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# The oxygen and carbon isotopic composition of Langhian foraminiferal tests as a paleoecological proxy in a marginal part of the Carpathian Foredeep (Czech Republic)

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**Abstract:** Foraminiferal assemblages from three locations of the Moravian part of the Carpathian Foredeep (Kralice, Přemyslovice, Židlochovice) have been studied in order to determine the paleoenvironmental conditions during the Early Badenian (Middle Miocene). Paleobiological characteristics (plankton/benthos-ratio, relative abundances of warm-water plankton species, five-chambered *Globoturborotalita* spp., *Coccolithus pelagicus* and high nutrient markers [benthos], test sizes and ranges of *Globigerina* sp. and cibicidoids, Benthic Foraminiferal Oxygen Index) were determined along with stable C and O isotope compositions. The stable isotope compositions show large variabilities indicating sample inhomogeneity in well preserved foraminiferal samples, interpreted as a sign of primary environmental variation and postmortem mixing of tests of different populations and sources. Based on the combined interpretation of paleobiological indicators and isotopic compositions, two theoretical models were established to describe the observed paleobiological and stable isotope data, that were used to categorize the locations studied. Several types of near-shore paleoenvironment were distinguished using the theoretical models: (i) bay influenced by seasonal phytodetritus supply from the continent (Kralice); (ii) dynamic shore characterized by variable isotopic compositions probably due to mixing of indigenous, transported and reworked tests (Přemyslovice); (iii) shore of alternating normal marine and continentally influenced environments (Židlochovice).

**Key words:** Middle Miocene, Badenian, Carpathian Foredeep, paleoecology, foraminifera, calcareous nannoplankton, oxygen and carbon stable isotopes.

## Introduction

Oxygen and carbon isotopic compositions of the foraminiferal tests represent routine geochemical proxies for paleoenvironmental conditions in the oceanic realm. In the epeiric seas, the application of the method is more problematic. Variable paleoenvironments with oscillations of evaporation/influx-ratio, variable input of organic matter from the continent and communication/isolation events influenced the isotopic composition of sea water and make interpretation of these proxies difficult.

The study area, the Central Paratethys, represents a chain of Oligocene and Miocene epeiric seas with marked oscillation of paleoecological parameters and episodic communication with the oceanic realm (Rögl 1998, 1999).

The study interval can be well biostratigraphically dated and represents a lower part of the local Central Paratethys Badenian stage which is correlated with the Langhian (Rögl et al. 2008; Hohenegger et al. 2009). The paleogeographic and paleoclimatic situation which could have influenced the isotopic composition of the Central Paratethys sea water is well known. The period was characterized by a large marine transgression affecting the entire circum-Mediterranean area. The transgression was connected with brief reopening of the Mediterranean–Indo-Pacific seaway and invasion of the tropical–subtropical water masses into the Central Paratethys basins (Rögl & Steininger 1983; Rögl 1998, 1999; Popov et al. 2004; Kováč et al. 2007; Piller et al. 2007). The Early Badenian climate of the Central Paratethys realm can be assumed as fairly uniform and corresponds with the Miocene Climatic Optimum (Böhme 2003; Slamková & Doláková 2004). The Mean Annual Temperature (MAT) of the Early Badenian has been estimated at 13 to almost 20 °C on the basis of percentage of evergreen taxa with a seasonal temperature change of less than 25 °C and with the temperature of the coldest month varying between 4 and 10 °C (Kvaček et al. 2006), although a minimum Sea Surface Temperature (SST) has been estimated at 16–18 °C based on stenothermic gastropods (Harzhauser et al. 2002).

Most of the oxygen and carbon isotopic data from the Central Paratethys originated from this interval (Foraminifera: Gonera et al. 2000; Bicchi et al. 2003; Báldi 2006; Báldi & Hohenegger 2008. Molluscs: Latal et al. 2004, 2006; Harzhauser et al. 2007. Bryozoa and bulk sediments: Hladíková & Hamršmíd 1986; Nehyba et al. 2008). Comparison of paleotemperatures estimated for the terrestrial biotopes (Kvaček et al. 2006) with calculations of paleotemperatures from the isotopic data suggest an $^{18}$O-enriched seawater system (due to evaporation), different from estimation for the oceanic realm (−1 ‰; Lear et al. 2000). Latal et al. (2006) and Nehyba et al. (2008) estimated the average $\delta^{18}$O value of the Central Paratethys sea water at approximately +1 ‰.

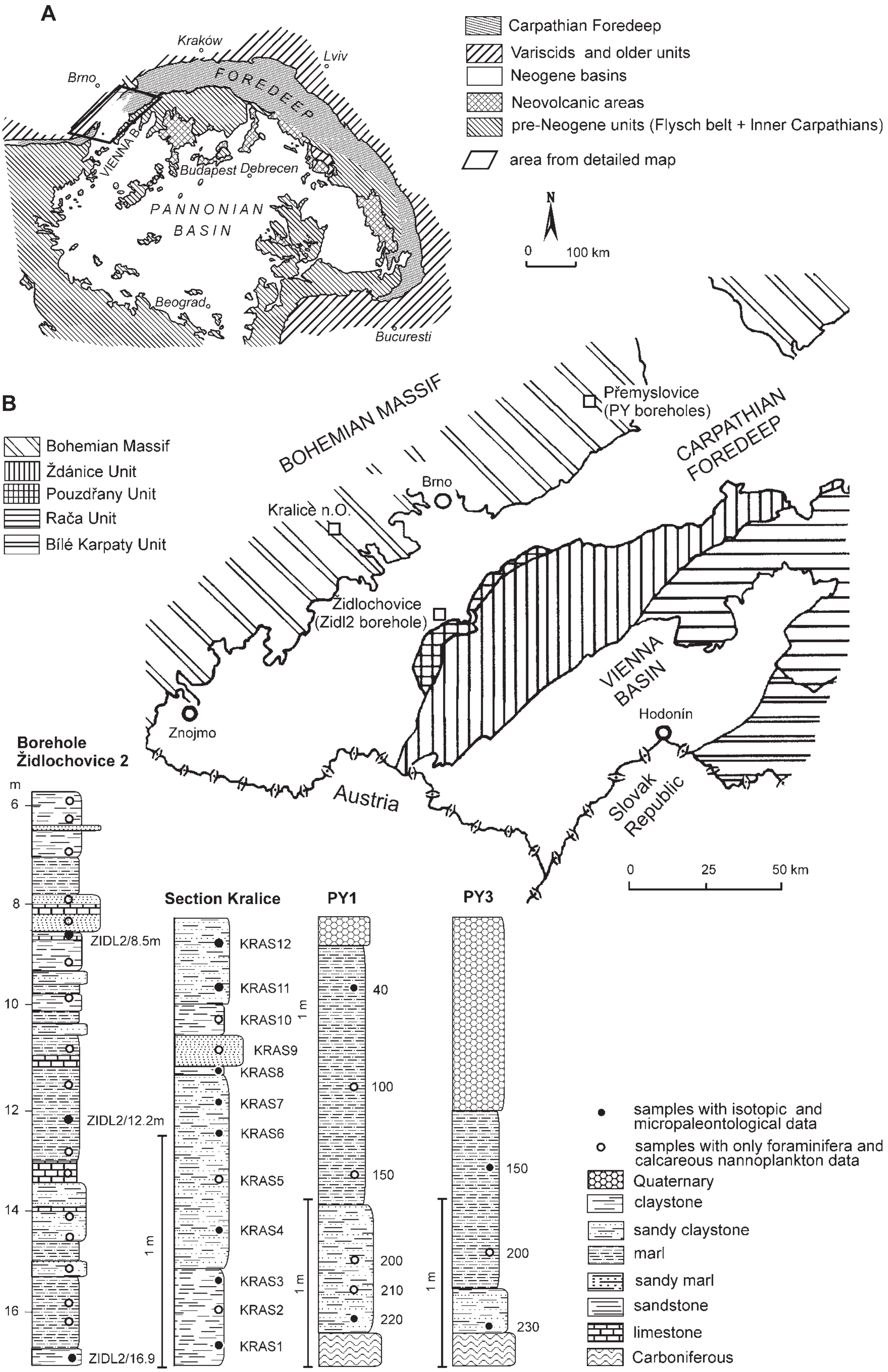

**Fig. 1.** Location and lithology of studied boreholes PY1, PY3, ZIDL2 and section at Kralice.

In this study, isotopic analysis was focused on the assemblages from the marginal shallow-water parts of the Carpathian Foredeep. The aim of the work is to analyse the causes of observed within-sample variabilities and discuss the potential of the isotopic proxy for paleoenvironmental interpretation in the marginal parts of epeiric seas.

## Materials

The studied materials originated from three shallow boreholes from the Carpathian Foredeep: Přemyslovice (PY1, PY3) (Zágoršek & Holcová 2009), Židlochovice (ZIDL2) and section Kralice (KRAS; Zágoršek et al. 2009). Samples KRAS 1, 3, 4, 6, 7, 8, 11, 12; PY1/40, PY1/220, PY3/230, PY3/150; ZIDL2/8.5m, ZIDL2/12.2m and ZIDL2/16.9m were analysed for isotopic composition of foraminiferal tests (Fig. 1). The assemblages can be correlated with calcareous nannoplankton Zone NN5 according to occurrence of *Sphenolithus heteromorphus* and absence of *Helicosphaera ampliaperta* (Martini 1971). The study interval can be well dated using two planktonic foraminiferal events: the first occurrence (FO) of *Orbulina suturalis* (Figs. 2, 3.1,2) and the last occurrence (LO) of *Praeorbulina* (Figs. 2, 3.3) (Berggren et al. 1995; Lourens et al. 2004; Rupp & Hohenegger 2008; Hohenegger et al. 2009). These biostratigraphical events characterize the Langhian (Gradstein et al. 2004) which can be correlated with the lower part of the local Central Paratethys Badenian stage (Hohenegger et al. 2009). Figure 1 shows transitional rock types including marls and sandstones (Fig. 1).

## Methods

The foraminifera were separated from washed residues (fraction 0.063 to 2 mm). The residues were dried at room temperature. Cooking, freezing or any chemical processes were omitted from the disintegration of rock samples. The washed residues were rinsed with hydrogen peroxide. Empty tests were hand-picked from floating ones for isotopic analyses and were cleaned in an ultrasonic bath of distilled water. Foraminiferal tests were checked for recrystallization on the inner test walls using scanning electron microscope (SEM) type JSM 6380 LV (Fig. 4). Groups of small-sized four-chambered *Globigerina* sp. (Fig. 3.6,7) and *Cibicidoides* spp. (Fig. 3.15,16) were chosen for isotopic analysis. Planktonic foraminifera for isotopic analysis were picked from the size fraction 63–200 μm in which no specimens with reproductive chambers were observed. The size ranges of analysed tests in individual samples are specified in Table 1. Benthonic foraminifera were picked from the 63–300 μm fraction.

The carbon and oxygen isotope compositions of calcite were determined at the Institute for Geochemical Research of the Hungarian Academy of Sciences (Budapest, Hungary) following the method of acid digestion of the carbonatite samples (for analytical details see Spötl & Vennemann 2003). The isotope analyses were conducted using automated GASBENCH equipment attached to a Finnigan Thermo delta plus XP mass spectrometer. The compositions are expressed as $\delta^{13}C$ and $\delta^{18}O$ values relative to V-PDB, according to the equation:

$$\delta = (R_{sample}/R_{standard}-1)\times 1000$$

where R is the $^{13}C/^{12}C$ or $^{18}O/^{16}O$ ratio in the sample or in the international standard V-PDB. The analytical precision was better than 0.15 ‰ based on multiple analyses of standards, but the standard deviation is much higher for most of the samples (discussed below).

During a first run of analyses only two tests were analysed from each sample that yielded a high within-sample variability. In order to investigate this variability in detail, recrystallization of inner test walls was re-evaluated for 10–15 specimens from every sample (Fig. 4). Assemblages with abraded and corroded tests were excluded from the isotopic analysis, thus, during a taphonomic analysis only size sorting of tests separately for benthic and planktonic assemblages were used as a criterion of postmortem test transport. The greatest diameter of tests from every sample were measured using a VIA video measuring system and data were summarized in histograms. The first hundred specimens of *Globigerina* spp. and the first hundred specimens of *Cibicidoides* spp. from fraction 0.063 to 2 mm were measured. As transported tests should be well-sorted, accumulation of small,

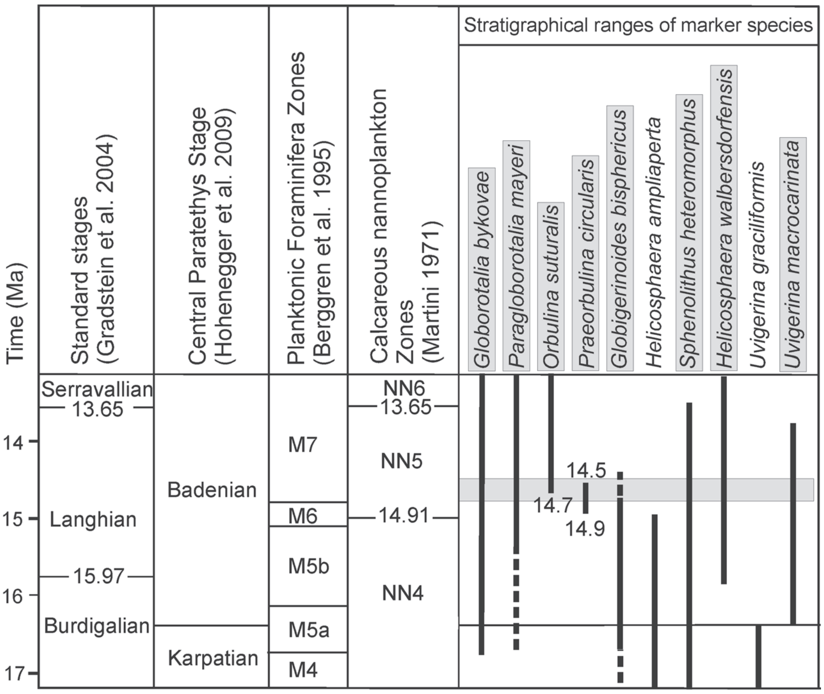

**Fig. 2.** Biostratigraphical correlation of studied interval.

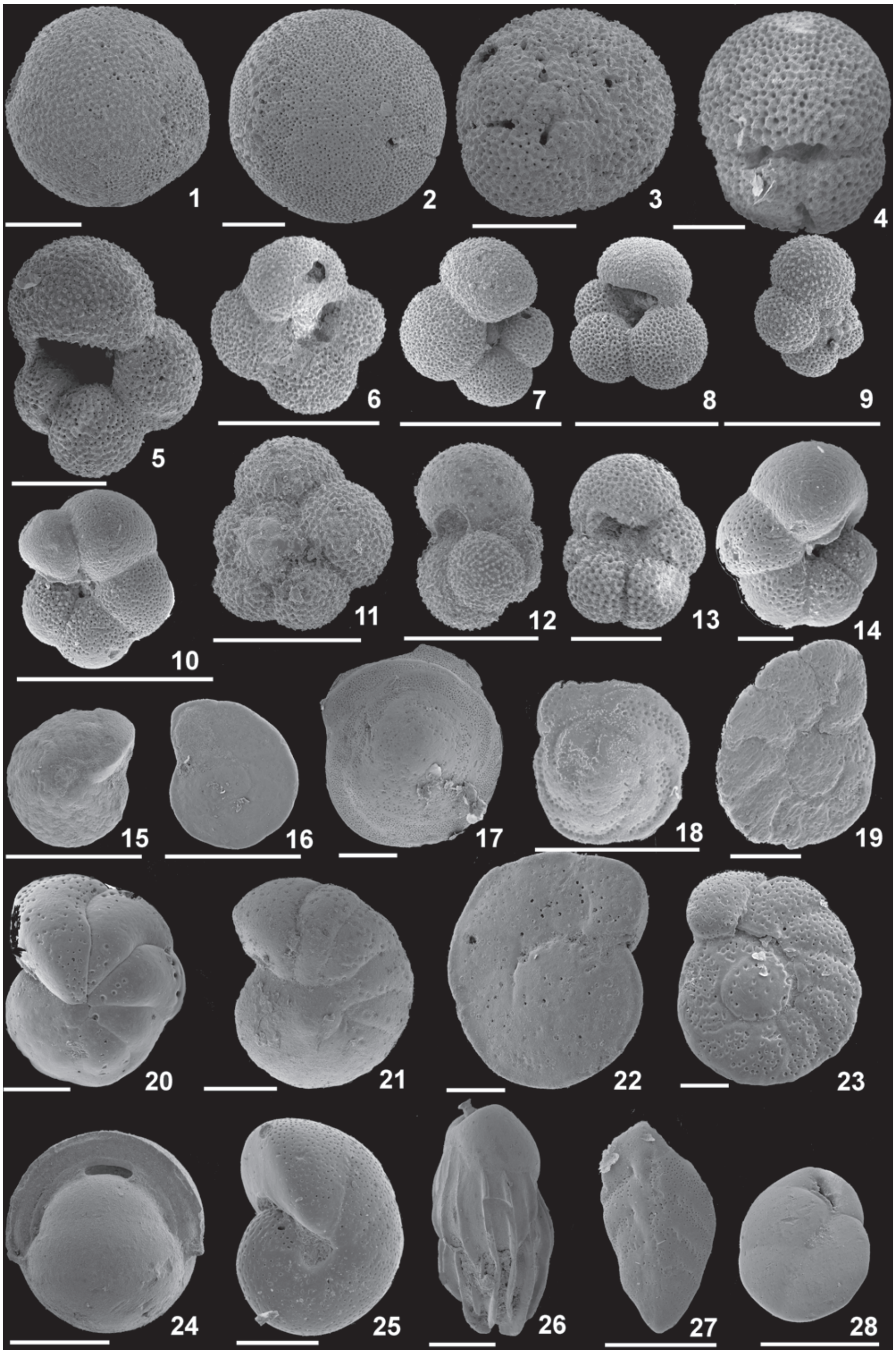

**Fig. 3.** Biostratigraphical markers and isotopically analysed foraminifera. **1–2** — *Orbulina suturalis* Brönnimann; 1 — KRAS1, 2 — PY3/150. **3** — *Praeorbulina circularis* Blow; PY3/150. **4** — *Globigerinoides bispherieus* Todd; PY1/40. **5, 8** — *Globigerina bulloides* d'Orbigny; 5 — PY1/220, 8 — PY3/230. **6–7** — Small four-chambered *Globigerina* spp.; 6 — KRAS6, 7 — PY1/40. **9, 11–12** — Small five-chambered *Globoturborotalita* spp.; 9 — PY3/230, 11 — ZIDL2/12.2, 12 — ZIDL2/16.6. **13** — *Globorotalia acrostoma* (Wezel); PY1/220. **10, 14** — *Globorotalia bykovae* (Aisenstat); 10 — ZIDL2/12.2, 14 — KRAS1. **15–16** — Small-sized *Cibicidoides* sp.; KRAS12. **17** — *Asterigerinata planorbis* d'Orbigny, adult specimen; KRAS4. **18** — *Asterigerinata planorbis* d'Orbigny, juvenile specimen; KRAS1. **19, 21–22** — *Cibicidoides ungerianus* d'Orbigny; 19 — spiral view, PY3/230, 21 — umbilical view, PY3/150, 22 — spiral view, PY3/150. **20** — *Lobatula lobatula* Walker & Jacob; PY 3/150. **23** — *Cibicidoides austriacus* d'Orbigny; PY1/220. **24** — *Pullenia bulloides* d'Orbigny; PY1/220. **25** — *Melonis pompilioides* (Fichtel & Moll); ZIDL2/16.6. **26** — *Uvigerina macrocarinata* Papp & Turnovsky; PY3/150. **27** — *Bolivina dilatata* Reuss; KRAS6. **28** — *Globocassidulina globosa* (Hantken); KRAS1. Length of scale bar 100 μm.

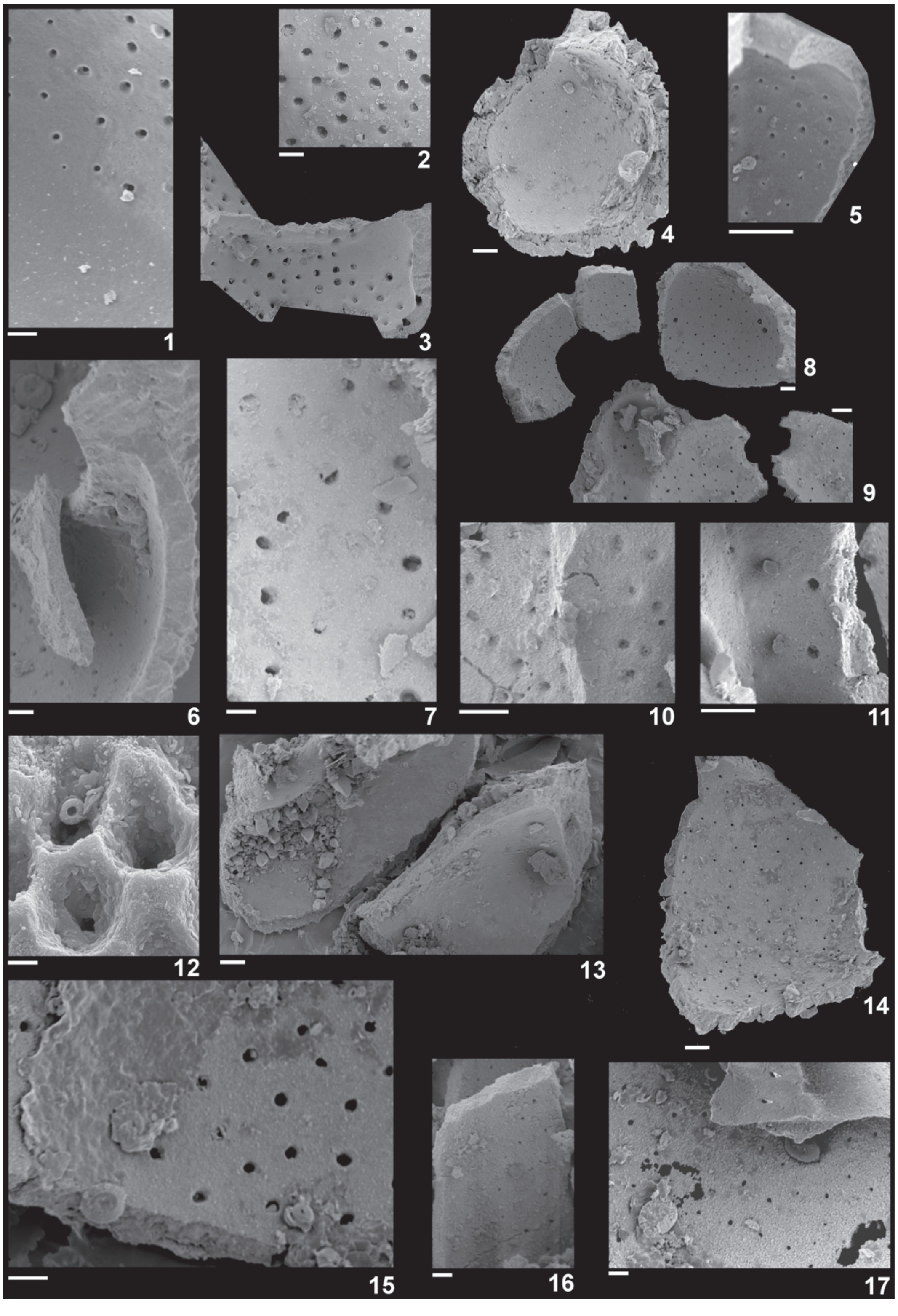

**Fig. 4.** Inner test wall of the isotopically analysed foraminifera. **1–7** — Well preserved inner test wall; 1 — four-chambered *Globigerina* spp., KRAS1; 2 — four-chambered *Globigerina* spp., KRAS6; 3 — *Cibicidoides* sp., PY3/230; 4 — four-chambered *Globigerina* spp., PY1/150; 5 — four-chambered *Globigerina* spp., KRAS4; 6 — *Cibicidoides* sp., PY1/40; 7 — *Cibicidoides* sp., PY1/40. **8–9** — Slightly recrystallized tests, four-chambered *Globigerina* spp., KRAS1. **10–11** — Slightly dissoluted tests, *Cibicidoides* sp., PY1/200. **12** — *Globigerinoides bisphericus* Todd — detail of outer test wall, PY3/150. **13** — Strongly recrystallized test, *Cibicidoides* sp., KRAS8. **14** — Well preserved to slight alternated test wall, four-chambered *Globigerina* spp., KRAS3. **15** — Rest of crust after ultrasonic cleaning, four-chambered *Globigerina* spp., KRAS7. **16** — Moderate recrystallized test, four-chambered *Globigerina* spp., KRAS7. **17** — Strong dissolution, four-chambered *Globigerina* spp., PY1/200. Length of scale bar 10 μm.

usually thin-walled tests (rounded forms < 200 µm) indicates suspended-load transport; accumulation of large, thick-walled tests (> 300 µm) and missing of smaller tests characterize tests which were transported as bed load (Murray 1965; Wang & Murray 1983; Holcová 1996).

### *Paleobiological proxies*

Isotopic data were compared with foraminiferal and calcareous nannoplankton paleoebiological proxies. In all studied samples, foraminiferal and calcareous nannoplankton assemblages were quantitatively evaluated from 200–500 specimens (for detailed methods see Zágoršek et al. 2009).

The upper part of the water column was characterized using the following proxies:

(1) Relative abundances of warm-water taxa of planktonic foraminifera according to the classifications of Spezzaferri (1995), Bicchi et al. (2003) and Rupp & Hohenegger (2008). Among warm-water taxa were classified orbulinids, *Globigerinoides* spp. and *Globigerinella* spp., cold-temperate indicators are *Globorotalia* spp. while *Globigerina* spp. and *Turborotalita* spp. indicate cold water.

(2) The ratio between five- and four-chambered small *Globigerina* and *Globoturborotalita*. Generally, in the normal oceanic realm small *Globigerina* are considered to be an indicator of the presence of nutrient-rich, cold water, whereas in the marginal part of the basin they may indicate deterioration of paleoenvironmental conditions, such as oscillation of salinity. The alternation of horizons dominated by four-chambered *Globigerina* or five-chambered *Globoturborotalita* is characteristic for the early Middle Miocene of the Central Paratethys (Rupp & Hohenegger 2008; Zágoršek et al. 2009). Hohenegger et al. (2008) consider "five-chambered globigerinids" to be indicators of cold, non-stratified water masses.

(3) Size distribution of tests of *Globigerina* spp. Histograms of the test diameter of approximately one hundred specimens of *Globigerina* spp. from every sample were constructed and used for estimation of postmortem transport.

(4) Relative abundances of the most common calcareous nannoplankton species: *Coccolithus pelagicus* and *Reticulofenestra minuta*. The presence of *Coccolithus pelagicus* is a traditional indicator of cold and nutrient-rich water (Okada & McInyre 1979; Winter et al. 1994), but this is weakened by the common occurrence of the species in waters up to 18 °C in which it can be used as a tracer of the periphery of areas of enhanced productivity (Cachao & Moita 2000). The species also may dominate secondarily in assemblages due to its higher resistance to dissolution (Roth & Berger 1975; Roth 1994; Flores et al. 2003).

The most common species *Reticulofenestra minuta* is generally opportunistic; its blooms are connected with environmental stress characterized by quick changes within environmental conditions (Wade & Brown 2006) and its high abundance distinguishes assemblages from continental margins (Haq 1980) where the species can tolerate the brackish to hypersaline, high productivity environments (Wade & Bown 2006). Wells & Okada (1997), Flores et al. (1997), Bollmann et al. (1998) and Kameo (2002) regard small *Reticulofenestra* spp. as eutrophic species while Hallock (1987), Beaufort & Aubry (1992) and Spezzaferri et al. (2009) suggested that blooms of small *Reticulofenestra* indicate oligotrophic warm water.

(5) Plankton/benthos (P/B) ratio. This indicator should change with paleodepth. The relationship between bathymetry and relative abundance of planktonic foraminifera has been determined by van der Zwaan et al. (1990). A discrepancy between calculated paleodepth and sedimentology has been pointed out, for example, in the Middle Miocene of the Central Paratethys (Hohenegger 2005). Therefore, estimation of paleodepth using modified plankton/benthos-ratio was compared with depth ranges of individual taxa (Culver & Buzas 1980, 1981; Murray 1991; de Stigter et al. 1998; Hohenegger 2005; van der Hinsbergen et al. 2005) and oxygenation of bottom water. The high P/B-ratio in comparison with assumed paleodepth may be caused by postmortem transport of plankton to the marginal part of the basin and/or by extra high production of plankton as well as low production of benthos.

Bottom environment has been characterized by several indicators:

(6) The BFOI = Benthic Foraminiferal Oxygen Index. BFOI expresses oxygen content (Kaiho 1994, 1999):

$$\mathrm{BFOI} = \mathrm{O}/(\mathrm{O}+\mathrm{D}) \times 100$$

where O is the number of oxic indicators and D is the number of disoxic indicators. Oxic and disoxic indicators were classified according to Kaiho (1994, 1999), den Dulk et al. (1998), den Dulk et al. (2000), Spezzaferri et al. (2002) and Báldi (2006).

(7) Relative abundances of high primary productivity indicators among benthic species (*Uvigerina grilli*, *Uvigerina macrocarinata*, *Uvigerina pygmoides*, *Uvigerina uniseriata*, *Melonis pompiloides*; Spezzaferri et al. 2002).

(8) Size distribution of cibicidoid tests. It is evaluated similarly to the size distribution of the *Globigerina*-plexus, namely providing information on postmortem transport.

Statistical analysis of data was done using PAST software (Hammer et al. 2001).

## Results

### *Stable isotope compositions, test recrystallization and taphonomic changes*

Repeated measurements of isotopic composition of foraminiferal tests showed standard deviations higher than acceptable value < 0.3 for 20 samples out of the 27 analysed (Table 1). To analyse the causes of this high variability, the recrystallization of the inner test walls was re-evaluated and taphonomical analysis of assemblages was done.

The recrystallization of inner test walls was re-analysed on 10–15 specimens from every sample. One to three recrystallized specimens were detected per sample in 7 out of the 25 samples. However, the variability of isotopic composition (expressed by standard deviation) does not correlate positively with recrystallization degree, since the highest values of standard deviations were recorded for samples with well preserved tests (Table 1).

**Table 1:** Standard deviations of $\delta^{18}O$ and $\delta^{13}C$ measurements, numbers of recrystallized tests in repeated SEM analysis of recrystallization and size ranges of isotopically analysed tests (for total ranges see Fig. 6).

| **Sample** | **Standard deviation: $\delta^{18}O$ measurements** | **Standard deviation: $\delta^{13}C$ measurements** | **Number of measurements** | **Number of well preserved tests** | **Number of recrystallized tests** | **Size range of isotopically analysed tests (μm)** |
|---|---|---|---|---|---|---|
| Z2/12.2/CIB | 0.82 | 0.28 | 6 | 12 | 0 | 200–300 |
| Z2/12.2/GL | 0.13 | 0.17 | 3 | 13 | 0 | 80–200 |
| Z2/16.9/CIB | 0.69 | 0.24 | 3 | 11 | 0 | 200–300 |
| Z2/16.9/GL | 0.29 | 0.07 | 3 | 15 | 0 | 130–200 |
| PY1/220CIB | 0.15 | 0.33 | 4 | 13 | 0 | 220–300 |
| PY1/220GL | 1.42 | 0.70 | 3 | 11 | 0 | 180–200 |
| PY1/40CIB | 0.64 | 0.33 | 4 | 13 | 0 | 200–300 |
| PY1/40GL | 0.55 | 0.37 | 5 | 14 | 0 | 180–200 |
| PY3/150CIB | 0.69 | 0.43 | 6 | 12 | 0 | 250–300 |
| PY3/150GL | 0.25 | 0.24 | 5 | 14 | 0 | 130–200 |
| PY3/230CIB | 0.35 | 0.17 | 3 | 13 | 0 | 210–300 |
| PY3/230GL | 1.10 | 0.53 | 3 | 15 | 0 | 180–200 |
| KRAS1CIB | 0.16 | 0.05 | 4 | 12 | 0 | 200–300 |
| KRAS1GL | 0.80 | 0.03 | 4 | 14 | 0 | 100–200 |
| KRAS4CIB | 0.34 | 0.15 | 3 | 11 | 0 | 200–300 |
| KRAS4GL | 0.23 | 0.27 | 6 | 14 | 0 | 80–200 |
| KRAS6CIB | 0.10 | 0.14 | 2 | 13 | 0 | 200–300 |
| KRAS6GL | 0.40 | 0.71 | 6 | 15 | 0 | 130–200 |
| KRAS11CIB | 0.21 | 0.26 | 4 | 12 | 0 | |
| KRAS12CIB | 0.16 | 0.36 | 4 | 13 | 0 | |
| KRAS3CIB | 0.63 | 0.25 | 3 | 12 | 1 | |
| KRAS3GL | 0.58 | 0.22 | 5 | 15 | 2 | |
| KRAS7CIB | 0.14 | 0.73 | 4 | 15 | 2 | |
| Z2/8.5/CIB | 0.79 | 0.44 | 5 | 13 | 1 | |
| Z2/8.5/GL | 1.07 | 0.15 | 6 | 15 | 1 | |
| KRAS8/CIB | 0.67 | 1.04 | 4 | 11 | 1 | |
| KRAS8/GL | 0.36 | 0.42 | 3 | 15 | 3 | |

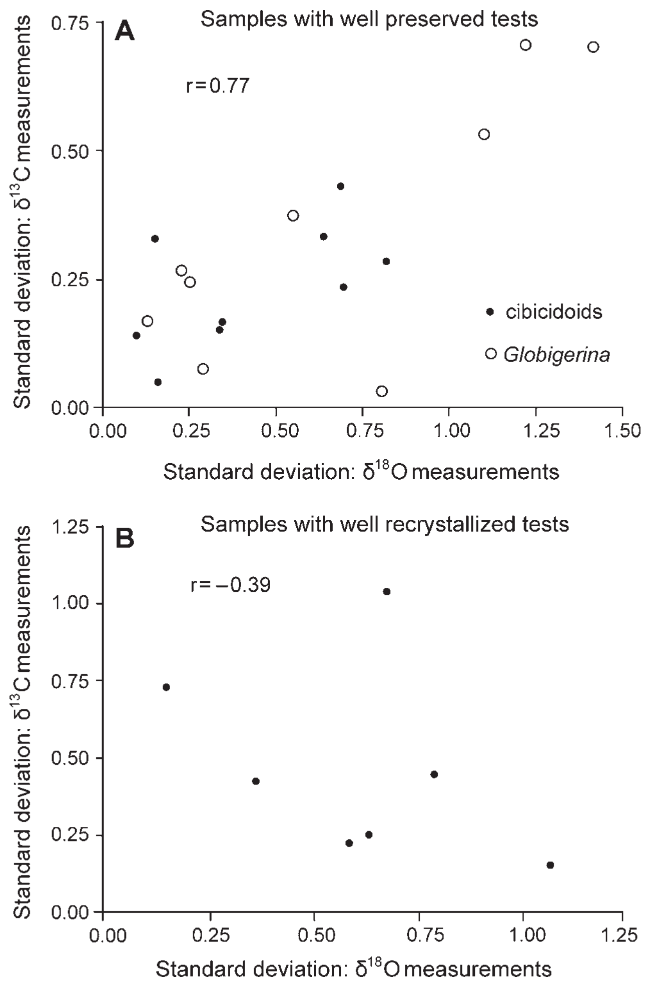

**Fig. 5.** Relations between standard deviations of $\delta^{18}$ O and $\delta^{13}C$ measurements for individual samples: **A** — samples with well-preserved tests, **B** — samples with admixture of slightly recrystallized tests.

It is remarkable that standard deviations of $\delta^{13}C$ and $\delta^{18}O$ values for individual samples are positively correlated for samples with only well preserved tests (correlation coefficient $=0.77$), while a slightly negative trend appears for samples with presence of recrystallized tests (correlation coefficient $=-0.39$). As the standard deviations for $\delta^{13}C$ and $\delta^{18}O$ values show a good positive correlation for well preserved samples and a slight negative one for recrystallized tests, the isotopic scatter seems to be related to primary characteristics rather than instrumental error, representing original water chemistry from the paleobiotops in which the analysed specimens lived (Fig. 5).

To recognize postmortem transport and reworking of tests, the taphonomic analysis of assemblages followed. Generally, marked evidence of transport was not recorded: abrasion, erosion and other damage to tests were not observed using SEM. All benthic assemblages are composed of taxa with comparable environmental requirements (shallow water, normal marine). Both planktonic and benthic species have corresponding stratigraphic ranges. However, two indications of postmortem changes of assemblages were recorded: (1) Size sorting of tests in samples from the PY-boreholes showed a lack of small-sized tests (Figs. 6, 7) that may be caused by destruction of small tests in high energy environment and/or dissolution of small tests. (2) Paleodepth calculated from the P/B-ratio (van der Zwaan et al. 1990) showed high values (excepting samples PY1/40, PY3/230) from 200 to 350 m which is in contrast with paleodepth estimated on the base of depth range of benthic species (from 20 to 100 m). It may be caused by postmortem transport of planktonic foraminifera and their accumulation in the marginal part of the basin. These indications of postmortem transport of tests are taken into account in the following interpretations.

### *Relations between isotopic compositions and other paleoenvironmental proxies*

Correlations between the paleobiological proxies and between paleobiological proxies and isotopic values were quantified using Spearman coefficients and statistically verified by p-value (Tables 2, 3). The following correlations were considered to be statistically significant:

a) Mean test sizes of *Globigerina* spp. in individual samples correlate very positively with sizes of *Cibicidoides* spp. (correlation coefficient $=0.85$, $p=0.006$);

**Table 2:** Values of Spearman coefficient (upper numeral) for paleobiological proxies based on species composition of assemblages and size variability. Only coefficients with p-values (measure of significance; lower numeral) under 0.05 are recorded.

| **Spearman coefficients**<br>**p-value** | **P/B-ratio** | **Warm-water plankton** | **Test size (*Globigerina*)** | **Size range (*Globigerina*)** | **Five-chambered *Globoturborotalita* spp. (%)** | ***Coccolithus pelagicus* (%)** | **Test size (cibicidoids)** | **Size range (cibicidoids)** | **High nutrient markers (benthos)** | **BFOI** |
|---|---|---|---|---|---|---|---|---|---|---|
| **P/B-ratio** | | | –0.71<br>0.031 | | | | | –0.68<br>0.049 | | |
| **Warm-water plankton** | | | 0.66<br>0.048 | | | | 0.81<br>0.008 | | | |
| **Test size (*Globigerina*)** | | | | | –0.80<br>0.007 | | 0.85<br>0.006 | 0.67<br>0.047 | | |
| **Size range (*Globigerina*)** | | | | | | | | | | –0.67<br>0.046 |
| **Five-chambered *Globoturborotalita* spp. (%)** | | | | | | | –0.69<br>0.047 | | | |
| ***Coccolithus pelagicus* (%)** | | | | | | | | | | |
| **Test size (cibicidoids)** | | | | | | | | 0.67<br>0.048 | | |
| **Size range (cibicidoids)** | | | | | | | | | | |
| **High nutrient markers (benthos)** | | | | | | | | | | –0.81<br>0.01 |
| **BFOI** | | | | | | | | | | |

b) Planktonic foraminifera: Mean test size of *Globigerina* spp. negatively correlates with relative abundances of five-chambered *Globoturborotalita* spp. (correlation coefficient =–0.80, p=0.007) and with P/B-ratios (correlation coefficient =–0.71, p=0.031), positively with relative abundances of warm-water plankton (correlation coefficient=0.66, p=0.048). Furthermore, sizes of *Globigerina* spp. negatively correlate with $\delta^{18}$O values (correlation coefficient =–0.83, p=0.006) and with ranges of $\delta^{18}$O and $\delta^{13}$C measurements. Relative abundances of five-chambered *Globoturborotalita* spp. positively correlate with $\delta^{18}$O values (correlation coefficient=0.70, p=0.049) and relative abundances of warm-water plankton with ranges of $\delta^{18}$O measurements (correlation coefficient=0.54, p=0.048).

c) Benthic and benthic vs. planktonic foraminifera: Negative correlation was recorded between BFOI and size ranges of *Globigerina* spp. (correlation coefficient =–0.67, p=0.046) and between test sizes and size ranges of cibicidoids (correlation coefficient=0.67, p=0.048). Relative abundances of high nutrient markers negatively correlate with differences in carbon isotopic composition of benthos and plankton (correlation coefficient =–0.70, p=0.043), positively with differences in oxygen isotopic composition of benthos and plankton (correlation coefficient=0.64, p=0.048) and with $\delta^{13}$C values (correlation coefficient=0.61, p=0.049).

According to the above mentioned correlations between geochemical and paleobiological proxies, theoretical models of two "boundary" foraminiferal assemblages can be defined (Fig. 8):

Model (1). The first "boundary" assemblage is characterized by small tests, plankton with higher abundances of five-chambered *Globoturborotalita* spp., benthos by lower abundance of high-nutrient markers correlative with higher BFOI index. Higher $\delta^{18}$O values for plankton, lower differences between oxygen isotope composition of benthos and plankton and larger differences between carbon isotope composition of benthos and plankton characterize isotopic values in this assemblage.

Model (2). The second "boundary" assemblage is composed of larger tests with higher abundance of warm-water taxa in plankton and higher abundance of high-nutrient markers at the bottom. The isotopic composition of tests is variable, which agrees with higher size variability of the analysed taxa. The isotopic values are characterized by larger differences between oxygen isotope composition of benthos and plankton and lower $\delta^{18}$O values, while the $\delta^{13}$C values for plankton and benthos are similar.

### *Types of marginal foraminiferal assemblages*

On the basis of quantitative isotopic (Fig. 9) and paleobiological data, the studied samples were classified using Non-

**Table 3:** Values of Spearman coefficient (upper numeral) for relations between geochemical and other paleobiological proxies. Only coefficients with p-values (measure of significance; lower numeral) under 0.05 are recorded.

| **Geochemical proxies**<br>**Spearman coefficients p-value**<br>**Paleobiological proxies** | **$\delta^{18}$O (*Globigerina*)** | **$\delta^{18}$O (cibicidoids)** | **Range of $\delta^{18}$O measurements (*Globigerina*)** | **Range of $\delta^{18}$O measurements (cibicidoids)** | **$\delta^{18}$O cibicidoids-$\delta^{18}$O *Globigerina*** | **$\delta^{13}$C (*Globigerina*)** | **$\delta^{13}$C (cibicidoids)** | **Range of $\delta^{13}$C measurements (*Globigerina*)** | **Range of $\delta^{13}$C measurements (cibicidoids)** | **$\delta^{13}$C cibicidoids-$\delta^{13}$C *Globigerina*** |
|---|---|---|---|---|---|---|---|---|---|---|
| **P/B-ratio** | | | | | | | | | | |
| **Warm-water plankton** | | | 0.54<br>0.048 | | | | | | | |
| **Test size (*Globigerina*)** | –0.83<br>0.006 | | 0.65<br>0.043 | | | | | 0.72<br>0.031 | | |
| **Size range (*Globigerina*)** | | | | | | | | | | |
| **Five-chambered *Globoturborotalita* spp.** | 0.70<br>0.049 | | | | | | | | | |
| ***Coccolithus pelagicus* (%)** | | - | | | | | | | | |
| **Test size (cibicidoids)** | | | | | | | | | | |
| **Size range (cibicidoids)** | | | | | | | | | 0.69<br>0.042 | |
| **High nutrient markers (benthos)** | | | | | 0.64<br>0.048 | 0.61<br>0.049 | | | | –0.70<br>0.043 |
| **BFOI** | | | | | | | | | | |

metrical Multidimensional Scaling (Euclidean distance), Principal Component Analysis and Cluster Analysis (Ward method) (PAST-software). The following types of foraminiferal assemblages can be distinguished (Fig. 10):

1. The "Přemyslovice" area is characterized by varying isotopic compositions of tests (Fig. 9) and markedly differs from the other sections (Fig. 9). Geochemical and paleobiological markers showed that assemblages from this area are near to the Model (2). Some isotopic values of planktonic tests are comparable to values from the central part of the basin, mainly from the Gliwice boreholes due to higher $\delta^{13}$C values (Fig. 11).

2. Foraminiferal assemblages in the "Kralice bay" (samples KRAS 1, 4, 6) and in the "Židlochovice" area are similar and agree with the Model (1) assemblage. However, some differences can be observed. In the "Kralice bay", the seawater system differs from the other part of the Central Paratethys by low $\delta^{13}$C values especially for the planktonic foraminifera, though the $\delta^{18}$O values are comparable (Fig. 11). A significant discrepancy between paleodepth estimated from the P/B-ratio (300–350 m) and depth range of taxa (20–100 m) were recorded (Zágoršek et al. 2009). In the "Židlochovice" area, two different assemblages were recorded. The assemblage from sample ZIDL2/16.9 is similar to those from the "Kralice bay" with respect to species composition and size distribution of tests but isotopic composition is specific with high $\delta^{13}$C values similar for benthos and plankton (Fig. 10). Isotopic values are near to those from the area of Gliwice (Fig. 11).

## Discussion

Taking the high standard deviations obtained for many of the analysed samples into account, reliability of the isotopic data is a major issue. The isotopic scatter seems to be related to primary characteristics rather than instrumental error, representing original water chemistry from paleobiotopes in which the analysed specimens lived. In order to display the internal variability, not only average values but also whole ranges of measured isotopic values were taken into consideration in the paleoenvironmental interpretations.

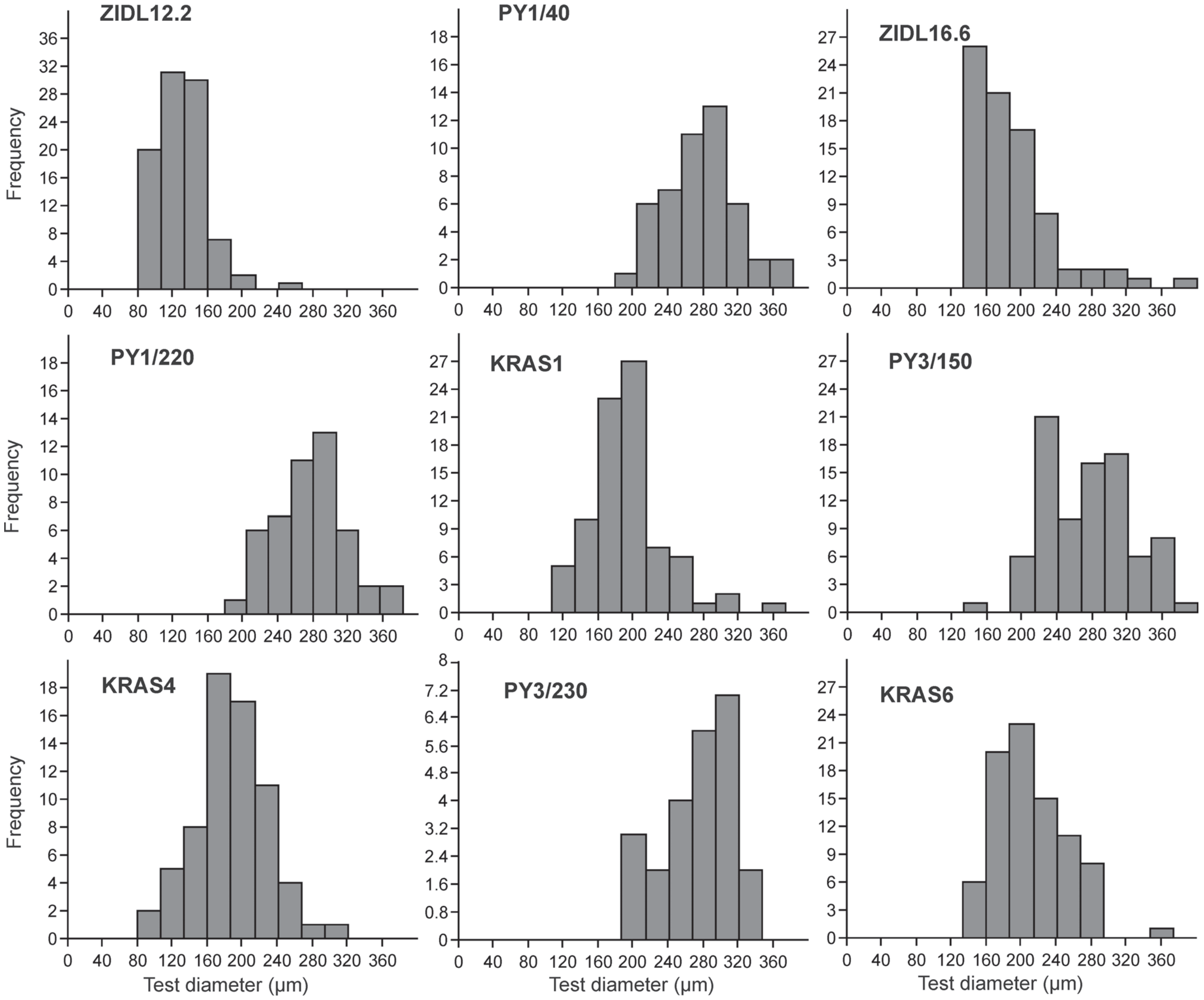

**Fig. 6.** Size sorting of planktonic tests; line indicates maximal diameter of suspension-transported tests.

### ***Factors influencing the oxygen and carbon isotopic variability in the marginal part of epicontinental seas***

In the shallow-water marine facies, indigenous, transported and/or reworked foraminiferal tests may be mixed. The following factors could have influenced the isotopic variabilities in the studied samples:

1. Intraspecific variability. The correlation between the size of planktonic foraminifera and their isotopic composition is documented but studies have given contradictory evidence. The factor was comprehensively described by Waelbroeckет et al. (2005). Within-test variations of $\delta^{18}$O values may exceed 2 ‰ depending on the actual species. The $\delta^{13}$C values may be influenced by the presence of symbiotic algae around the shell (Pearson & Wade 2009). They form a local microenvironment with relatively heavy $\delta^{13}$C value (Spero & Williams 1988; Pearson et al. 1993; Wade et al. 2008). On the other hand, incorporation of metabolic light carbon into the shells can cause an anomalously light $\delta^{13}$C ratio (e.g. Douglas & Savin 1978). This effect seems the most common in small species and juveniles, while larger species and larger size fractions generally give isotopic ratios closer to equilibrium with the $\delta^{13}$C value of the surrounding water (Berger et al. 1978). However, laboratory experiments conducted on the planktonic foraminifera *Globigerinoides sacculifer* under controlled temperature and light levels show that chamber $\delta^{13}$C values increase with increasing light levels; the effect of ontogeny on chamber $\delta^{13}$C is minimal. Chamber $\delta^{18}$O values are also not affected by ontogeny, but decrease with increasing light levels (Spero & Lea 1993). Within size differences in our planktonic foraminifera (80–200 μm; Table 1), the test sizes of *Globigerina* spp. correlate negatively with $\delta^{18}$O values (correlation coefficient = –0.76; Table 2) in agreement with observation of Waelbroecket et al. (2005) for comparable size fractions 200–250 μm vs. 250–315 μm. Spero et al. (2003) recorded opposite correlation but they compared the isotopic composition of size fractions 250–350 μm vs. >650 μm. Significant correlation between test size of benthic foraminifera and isotopic values has not been observed (Table 2).

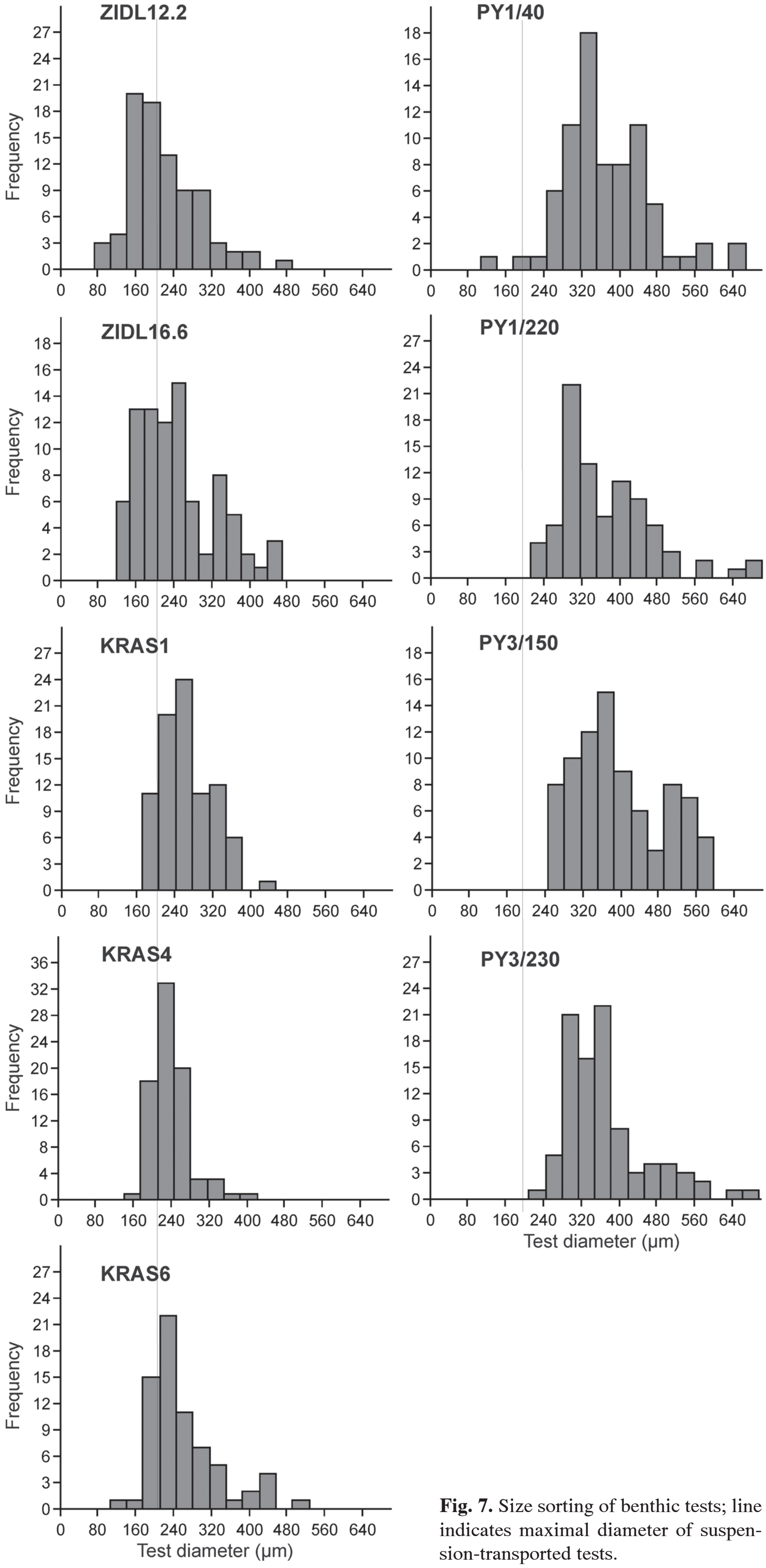

**Fig. 7.** Size sorting of benthic tests; line indicates maximal diameter of suspension-transported tests.

2. Seasonal variability: foraminifera which grew during the warmer and colder seasons (e.g. spring and summer population) may be mixed in one sample and increase variability of isotopic composition in this sample. The seasonality was detected for the Early Badenian of the Central Paratethys using stable isotope profiles of *Turitella* that showed seasonal differences in oxygen isotopic composition from –0.5 to 1.5 ‰ (Latal et al. 2006). Seasonality during the Early Badenian is also expected from the paleobotanic studies (Kvaček et al. 2006). However, the question arises whether the seasonal differences can be recorded in isotopic composition of foraminiferal tests. The life cycles of planktonic foraminifera are 2–4 weeks (Bijma et al. 1990); for individual species it is restricted to a specific period of the year. Blooms of the analysed genus *Globigerina* are reported from the early spring (Kleijne et al. 1989; Thunell & Reynolds Sautter 1992; Oda & Yamasaki 2005). Then, measured isotopic values of *Globigerina* plexus record water chemistry during early spring flourishing of *Globigerina* and their high variability cannot be caused by seasonal differences in the isotopic composition of sea water.

The situation is different for benthic foraminifera. The majority of *Cibicidoides* sp. tests is larger than 150 µm (Fig. 7). For this size fraction Fontanier et al. (2006) supposed rather long-term calcification processes (several weeks or months), which limit the impact of ephemeral $^{12}$C enrichment during eutrophic periods. However, Mackensen et al. (1993) showed that *Cibicidoides wuellerstorfi* $\delta^{13}$C values may be influenced by seasonally high organic matter fluxes. Therefore, these inconsistent actuoecological data cannot explain whether the isotopic composition of *Cibicidoides* sp. reflects the "mean" annual isotopic value of the sea water or the value during a seasonal influx of organic matter. The $\delta^{13}$C and $\delta^{18}$O ranges at normal marine isotopic compositions around 0 ‰ (Fig. 10) support the assumption of long growth over the year averaging the carbon input from various sources such as continental influx or planktonic organic matter.

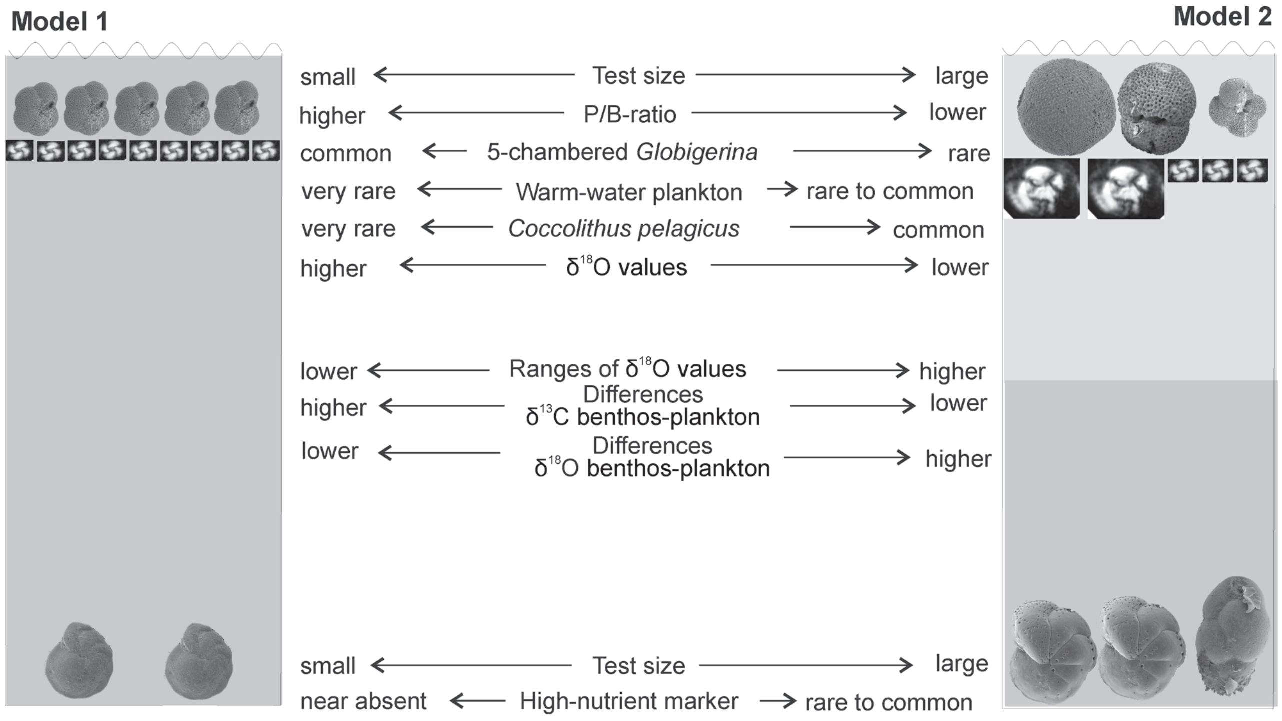

**Fig. 8.** Models of two "boundary" marginal-sea environments based on paleontological and geochemical proxies and their correlations.

3. Interannual climatic variability. Populations of decades to some hundred years (depending on sedimentation rate) may be mixed in one sample (due to bioturbation). During this time, wet and dry and/or colder and warmer years can alternate which may cause short-time oscillations of salinity, temperature and influx of organic matter from the continent. Such disturbances could be expected particularly in the upper part of the water column that can be interpreted from the significant dominance of stress-tolerant small-sized *Globigerina*-plexus (foraminifera) and *Reticulofenestra minuta* (calcareous nannoplankton; Wade & Bown 2006). However, the ranges of these oscillations and their influence on the isotopic values cannot be quantified.

4. Postmortem transport. Lateral transport of the sinking tests of planktonic foraminifera leads to differences between living and sedimented assemblages. A site of deposition, therefore, collects faunas from a certain area depending on combined effect of current directions and current speeds (Takahashi & Bé 1984). The source areas of planktonic foraminifera may be characterized by paleoenvironments and water chemistries different from the area of their deposition. Specimens from different areas may mix in one fossil assemblage and increase its variability. Transport of planktonic tests may be promoted by downwelling antiestuarine circulation assumed for the Early Badenian by Brzobohatý (1987) and Báldi (2006), although a complex model of water mass circulation has not been established yet. Though direction and distance of the test transport cannot be determined from the paleoceanographical model, a lateral transport of tests is probable.

5. Reworking of foraminiferal tests. Reworking may be expected in the study area because abundant intraclasts indicating cannibalization of older sediments characterize the marginal Early Badenian lithofacies in the Carpathian Foredeep (Nehyba & Šikula 2007). Reworked tests may isotopically differ due to different paleoenvironments or a more complex sedimentary history including secondary diagenetic effects. Besides the slightly recrystallized tests recorded in some assemblages (Table 1), reworked tests can also be expected in samples with no indications of postmortem changes.

### *Marginal marine environments in the Carpathian Foredeep*

To summarize isotopic and paleontological data (Figs. 8, 11, Tables 2, 3), the following types of marginal environments in the Carpathian Foredeep can be suggested:

1. Paleoenvironment in the "Kralice bay". The Middle Miocene sediments in this area represent a denudation relict (situated about 30 km from the continuous extent of the Early Badenian deposits; Nehyba & Šikula 2007), which were deposited during the second Langhian transgression (Hohenegger et al. 2007) on the Variscan basement. Significant disturbances from the continent are expected. This hypothesis can be supported by different carbon isotope values of planktonic foraminiferal tests in comparison with similar foraminifera from the central part of the Paratethys (Fig. 11).

The interpretation of the paleoenvironment in the "Kralice bay" is based mainly on dominance of opportunistic taxa (small *Globigerina*, *Reticulofenetra minuta*, small *Cibicidoides* sp.), low δ$^{13}$C values and larger differences between carbon isotopic composition of benthos and plankton and no indication of postmortem tests transport. Though δ$^{13}$C values may depend on many factors, the δ$^{13}$C values for plankton are near to areas with phytodetritus supply where

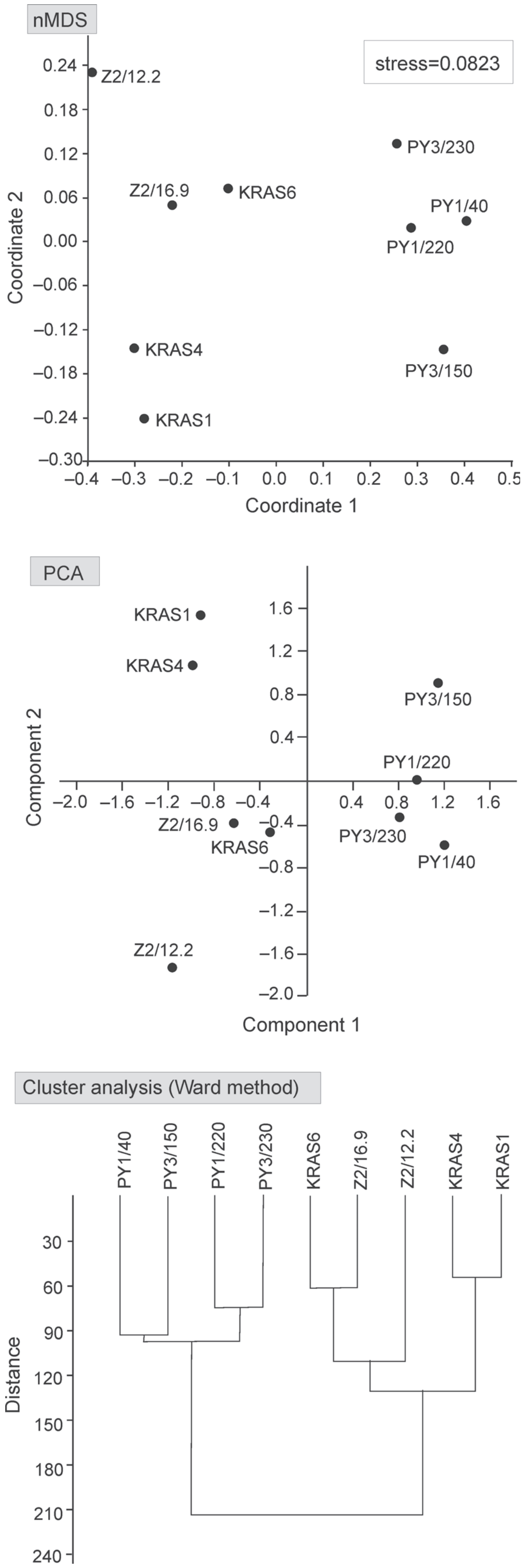

**Fig. 9.** Classification of samples based on geochemical and paleobiological markers using Nonmetrical Multidimensional Scaling (nMDS), Principal Component Analysis (PCA) and Cluster Analysis.

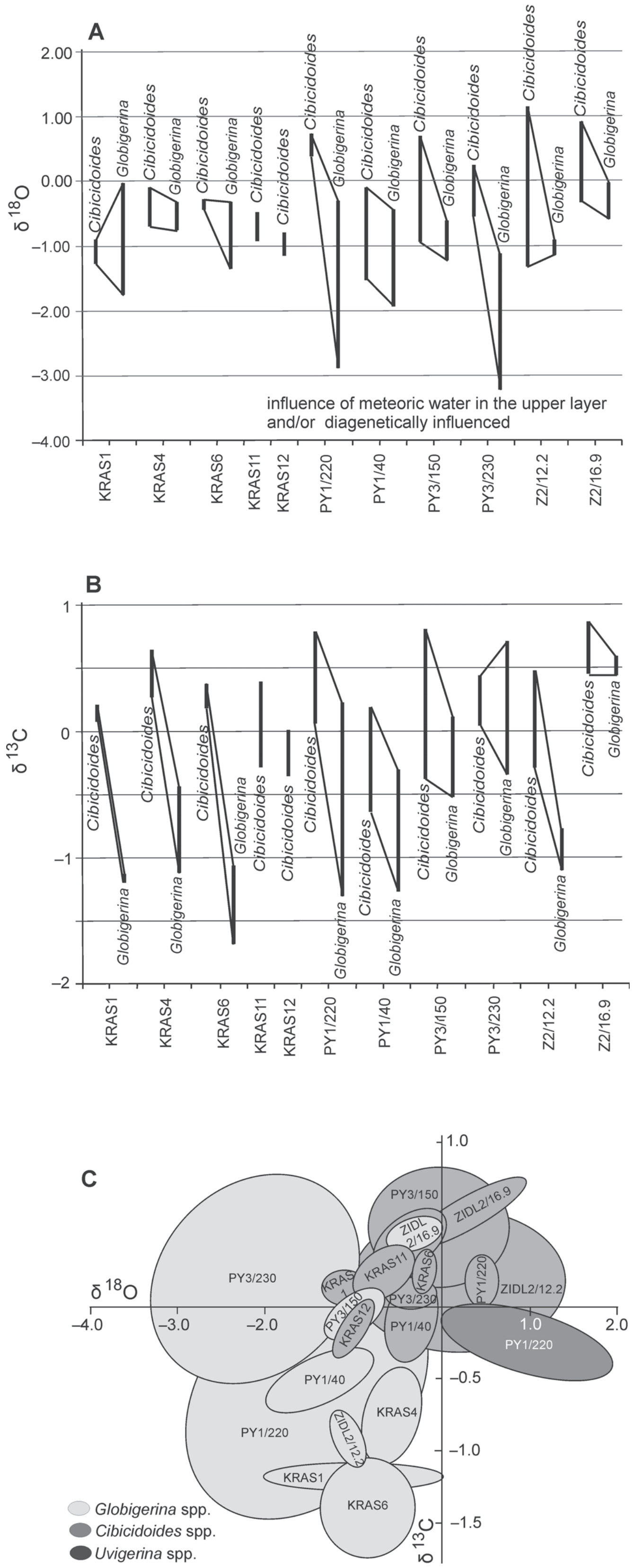

**Fig. 10.** Ranges of oxygen and carbon isotopic values for individual samples. **A** — Ranges of oxygen isotopic values; **B** — Ranges of carbon isotopic values; **C** — Ranges of oxygen and carbon isotopic values.

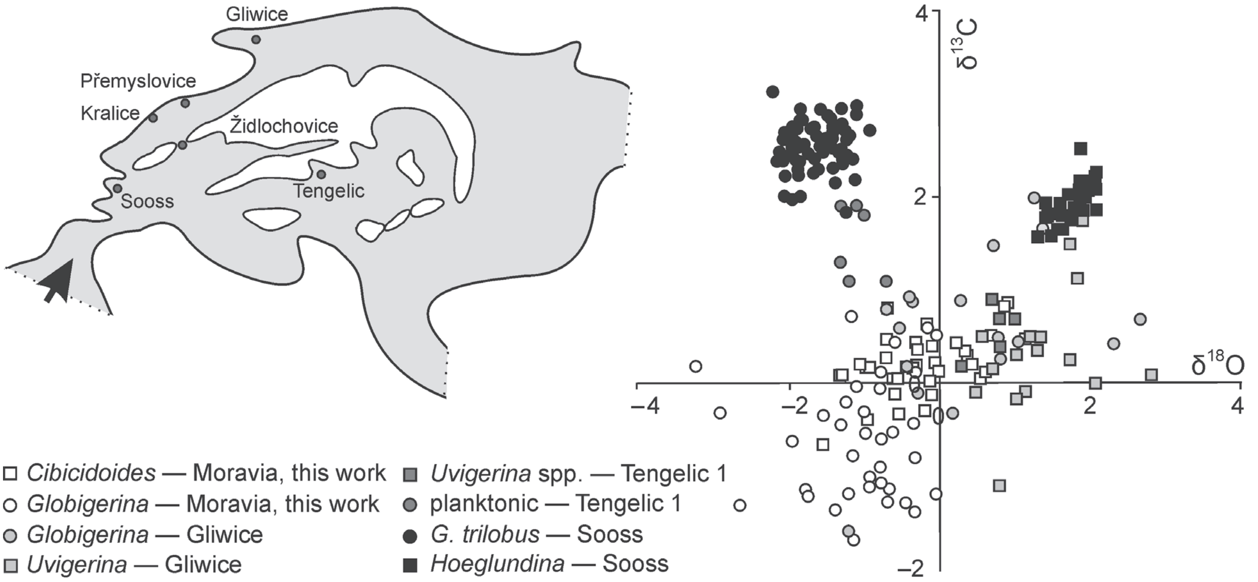

**Fig. 11.** Foraminiferal oxygen and carbon isotopic data for the Early Badenian of the northern part of the Central Paratethys (Gonera et al. 2000; Bicchi et al. 2003; Báldi 2006; Báldi & Hohenegger 2008). Paleogeography after Rögl (1998).

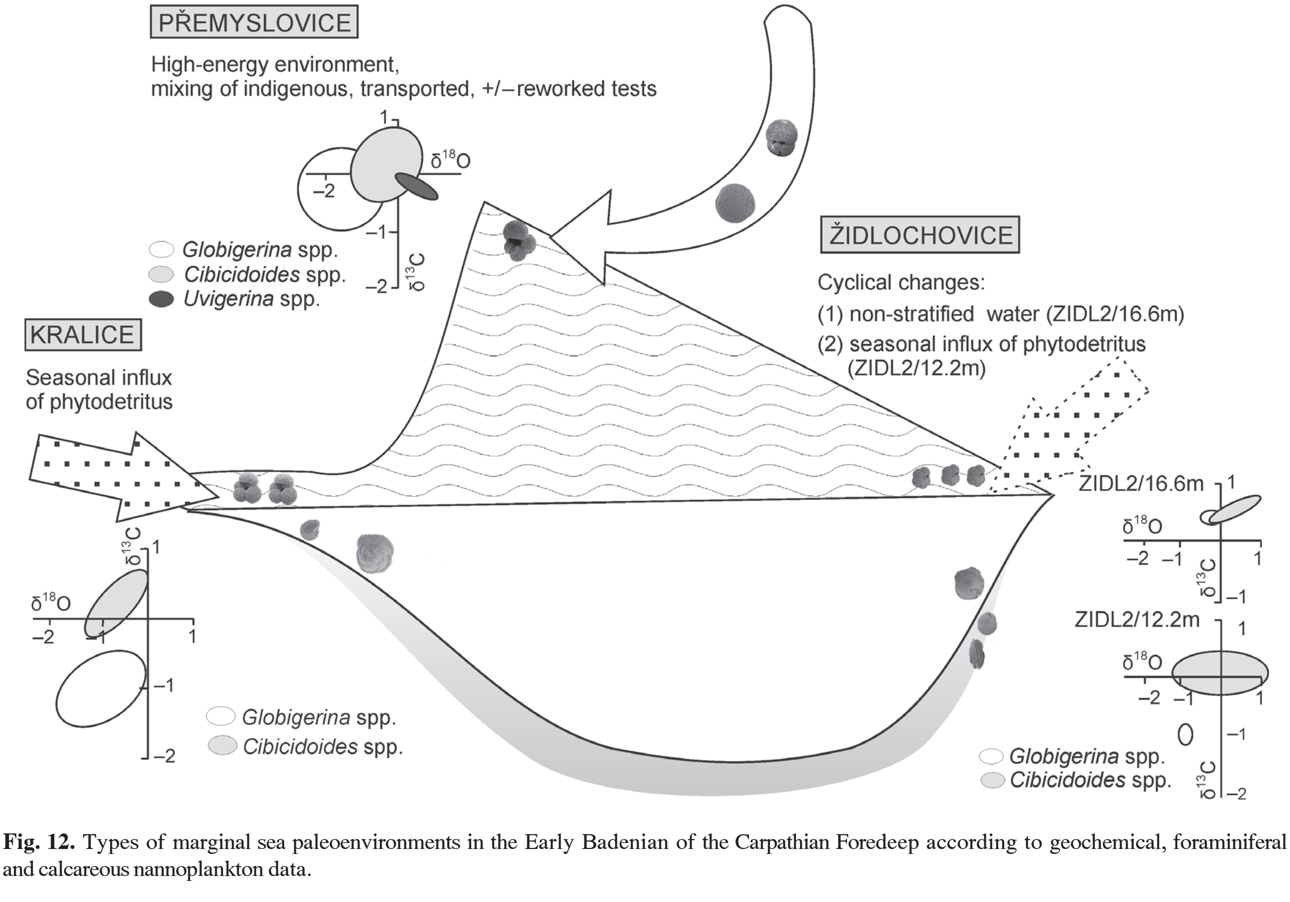

**Fig. 12.** Types of marginal sea paleoenvironments in the Early Badenian of the Carpathian Foredeep according to geochemical, foraminiferal and calcareous nannoplankton data.

low $\delta^{13}C$ values are indicative for short productive periods (Fontanier et al. 2006). Increasing influx of meteoric water would shift the C and O isotope compositions of sea water in a negative direction that appears in the planktonic tests that grow in this particular period. Short term early spring bloom may accelerate zooplankton production including opportunistic species (numerous small-sized specimens) which results in high values of P/B-ratio. As a consequence, the van der Zwaan et al. (1990) correlation between depth and P/B-ratio cannot be used.

2. The "Přemyslovice" area is characterized by peculiar isotopic compositions of planktonic foraminiferal tests and absence of small-sized tests. Samples PY1/220 and PY3/230 show high $\delta^{13}C$ and $\delta^{18}O$ variations. Higher abundance of warm-water planktonic taxons indicating warmer rather oligotrophic conditions does not agree with higher abundance of high-nutrient markers at the bottom. Increased isotopic variability may be generally explained by several taphonomic disturbances in assemblages: (i) mixing of indigenous, transported and/or reworked tests with different isotopic ranges in a dynamic environment in which small tests could be mechanically destroyed, (ii) missing of small-sized foraminifera and higher abundance of resistant calcareous nannoplankton species *Coccolithus pelagicus* (Roth & Berger 1975; Roth 1994; Flores et al. 2003) due to dissolution that may remove a component with specific isotopic values or affect the isotopic compositions via dissolution/reprecipitation. It is important to note that dissolution was observed in sample PY1/200 with rare foraminifera (Fig. 4.10,11,17), although their isotopic compositions were not determined concerning preservation stage. The low $\delta^{18}O$ end of the field of samples PY1/220 and PY3/230 (Fig. 10) may indicate input of meteoric water from the continent to the sea water, as diagenetic changes can be excluded due to the lack of recrystallization signs.

3. The "Židlochovice" area is represented by two samples. The assemblages are similar to those from "Kralice bay" and a similar environment influenced by phytodetritus supply can be expected. Sample ZIDL2/16.6 has high $\delta^{13}C$ values comparable for benthos and plankton suggesting a non-stratified, well-mixed water column. The normal marine $\delta^{13}C$ and $\delta^{18}O$ values indicate the lack of riverine water influx from the continent at this particular site.

## Conclusions

Foraminiferal assemblages from three localities on the marginal parts of the Moravian part of the Carpathian Foredeep have been studied by means of paleobiological and stable C and O isotope analyses. The complex interpretation of paleobiological characteristics and isotope compositions has led us to the following conclusions:

1. For reliable interpretation of isotopic data in a marginal nearshore environment, detailed taphonomical analysis of assemblages is necessary. Recrystallized tests may represent only a small part of fossil assemblages. The influence of mixing of indigenous, postmortem transported and reworked tests should be expected even if no indicators of postmortem transport and resedimentation of tests are observed. The postmortem transport and resedimentation of tests is a considerable cause of large variability of the isotopic composition of tests.

2. Even in indigenous assemblages, the isotopic composition of foraminiferal tests in marginal marine environment is influenced by many factors including strong continental influx of meteoric water, detrital organic matter and nutrients. Due to the spatially varying influences, the isotopic compositions show distinctions between different parts of epeiric basin and groups of taxa with different life strategy (plankton, benthos).

3. In the studied parts of the Carpathian Foredeep, comparison of geochemical and paleobiological proxies enables us to distinguish two types of shallow marine environments: (i) bay influenced by seasonal phytodetritus supply connected with bloom of opportunistic taxa and carbon isotopic values different from other parts of the Central Paratethys; (ii) dynamic shore characterized by variable isotopic compositions probably due to mixing of indigenous, transported and reworked tests.

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