same habitat-depth, and even in the stratified water, the temperature should not be very different. There are, however, also suggestions that a species like *Globigerina bulloides* may calcify as a juvenile at depth and migrate to shallower depths in later growth stages (Spero & Lea 1996; Bemis et al. 1998). This opinion could explain the strong contrast between the water temperature indicated by $\delta^{18}O$ of *G. bulloides* and *G. trilobus*. Nevertheless, in this case, we believe that, as well as the $\delta^{13}C$ signal, the $^{18}O/^{16}O$ ratio was influenced and changed by the vital effect due to symbiotic algae, which depleted and consequently suggested a higher temperature.

Conclusions

The stable isotope signal of foraminiferal shells from the Vienna Basin (Central Paratethys) was influenced by the global temperature changes, but the local factors also played an important role. Stable isotope analyses were done on planktonic and benthic foraminiferal shells from the upper Middle to Upper Badenian (Middle Miocene) sediments of the Devínska Nová Ves-clay pit (DNV) in the Vienna Basin (in Slovakia). The most frequent foraminiferal taxa (benthic *Uvigerina semiornata* and planktonic *Globigerinoides trilobus* and *Globigerina bulloides*) have been selected for stable isotope measurements.

A nutrient enrichment in the water column and in the sea floor of the Vienna Basin was observed. The enhanced accumulation of organic matter at the sea floor followed by decomposition produced an oxygen deficiency in the bottom indicated by the low-oxygen tolerant taxa *Uvigerina*, *Bolivina*, *Bulimina* and mainly by the absence of oxic indicators.

The global cooling phase, recognized in the world ocean during the Middle Miocene, also affected the Vienna Basin. Positive benthic $\delta^{18}O$ values represent the influence of ice-buildup. The planktonic $\delta^{18}O$ record is apparently influenced by isotopically depleted freshwater arriving from the paleo-Danube runoff.

Calculated paleotemperatures showed the differences between the bottom and the water column. The bottom-water temperature indicates stable conditions whereas the surface water was apparently influenced by the temperature changes, related to the warmer fluvial and rain input. We cannot exclude the seasonal temperature changes affecting the surface water. The difference between the bottom-water and surface-water temperature could represent a stratification of the water column, which might relate to the isolation process of the Central Paratethys sea during the Badenian.

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