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Foraminiferal record of the Middle Miocene climate transition prior to the Badenian salinity crisis in the Polish Carpathian Foredeep Basin (Central Paratethys)

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Foraminifers occurring in marls underlying the Middle Miocene Badenian gypsum in the northern Polish Carpathian Foredeep in one borehole section [Młyny (Busko) PIG 1] and in two dewatering pits in operating quarries (Leszcze and Borków) contain well-preserved foraminifers. Sixty-seven species of benthic and twenty-one species of planktonic foraminifers are recorded in the 12-m-thick section of the Młyny borehole. Benthic assemblages are characterized by the dominance of *Bulimina* and *Uvigerina* while planktonic assemblages are composed mainly by warm-water orbulinids and *Globigerinoides* spp. in the lower part of the Młyny section and by temperate-cold water *Globigerina* spp. in the upper part of the Młyny section as well as the Leszcze and Borków sections. The taxonomic composition of foraminiferal assemblages makes it possible to distinguish two foraminiferal zones in the Młyny borehole: the *Orbulina suturalis* and *Uvigerina costai* zones, and only the latter zone is accessible at Leszcze and Borków. The benthic foraminiferal successions in the studied interval suggest oxygenation and productivity changes in the Carpathian Foredeep Basin prior to the Badenian salinity crisis. Four intervals of lowered oxygenation and/or elevated organic flux to the sea-floor are recognized; the intervals in which foraminiferal assemblages suggest marine environments with lowered oxygenation in bottom waters alternate between the intervals where stress markers form less than 50% of the benthic foraminiferal assemblages. Benthic assemblages are moderately to highly diversified, and species have more equal frequencies. The upsection decrease in the proportion of planktonic foraminifers reflects the shallowing of the basin accompanied by a decrease in the temperature gradient between the upper (warmer) and deeper (colder) water beds. The average palaeotemperature of water based on $\delta^{18}O$ of *Uvigerina* and *Globigerina* decreased by ca. 2 and ca. 6°C, respectively (from 9.9 and 17.4°C in the *Orbulina suturalis* Zone to 7.9 and 11.5°C in the *Uvigerina costai* Zone, respectively). Below the gypsum, the $\delta^{18}O$ values of both benthic and planktonic foraminifers show quite large variations possibly due to the salinity increase. Coeval domination of benthic foraminiferal assemblages by *Bulimina* suggests increased surface water productivity and an increased organic flux to the sea-floor prior to the onset of evaporite deposition and/or salinity increase.

Key words: Middle Miocene, foraminifers, Paratethys, Badenian, salinity crisis, Carpathian Foredeep.

INTRODUCTION

The Paratethys was an epicontinental sea that developed as a relic of the Tethys. It existed from the Early Oligocene to late Middle Miocene times, and until the Middle Miocene it was in communication with the normal marine environments of the Mediterranean Basin and Indian Ocean (e.g., Harzhauser and Piller, 2007; Filipescu and Silye, 2008; Beldean et al., 2010). The repeated occurrence of isolation resulted in several salinity crises in the Carpathian region and other places in the Eastern Paratethys as well as in the Red Sea and the Middle East (Rögl, 1998; Popov et al., 2004). The Middle Miocene salinity crisis in the Central Paratethys started shortly after 13.81 ± 0.08 Ma, as indicated by $^{40}Ar/^{39}Ar$ dating of volcanic tuffs below and within the Badenian salts in southern Poland (de Leeuw et al., 2010). The major step in Middle Miocene global cooling is dated at 13.82 ± 0.03 Ma in the Mediterranean (Abels et al., 2005) and because of this temporal relationship the cooling is interpreted to be the trigger of evaporite deposition (de Leeuw et al., 2010). The temperature decline after the Miocene climatic optimum (Böhme, 2003) that preceded evaporite deposition found its expression in the disappearance of warm-water planktonic foraminiferal assemblages and the expansion of the cool-water populations that was recorded both in the Paratethys (e.g., Szczechura, 1982; Gonera et al., 2000; Báldi, 2006; Kováčová et al., 2009) and the Tethys area (Bicchi et al., 2003). The signal of the Badenian cooling trend in the Carpathian Foredeep is stronger than in the Mediterranean (Bicchi et al., 2003) possibly due to the changing circulation (Báldi, 2006).

A pilot study of the uppermost part of marls (2-m-thick) underlying the Badenian gypsum in one locality in southern Poland (Borków, Nida River Valley; Fig. 1) showed that a clear environmental change took place during the deposition of the marls, from a middle to outer marine shelf, well-ventilated environment with moderate primary productivity to an inner shelf environment (Peryt and Gedl, 2010). The marls were deposited in

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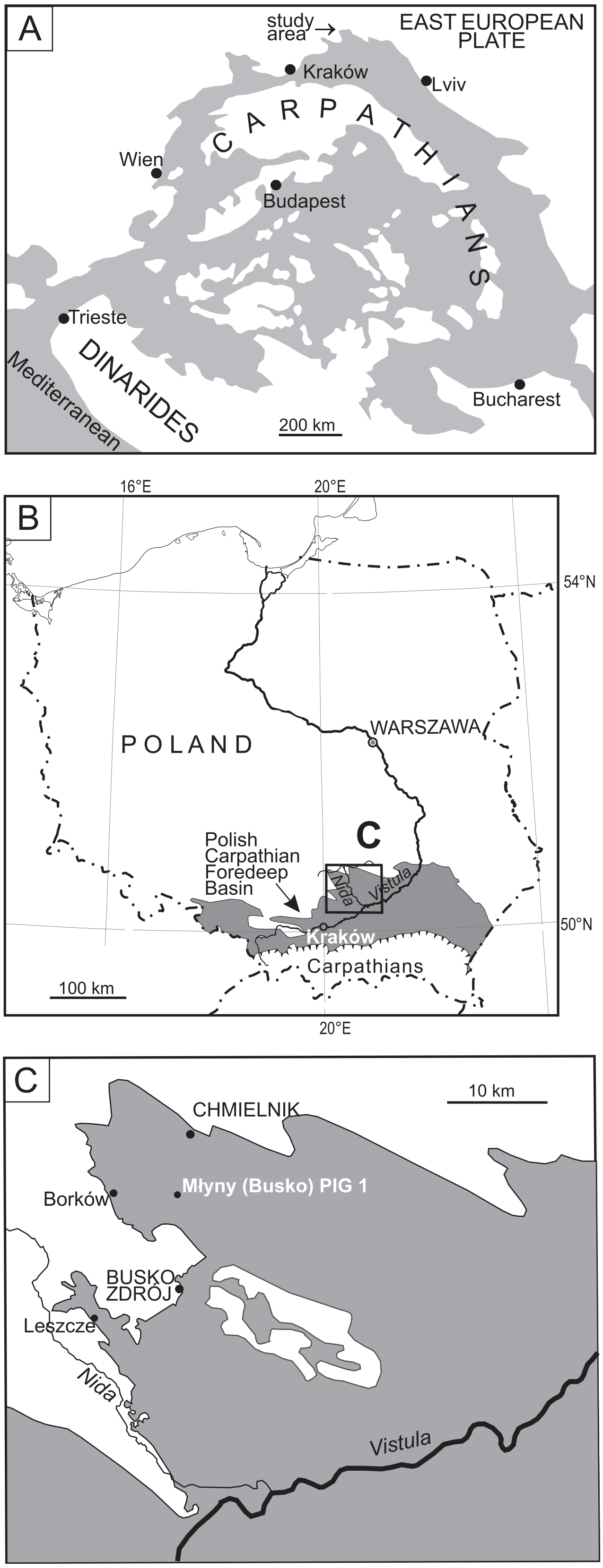

Fig. 1. Location map

A – palaeogeographic reconstruction of the Central Paratethys (Early Badenian marine sedimentation; after Rögl, 1998); **B** – Carpathian Foredeep Basin in Poland (grey); **C** – location of sections studied (grey – occurrence of Badenian sulphates; after Kasprzyk, 1993, modified by Gonera et al., 2012, fig. 1)

temperature-stratified water, and the calculated palaeotemperatures for particular foraminifer taxa (*Globigerina* spp., *Cibicidoides* spp. and *Bulimina elongata*) show a slight upsection decrease and a decrease in the temperature differences between the bottom and intermediate waters (Peryt and Gedl, 2010). At the Borków site there is a clear upsection decrease in the frequency of planktonic foraminifers within a 2 m-interval of marls albeit the planktonic forms, although very rare, occur even below the gypsum, being accompanied by benthic taxa. Peryt and Gedl (2010) concluded that the time duration between the onset of the Badenian salinity crisis and the onset of gypsum precipitation was therefore much shorter than in the Messinian of the Mediterranean (about 60,000 years; Lozar et al., 2010).

The aim of this paper is to estimate temperature, depth, salinity, and oxygenation of the water column prior to Badenian evaporite sedimentation in the northern part of the Central Paratethys. To achieve this, foraminifers from marls which underlie the gypsum in one borehole section (Busko [Młyny] PIG 1) have been studied (Figs. 1 and 2). In addition, one key locality (Leszcze) and another locality (Borków), which was subject to a pilot study (Peryt and Gedl, 2010), were analysed (Figs. 1 and 3). The estimate of environmental factors such as depth, salinity, and oxygen content of water prior to evaporite sedimentation was done using the data on environmental requirements of recent Mediterranean foraminifers (see review in Murray, 1991, 2006). For more detailed environmental analysis of the marls, stable carbon and oxygen isotopes of selected foraminifer taxa have been studied.

GEOLOGICAL SETTING

The Badenian deposits in the northern part of the Carpathian Foredeep Basin in Poland lie transgressively on eroded Cretaceous and Jurassic strata (Radwański, 1969; Oszczypko et al., 2006). The Badenian section is tripartite owing to the occurrence of the Krzyżanowice Formation (gypsum deposits up to 50 m thick) in the middle. Below the gypsum various carbonate and siliciclastic rock units up to several tens of metres thick occur; they are included into the Pińczów Formation (Czapowski, 2004). The upper part of the Pińczów Formation is composed of marls of the Baranów Beds. These marls are several metres thick in the Borków area (Peryt and Gedl, 2010), they attain the thickness of ca. 10 m in the Gacki Quarry that is adjacent to the Leszcze Quarry (see Alexandrowicz and Parachoniak, 1956 and Bąbel et al., 2010, fig. 1C), and 100 m in the northern part of the Połaniec Trough (Wilczyński, 1984), a tectonic unit located east of the Borków gypsum quarry. In the marls tuffite intercalations occur: Bukowski (2011) recorded a thin (6 cm thick) rhyolitic tuffite intercalation ca. 3.6 m below the gypsum base in the Młyny (Busko) PIG 1 borehole that can be correlated with the Wiatowice tuffite (Bukowski et al., 2010) and with the tuffite from Gacki (Dudek and Bukowski, 2004). In the marls rich foraminiferal assemblages are observed. Peryt and Gedl (2010) have shown the presence of 49 species of benthic foraminifers and 11 species of planktonics in a 2-m-thick marl outcropping in the Borków gypsum quarry, and Dudziak and Łuczkowska (1991) recorded 24 species (including two planktonic species, *Globigerina decoraperta* and *Globigerina glutinata*) in a sample occurring ca. 1 m below the top of the marls at Gacki and indicated that they represent the *Uvigerina costai* Zone.

The Badenian marls in the studied quarries are overlain by the giant gypsum intergrowths unit (see Bąbel, 1987) followed by bedded selenites with intercalations of alabastrine and

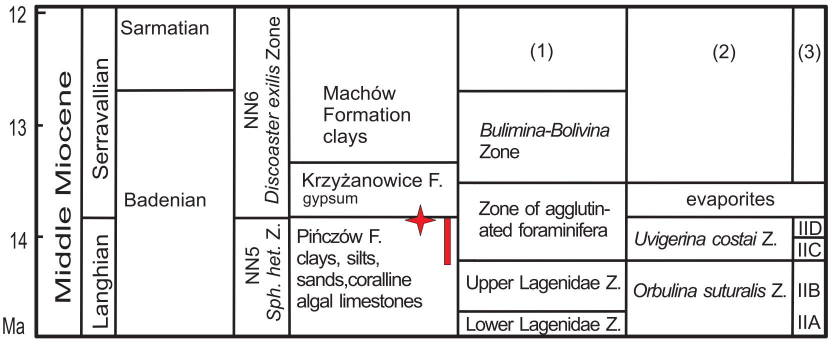

Fig. 2. Stratigraphic position of succession studied

Red asterisk for Leszcze and Borków sections and red bar for Młyny (Busko) PIG 1 borehole; the Miocene time scale after Hilgen et al. (2009), partly recalibrated and correlated to regional stages of the Central Paratethys; the lower limit of Badenian evaporites after de Leeuw et al. (2010); calcareous nannoplankton zones after Peryt (1997), NN5 *Sph. het.* Z = NN5 *Sphenolites heteromorphous* Zone; lithostratigraphy after Jasionowski (1997) and Oszczypko-Clowes et al. (2012); foraminiferal zones after: (1) – Mandic et al. (2002), (2) – Łuczkowska (1964) and Alexandrowicz (1963)

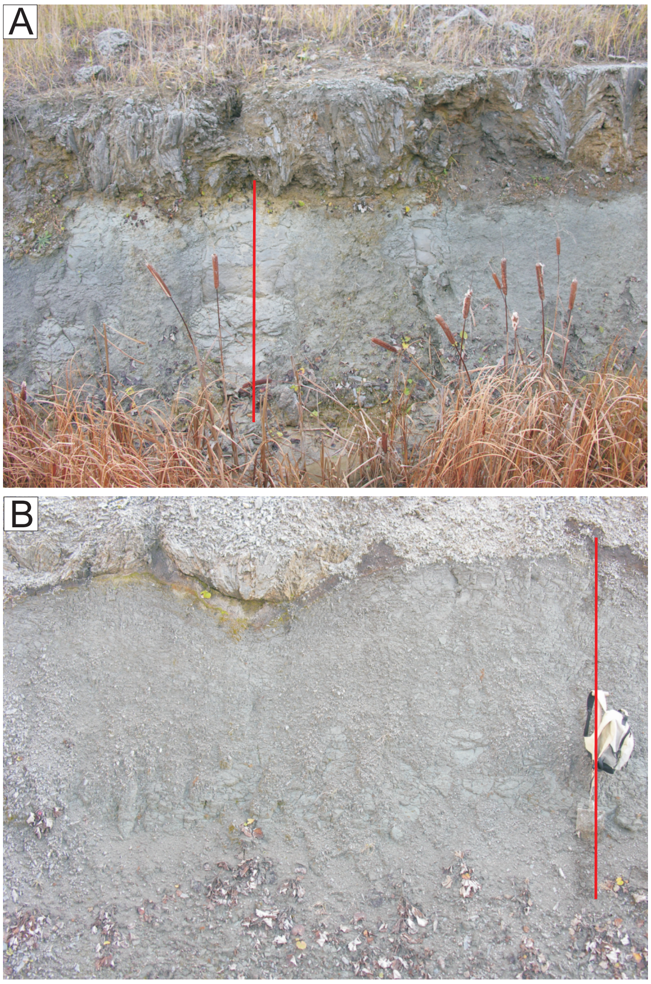

Fig. 3. Photographs of sampling sites

A – Leszcze, **B** – Borków; red lines (A – 1.25 m long; B – 2.4 m long) show the sections sampled

stromatolitic gypsum, overlain by sabre gypsum. The upper part of the gypsum sequence consists primarily of various facies of clastic gypsum (Bąbel, 1991; Kasprzyk, 1991, 1993). In the Połaniec Trough the Badenian marls are overlain by nodular anhydrites considered by Kasprzyk (1991) to be sabkha deposits, however, such an interpretation contrasts with the general palaeogeographic pattern as the Młyny (Busko) PIG 1 borehole is located in the northern, more basinal location of the Połaniec Trough, and the Borków and Leszcze quarries are located in the Pińczów area, Nida River Valley, in a more nearshore location (Kwiatkowski, 1974). The gypsum section in the Młyny (Busko) PIG 1 borehole and Leszcze outcrop are covered by Upper Badenian siliciclastic facies (Machów Formation); at Borków, Quaternary siliciclastics occur above the gypsum, but in the sinkholes Upper Badenian marls with quite abundant foraminiferal assemblages can be found (Peryt, 2013).

MATERIAL AND METHODS

Seventy-four samples from three sections have been studied for foraminifers: 41 samples from the Młyny (Busko) PIG 1 borehole section (N 50°33'20.8'', E 20°44'04.9''; Fig. 1), 12 samples from the Leszcze Quarry N 50°27.315', E 20°36.180'; Fig. 3A) and 21 samples from the Borków Quarry (N 50°33.518', E 20°37.973'; Fig. 3B), in addition to five samples from the Borków Quarry studied previously (Peryt and Gedl, 2010).

In the Młyny (Busko) PIG 1 borehole, the interval underlying Badenian sulphates occurs at a depth of 188–200 m (the borehole was stopped then) and it consists of marls that are dark beige in colour in the lower part of the interval (195–200 m), then are beige (192–195 m) and grey except in the uppermost part where they are black in colour. As already mentioned, a thin tuffite intercalation is seen at a depth of ca. 191.6 m. In the lower part of studied interval, bivalves (either whole shells or their fragments) occur, and in the upper part phytogenic material occurs (G. Czapowski, pers. comm., 2010). In Leszcze and in Borków, sections 1.25 and 2.4 m thick, respectively, exposed in dewatering pits were studied; the section in Borków is located four metres apart from the section subject to pilot study (Peryt and Gedl, 2010, fig. 3C).

Washed residues for foraminiferal study were obtained from the rocks by disaggregation using Na_2SO_4. An aliquot of about 200–300 specimens of foraminifers from the 125–700 μm size fraction was picked under a microscope for the faunal analyses. Well-preserved specimens were separated for isotopic analyses and then ultrasonically cleaned in order to remove particles adhered to the tests. The taxonomy of the foraminifers follows Loeblich and Tappan (1987), Odrzywolska-Bieńkowa and Olszewska (1996) and Cicha et al. (1998). The stratigraphically and palaeoenvironmentally important specimens were studied in detail and documented using a *Philips XL20* SEM (Figs. 4–9).

The relative abundance of infaunal and epifaunal forms within benthic foraminiferal assemblages, simple benthic diversity, the Shannon-Weaver heterogeneity index H(S) (Buzas and Gibson, 1969), and planktonic foraminifers within total foraminiferal assemblages (P/B ratio) were calculated. The palaeoenvironmental interpretation based on foraminifers applies the requirements of present-day representatives of recorded taxa (Thomas, 1980; van der Zwaan, 1982; Culver, 1988; Lutze and Thiel, 1989; Verhallen, 1991; Murray, 1991, 2006; Sjoerdsma and van der Zwaan, 1992; Kaiho, 1994; Hohenegger, 2005; Kouwenhoven and van der Zwaan, 2006; Kaminski, 2012). Palaeobathymetry was estimated on the basis of benthic fauna characteristics and the P/B ratio (100 × planktonic foraminifera/total foraminifera).

Changes in water salinity and other environmental parameters such as productivity, oxygen level in bottom waters, were interpreted using qualitative and quantitative analyses (Murray, 2006). To estimate the level of oxygenation of the sea-floor the benthic foraminifera were grouped into oxic, suboxic and dysoxic indicators according to Thomas (1980), van der Zwaan (1982, 1983), Verhallen (1991), Jorissen et al. (1992), Kaiho (1994), Loubère (1996, 1997), Bernhard and Sen Gupta (1999), Kouwenhoven and van der Zwaan (2006) and Kaminski (2012).

The following taxa are included into the oxic group: *Cibicidoides* spp., *Heterolepa dutemplei*, *Lobatula lobatula*, *Siphonina reticulata*, *Anomalinoides* spp., *Cibicides* sp., *Hansenisca soldanii, Oridorsalis umbonatus*. Oxic indices represent epifaunally living species. Taxa tolerant of suboxic environments are: *Lenticulina* spp., *Nodosaria* spp., *Laevidentalina* spp., *Melonis pompilioides*, *Pullenia bulloides*, *P. miocenica*, *Sphaeroidina bulloides*, *Cassidulina laevigata*, *Globobulimina pyrula*, and taxa tolerant of dysoxic environments – *Bolivina* spp., *Bulimina* spp., *Uvigerina* spp., *Fursenkoina acuta, Praeglobobulimina pyrula, Globocassidulina* spp.

Foraminifers tolerant of suboxic environments represent mostly shallow infaunally living species, while foraminifers tolerant of dysoxic environments represent mostly deep infauna and species with opportunistic behaviour. They are commonly used as stress markers (e.g., van der Zwaan et al., 1999; van Hinsbergen et al. 2005).

Changes in planktonic foraminiferal assemblages were used to reconstruct palaeoclimatic changes. Planktonic foraminifera were grouped into cool-temperate indices (*Globigerina bulloides*, *G. praebulloides*, *G. tarchanensis*, *G. diplostoma*, *G. concinna*, *Globorotalia bykovae*) and warm indices (*Orbulina suturalis*, *O. bisphaerica, Globigerinoides* spp., *Paragloborotalia mayeri, P. siakensis*; Szczechura, 1982, 1984, 2000; Spezzaferi et al., 2002; Bicchi et al., 2003).

The $\delta^{18}O$ and $\delta^{13}C$ ratios of two foraminifer taxa: *Globigerina* (in most cases, *G. bulloides*) and *Uvigerina* (mostly *U. aculeata*), were studied in 52 samples to estimate absolute water temperature. In a few cases when *Uvigerina* specimens were too rare to allow for isotopic studies, I used *Bulimina* for that purpose, the taxon applied in the pilot study at Borków (Peryt and Gedl, 2010), as both had similar environmental requirements. I assume that the isotope values for *Globigerina* and *Uvigerina* are indicative of the surface and deep-water isotope composition, respectively. Foraminifer tests were reacted with 100% phosphoric acid at 75°C using a *KIEL IV* online automatic carbonate preparation line connected to the *Finnigan Mat delta plus* mass-spectrometer at the Light Stable Isotopes Laboratory of the Institute of Geological Sciences and Institute of Paleobiology, Polish Academy of Sciences, Warszawa. All isotopic data were reported in per mil relative to VPDB related to NBS 19. The precision (reproducibility of replicate analyses) of both carbon and oxygen isotope analyses was usually better than ±0.2‰. To calculate palaeotemperatures, the equation established by Epstein et al. (1953) was applied.

The figured specimens are deposited in the Institute of Paleobiology, Polish Academy of Sciences, Warszawa (ZPAL F. 59).

RESULTS

FORAMINIFERA

MŁYNY (BUSKO) PIG 1 BOREHOLE

The examined sediments contain well-preserved foraminifers. Sixty-seven species of benthic and twenty-one species of planktonic foraminifers were recorded in the studied interval of the Młyny PIG 1 borehole (Appendix 1* and Figs. 4–9). Benthic assemblages are characterized by the dominance of *Bulimina* and *Uvigerina* while planktonic ones are composed mainly of orbulinids and *Globigerinoides* spp. in the lower part of the section and of *Globigerina* spp. in its upper part.

Figure 10 shows the relative percent abundances of common and dominant species, i.e. species that show abundance >5% in at least in one sample, the diversity of benthic assemblages, and relative abundances of planktonic and benthic foraminifers as well as relative abundances of dysoxic, suboxic and oxic species or groups of species.

In the Młyny (Busko) PIG 1 section, simple species diversity of benthic foraminifers is low to moderate and varies between 8 and 26. H(S) values vary between 1.8 and 2.8. Lowest values correspond to low diversified and with high dominance benthic foraminiferal assemblages, which in this section correlate with assemblages where deep infaunal species (= stress markers) are dominant.

Benthic foraminiferal assemblages are dominated by calcareous forms; agglutinated foraminifera are represented by only four species: *Vulvulina pennatula*, *Spiroplectinella carinata*, *Spirotextularia* cf. *fistulosa* and *Martinotiella communis*. They are present mainly only in the lower part of the studied interval and completely disappear 6 m below the base of the gypsum except for *Martinotiella communis* which is also recorded in small numbers in the upper part of section. The agglutinants are a minor contributor to the assemblages and usually do not exceed 10% except of the 2-m-thick interval in the lower part of the section where they form up to 20% of the assemblages.

Heterolepa dutemplei is a common component of the lower and middle parts of the section. Its contribution to assemblages varies from 2 to 20%. *Cibicidoides* spp., *Melonis pompilioides*, *Pullenia miocenica*, *Sphaeroidina bulloides* are recorded in the entire section but their abundances fluctuate. In places they form up to 20% of the assemblages. Nodosariaceans are common in the lower part of the section, then, in its middle part, they are not recorded and they reappear in small numbers in the upper part of the section. In that part of the section the first occurrences of two species were found: *Hoeglundina elegans* which about 2 m below the gypsum forms 20% of the assemblage and *Fursenkoina acuta* which at the level about 1 m below the gypsum forms 25% (Fig. 10).

Bulimina and *Uvigerina* are the dominant foraminifers in the whole section. The abundances of the two groups fluctuate sig-

* Supplementary data associated with this article can be found, in the online version, at doi: 10.7306/gq.1080

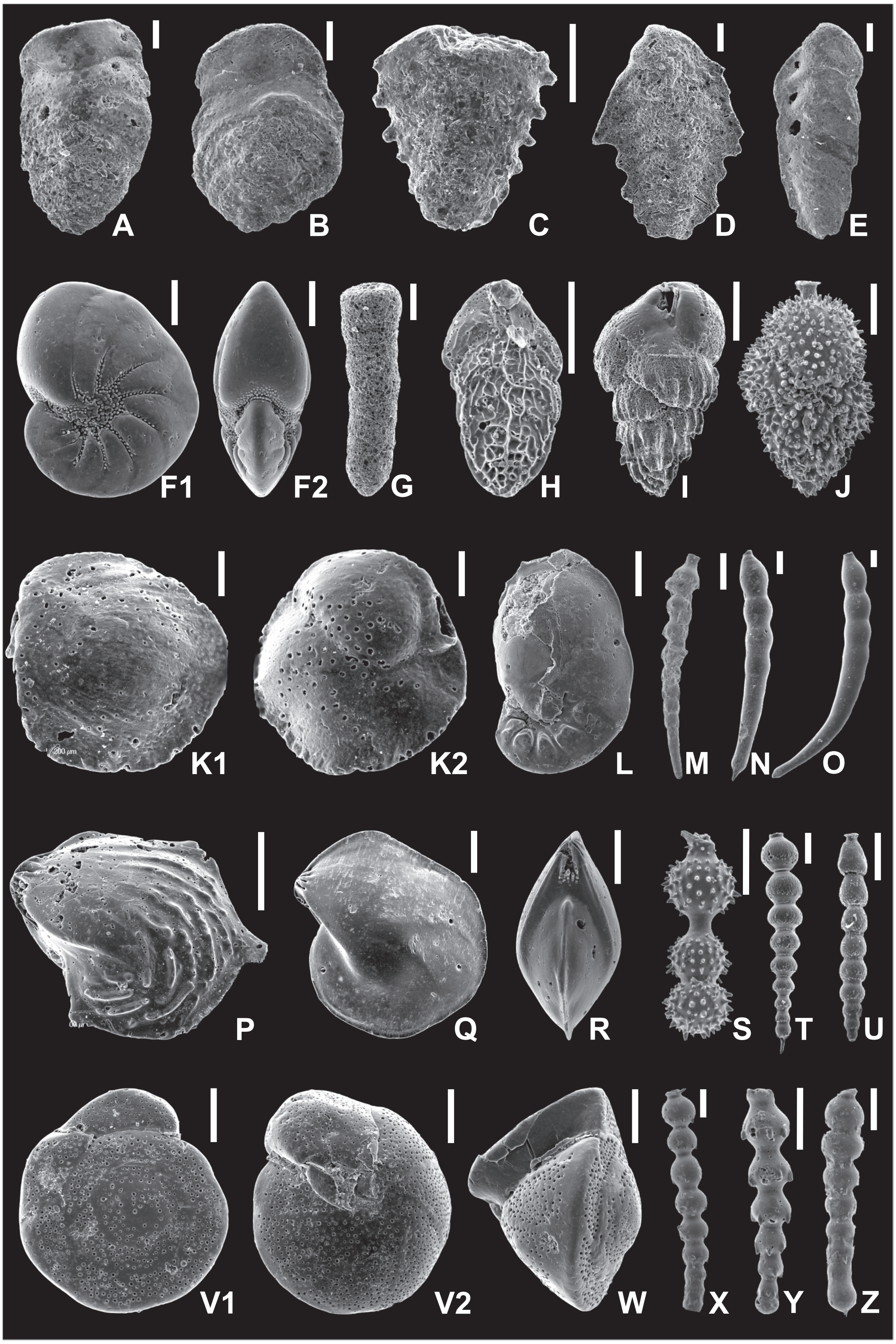

Fig. 4. Benthic foraminifers from the Młyny (Busko) PIG 1 borehole

A, **B** – *Vulvulina pennatula*; **C** – *Spirotextularia* cf. *fistulosa*; **D** – *Spiroplectinella carinata*; **E** – *Spiroplectinella* sp.; **F1**, **F2** – *Nonion commune*; **G** – *Martinotiella communis*; **H** – *Bolivina viennensis*; **I** – *Bulimina striata*; **J** – *Uvigerina pygmea*; **K1**, **K2** – *Siphonina reticulata*; **L** – *Cancris auriculus*; **M**–**O** – *Laevidentalina elegans;* **P** – *Lenticulina echinata*; **Q**, **R** – *Lenticulina inornata*; **S** – *Nodosaria hispida*; **T**, **X**, **Z** – *Stilostomella adolphina*; **U** – *Stilostomella* sp. 1; **V1**, **V2, W** – *Heterolepa dutemplei*; **Y** – *Stilostomella lepidula*; scale bar is 200 μm; A, C, G, N, S–U, W – sample 38; B, D, H–L, O, P, V – sample 41; E, R – sample 37; F, Q – sample 36; I, M, X, Y – sample 24; M, Z – sample 21

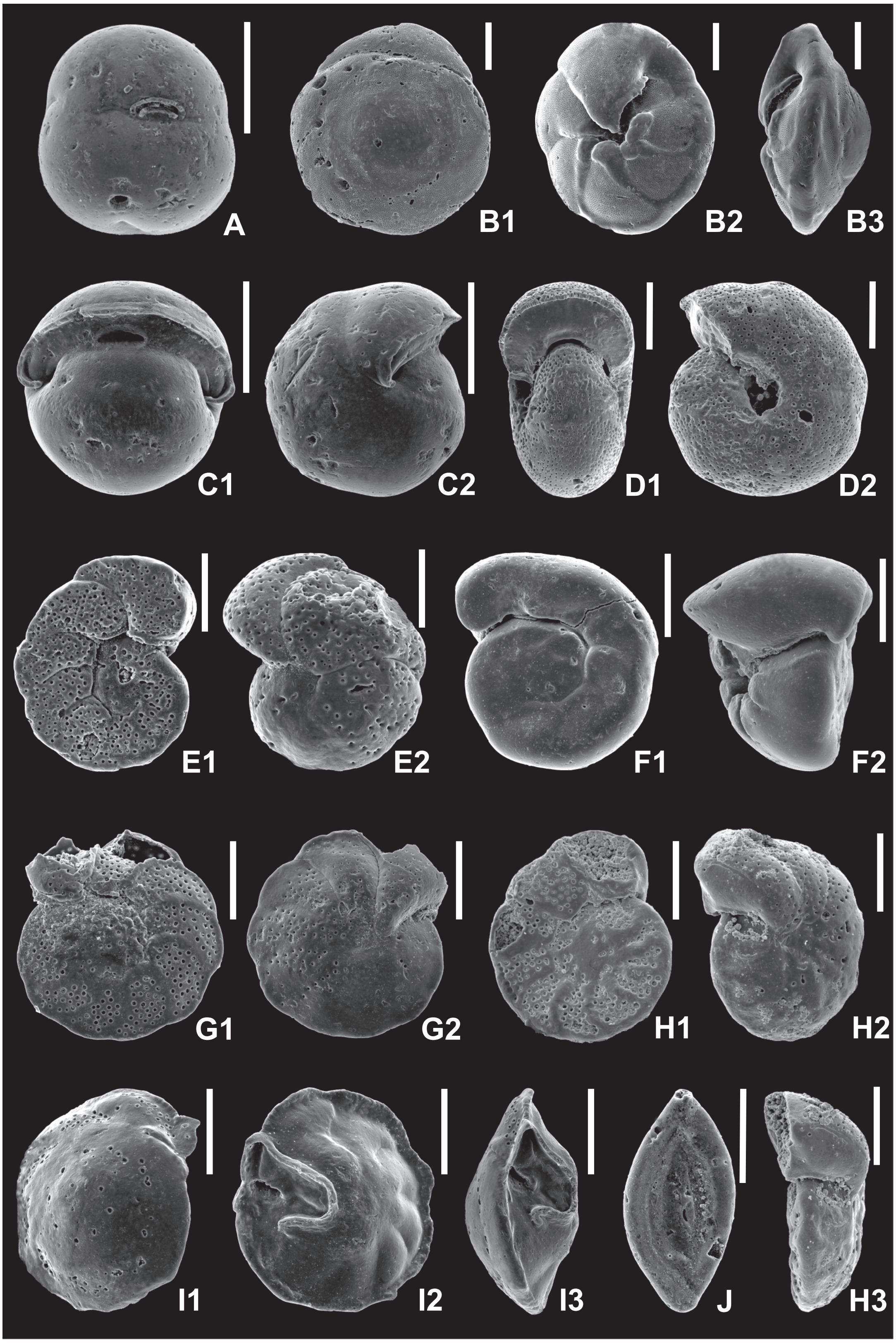

Fig. 5. Benthic foraminifers from the Młyny (Busko) PIG 1 borehole

A – *Sphaeroidina bulloides*; **B1**–**B3** – *Neoeponides schreibersi*; **C1**, **C2** – *Pullenia miocenica*; **D1**, **D2** – *Melonis pompilioides*; **E1**, **E2** – *Lobatula lobatula*; **F1**, **F2** – *Hansenisca soldanii*; **G1**, **G2** – *Cibicidoides ungerianus*; **H1**–**H3** – *Cibicidoides austriacus;* **I1**–**I3** – *Oridorsalis umbonatus*; **J** – *Sigmoilinita tenuis*; scale bar is 200 μm; A, E – sample 38; B – sample 37; C, D – sample 20; F–I – sample 41; J – sample 9

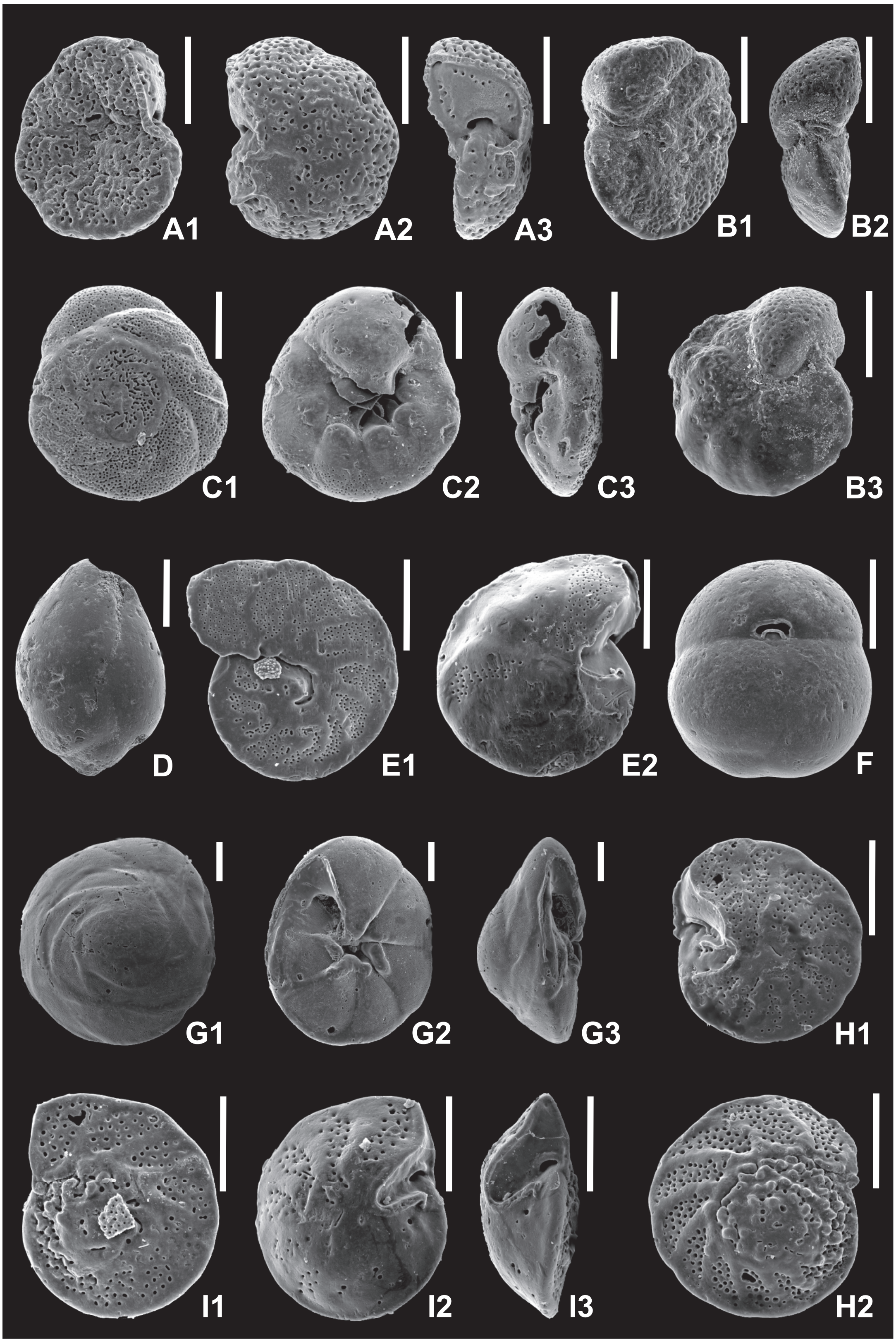

Fig. 6. Benthic foraminifers from the Młyny (Busko) PIG 1 borehole

A1–**A3** – *Anomalinoides badenensis*; **B1**–**B3** – *Anomalinoides* sp.; **C1**–**C3** – *Valvulineria complanata*; **D** – *Globobulimina pyrula*; **E1**, **E2** – *Cibicides* sp.; **F** – *Sphaeroidina bulloides*; **G1**–**G3** – *Neoeponides schreibersi*; **H1**, **H2** – *Cibicidoides ungerianus*; **I1**–**I3** – *Cibicidoides pseudoungerianus*; scale bar is 200 µm; A, C – sample 14; B – sample 21; D – sample 12; E, H, I – sample 7; F – sample 9; G – sample 36

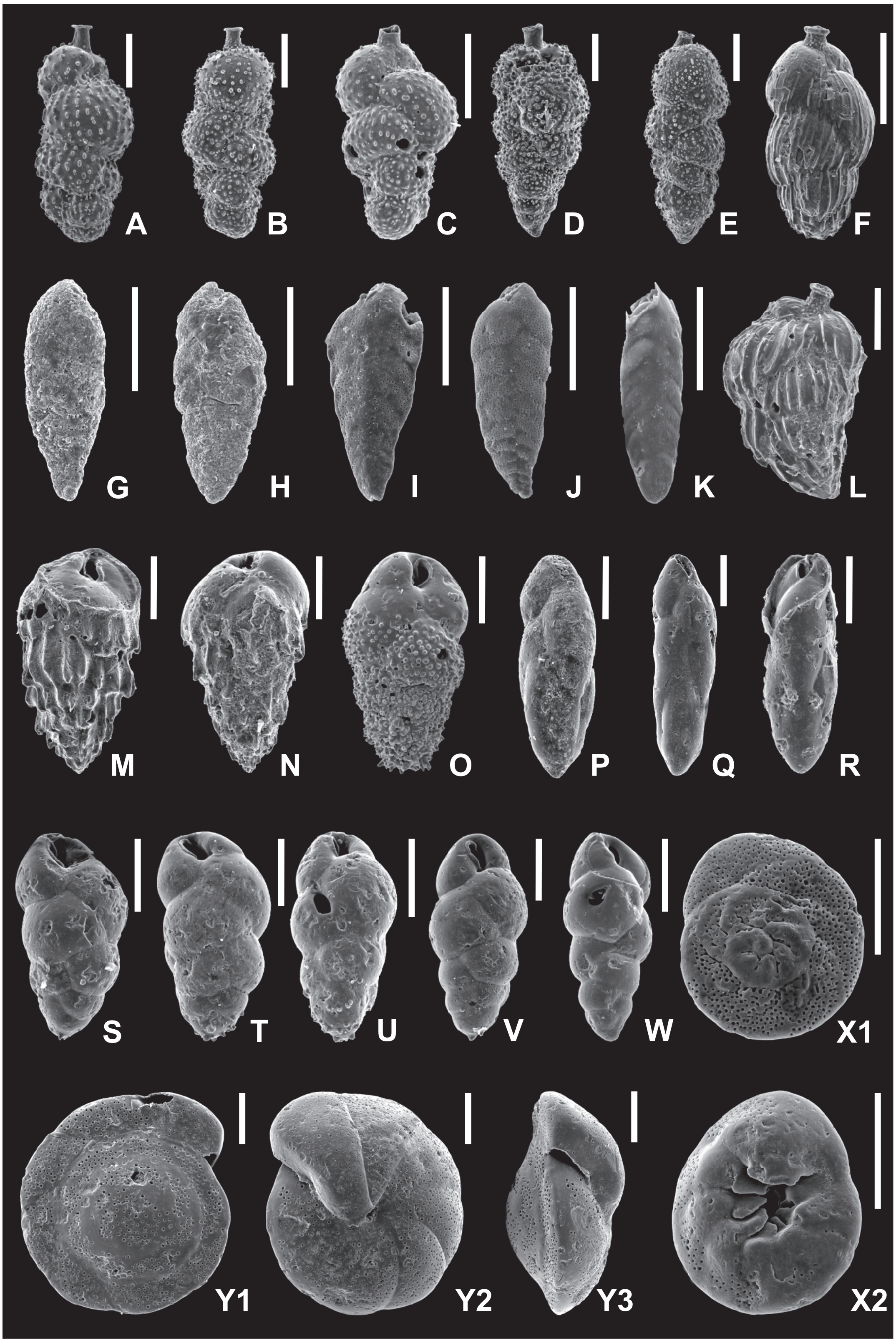

Fig. 7. Benthic foraminifers from the Młyny (Busko) PIG 1 borehole

A–**C** – *Uvigerina aculeata*; **D**, **E** – *Uvigerina hispida*; **F** – *Uvigerina semiornata*; **G** – *Bolivina* sp.; **H**, **I** – *Bolivina dilatata*; **J** – *Bolivina scitula*; **K** – *Bolivina* cf. *dilatata maxima*; **L** – *Uvigerina pygmoides*; **M**, **N** – *Bulimina striata*; **O** – *Bulimina untonsa*; **P**, **R** – *Fursenkoina* sp.; **Q** – *Fursenkoina acuta*; **S**–**V** – *Bulimina subulata*, **W** – *Bulimina elongata*; **X1**, **X2** – *Valvulineria complanata*; **Y1**–**Y3** – *Heterolepa dutemplei*; scale bar is 200 µm; A–F, T, X – sample 7; G, H, P – sample 12; I–K,– sample 9; L–N, Q–S, U–W – sample 6; O – sample 15; Y – sample 26

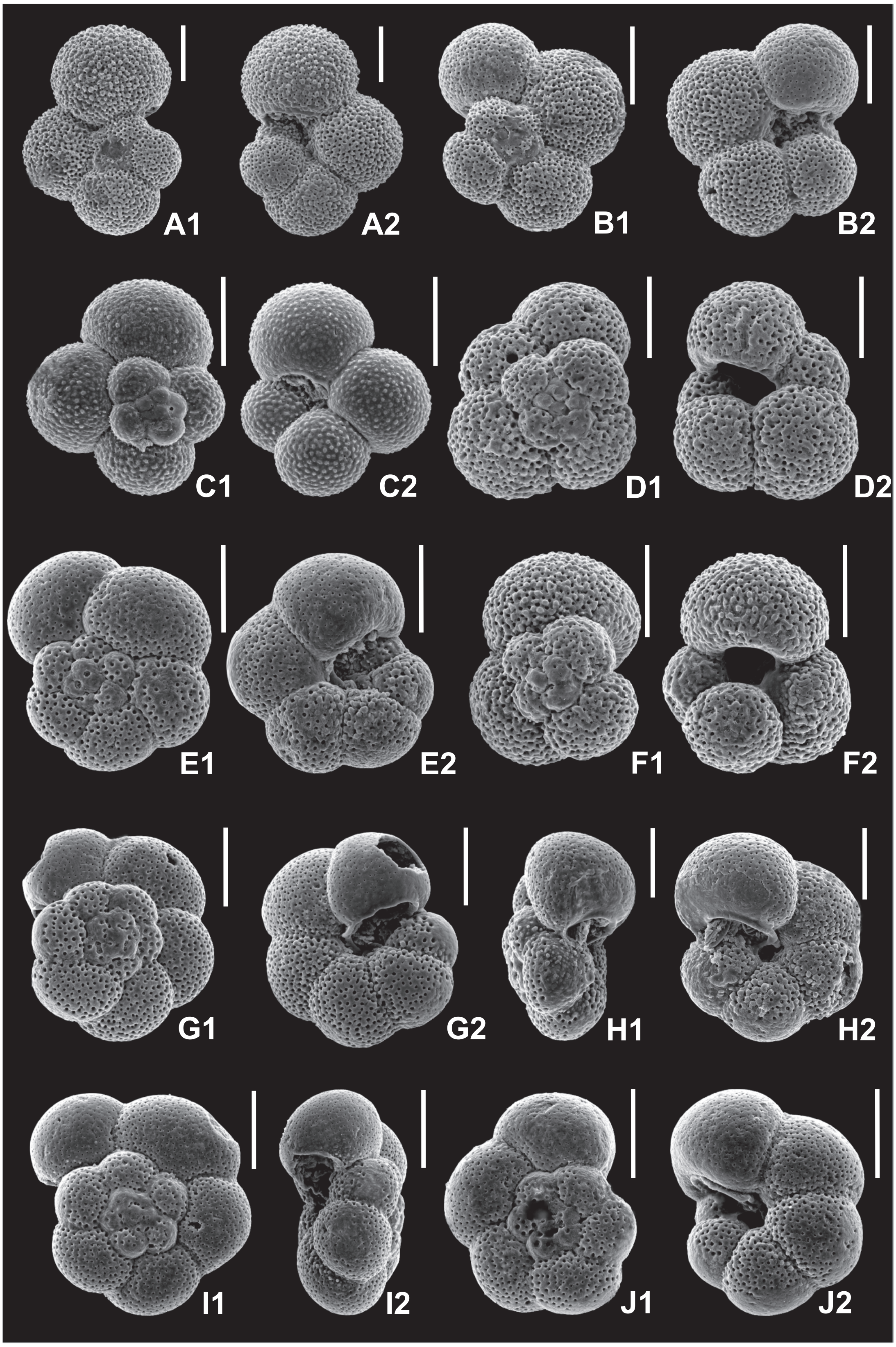

Fig. 8. Planktonic foraminifers from the Młyny (Busko) PIG 1 borehole

A1, **A2** – *Tenuitella obesa*; **B1**, **B2** – *Tenuitella subcretacea*; **C1**, **C2** – *Tenuitellinata juvenilis*; **D1**, **D2** – *Globoturborotalita* sp.; **E1**, **E2** – *Paragloborotalia transsylvanica*; **F1**, **F2** – *Globigerina bulloides*; **G1**, **G2**, **I1**, **I2** – *Paragloborotalia* sp.; **H1**, **H2** – *Paragloborotalia siakensis*; **J1**, **J2** – *Paragloborotalia mayer*i; scale bar is 100 μm; A–C, E, G–J – sample 36; D, F – sample 7

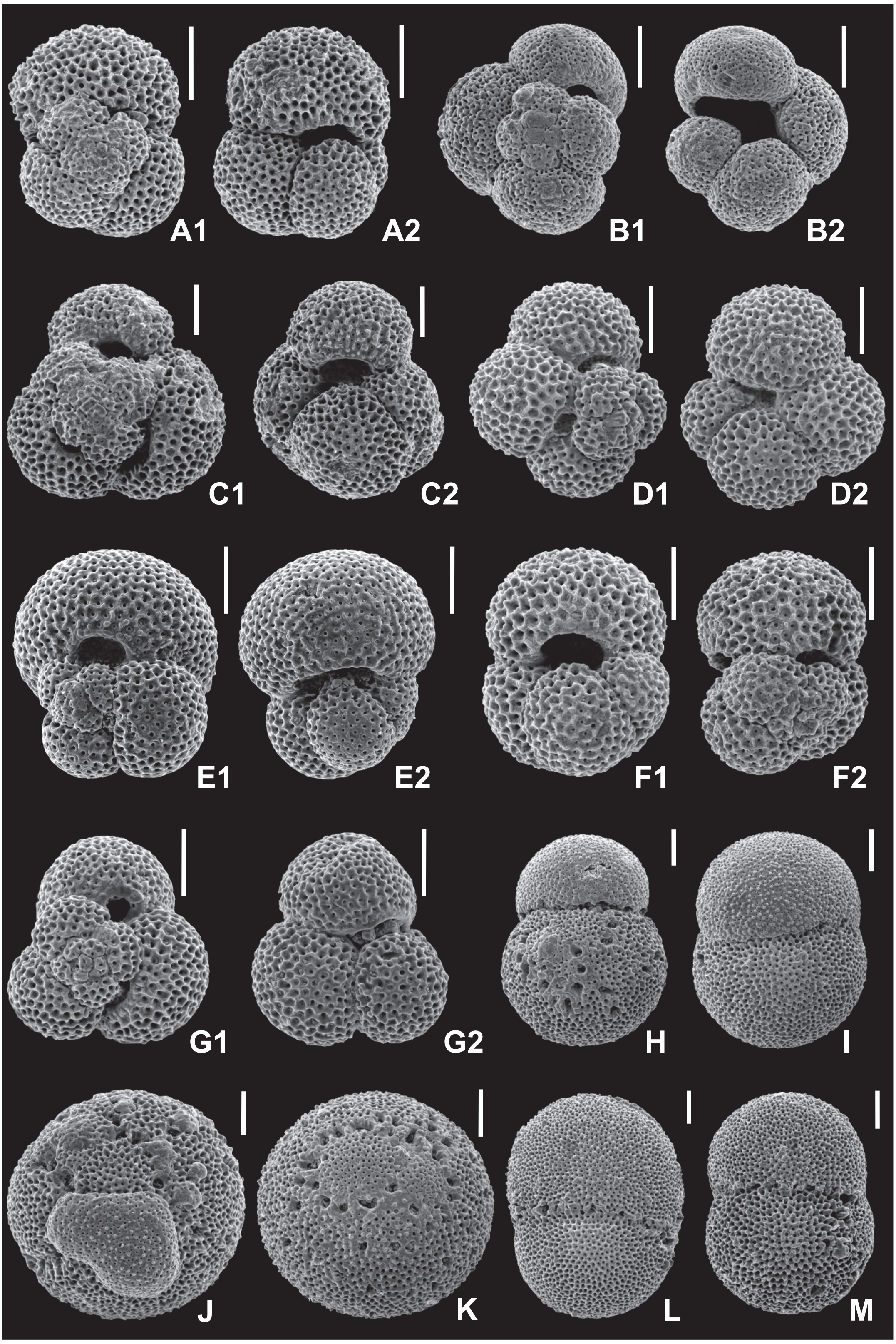

Fig. 9. Planktonic foraminifers from the Młyny (Busko) PIG 1 borehole

A1, **A2** – *Globigerinoides immaturus*; **B1**, **B2** – ?*Tenuitella* sp.; **C1**, **C2**, **D1**, **D2**, **G1**, **G2** – *Globigerinoides quadrilobatus*; **F1**, **F2** – *Globigerinoides trilobus*; **E1, E2** – *Globigerinoides primordius*; **H**, **I**, **L**, **M** – *Orbulina bilobata*; **J**, **K** – *Orbulina suturalis*; scale bar is 100 μm; A–C, F – sample 24; D, E, G, H, J–L – sample 36; I, M – sample 37 nificantly, forming from 0 to 85% of the assemblages. In places their contribution to the assemblages is equal but in most cases their abundances show opposite tendencies: an increase in the abundance of representatives of one genus is accompanied by a decrease in representatives of the second one. In the topmost part of the section *Uvigerina* almost disappears while *Bulimina*, mainly *B. elongata*, forms up to 80% of the assemblage. *Bolivina* is present in the entire section but only at the level about 2 m below the gypsum it forms almost 10% of the assemblage.

The contribution of planktonic foraminifera varies significantly throughout the section. In its lower part the P/B ratio is rather high and varies between 60 to 85%. Then, it decreases to 25–40%, and again increases to 80%. In the upper part of the section the P/B ratios drop to 2–30% except for a short interval at 2 m below the gypsum where it increases to 57%. In the uppermost 0.6-m-thick interval just below the gypsum planktonic foraminifers are very rare.

The lowermost (3 m thick) part of the section yields an abundant warm-water planktonic foraminiferal assemblage composed mainly by orbulinids (i.e., *Orbulina suturalis* and *O. bilobata*) and *Globigerinoides* spp. (*G. trilobus*, *G. immaturus*, *G. primordius* and *G. bisphericus*). *Paragloborotalia siakensis* and *P. mayeri* are also recorded in this interval. This warm-water planktonic fauna suddenly almost completely disappears 8 m below the gypsum. Only *Globigerinoides trilobus* is recorded as a very rare component in planktonic assemblages in the next five metres and its highest occurrence is recorded 3 m below the gypsum. The succeeding planktonic assemblage is dominated by *Globigerina bulloides*, which is a cool water index. Cool-temperate species, e.g. *Globorotalia bykovae*, are subordinate.

LESZCZE

The studied 1.25 m thick marls underlying the gypsum yielded very well-preserved foraminiferal assemblages consisting of 47 benthic taxa and 5 planktonic species (Fig. 11 and Appendix 2). The number of benthic species is 23–26 in the lower 0.8 m of the section; then it drops to 6 in the sample from the bed underlying the gypsum. The H(S) diversity index varies from 2.3–2.5 in the lower 0.8 m of the section, but then drops to 1.5 in the sample below the gypsum. *Bulimina* spp. and *Uvigerina* spp. dominate among benthic foraminiferal assemblages (Fig. 11), forming 60 to 80% of the assemblages. Similarly as in the Młyny (Busko) PIG 1 borehole, *Bulimina elongata* forms 80% of the assemblage in the sample below the gypsum. *Fursenkoina acuta* is also an important component of the assemblages in the upper part of the section. *Pullenia bulloides*, *Sphaeroidina bulloides*, *Melonis pompilioides* and *Cibicidoides* spp. are common. Rare species in this interval are: *Hoeglundina elegans*, *Sigmoilinita tenuis*, *Laevidentalina* spp., *Stilostomella*, *Glandulina hispida*, *Lobatula lobatula*, and *Pseudotriplasia elongata* – the only agglutinated form in the section.

Planktonic foraminifera form 30–40% of the foraminiferal assemblages in the lower 0.8 m of the section. In the 0.4 m thick interval below the gypsum their contribution to the assemblages drops to 2–5% (Fig. 11). They consist of *Globigerina* spp. (mainly *G. bulloides*). The species *Globorotalia bykovae* also occurs rarely. The taxonomic composition of these assemblages is indicative of temperate-cold water.

BORKÓW

The studied 2.4 m thick marls underlying the gypsum showed the presence of 49 benthic foraminiferal species and 11 planktonic ones (see Peryt and Gedl, 2010, appendix 1). Benthic foraminiferal assemblages are almost completely composed of calcareous taxa. Only two agglutinated species (*Pseudotriplasia elongata* and *Vulvulina pectinata*) occur sporadically in the lowermost part of the section. The number of benthic species varies from 5 (in the 8 cm thick interval underlying the gypsum) to 19 (in the lowermost part of the section). The H(S) values vary insignificantly throughout almost the entire section with values between 2.3 to 2.5. Only in the uppermost 20-cm-thick bed just below the gypsum the H(S) values drop to 1. Benthic foraminiferal assemblages from this section are characterized by high dominance and low diversity (Fig. 12). *Bulimina* predominates in the section. In its lower part it forms 15 to 30% of the assemblages and in its upper part the abundance of *Bulimina* grows rapidly to 80%. Other important contributors are *Bolivina*, *Fursenkoina* and *Uvigerina*. They form at different levels up to 25% of the assemblages – *Bolivina* in the lower part, *Fursenkoina* – in the middle and *Uvigerina* in the upper part of the section. *Hoeglundina elegans* appears suddenly and has its acme at 1.8 to 2.4 m below the gypsum (Fig. 12). In this part of the section it forms up to 40% of the assemblages. Common are also *Globocassidulina oblonga* (up to 15%), *Pullenia bulloides*, *Melonis pompilioides* and the oxic marker – *Cibicidoides. Elphidium* is very rare in the upper part of the section.

Planktonic foraminifera form 15 to 30% of the assemblages except in two samples where their contribution increases significantly – up to 50% at 0.5 m below the gypsum and to 70% about 2.0 m below the gypsum. Cold and cool-temperate species are present. The assemblage is dominated by *Globigerina bulloides*; minor contributors are: *G. praebulloides*, *G. tarchanensis*, *G. diplostoma*, *G. concinna*, and *Globorotalia bykovae*.

STABLE ISOPES

The results of stable isotopic analyses are given in Appendix 3 and Figures 13A–15, but in several cases the measured values were omitted during subsequent interpretations due to the inferred diagenetic alterations that affected both benthic and/or planktonic foraminifers. The reliable data are shown in Figure 13B and are summarized in Table 1.

MŁYNY (BUSKO) PIG 1 BOREHOLE

The benthic carbon isotope record ($\delta^{13}C_b$) of the Młyny section shows a small variation throughout the major part of the section, with the $\delta^{13}C$ values being close to 0‰, however, at 8 to 10 m below the gypsum there is a negative excursion down to –2.5‰. Ca. 3.1 m below the gypsum there is another, smaller excursion (down to –1.2‰) followed by an increase (to ca. –0.3‰ 2.6 m below the gypsum). The upper 2 m of the section show variation of $\delta^{13}C$ values from –0.3 to –1.5‰ (Fig. 14). The planktonic carbon isotope record ($\delta^{13}C_p$) shows a very similar pattern to the $\delta^{13}C_b$ record, with most values ranging from 0.5 to 1.0‰ and with an excursion (8 to 10 m below the gypsum) down to –2.9‰, and a slight decrease (to –0.64‰) in the topmost 2 m of the section, but with two eminent negative excursions (down to below –5‰ in that part). In addition, there is one positive excursion (to 1.66‰) 7.7 m below the gypsum, just above the negative excursion (Fig. 14).

The benthic oxygen isotope record ($\delta^{18}O_b$) shows a similar trend of changes as the $\delta^{13}C_b$ record except in the upper part of the section (Fig. 14): below the excursion down to –2.8‰ the values vary from 1.2 to 1.7‰, and above the excursion they are from 1 to 2.6‰; the smallest value coincides with the small neg-

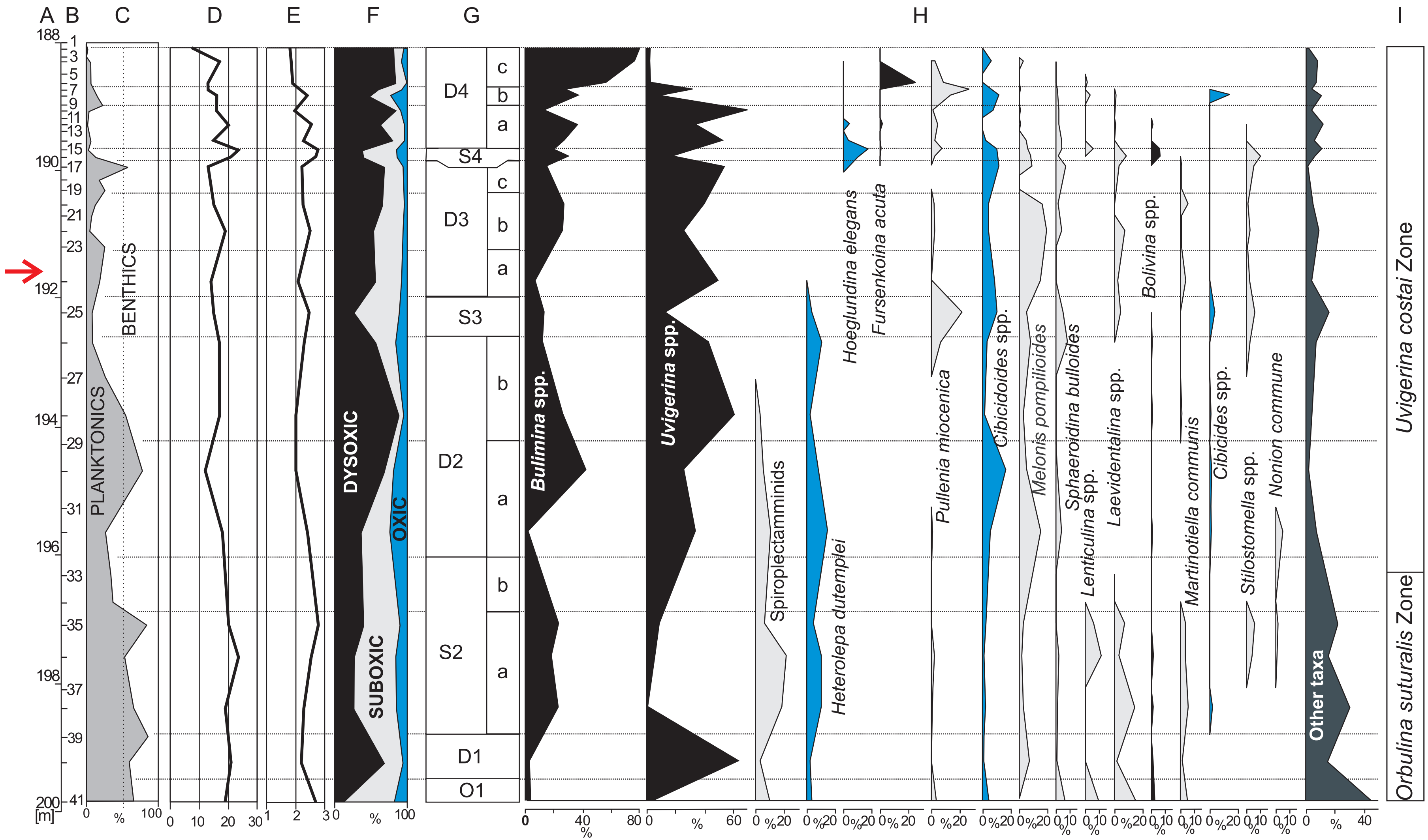

Fig. 10. The Młyny (Busko) PIG 1 borehole section studied

A – depth; B – sample number; C – relative abundance of planktonic and benthic foraminifers; D – simple benthic diversity (number of species); E – H(S) – Shannon-Wevear heterogeneity index; F – relative abundances of dysoxic, suboxic and oxic taxa; G – benthic foraminiferal assemblages; H – relative abundances od dominant and common species or groups of species; the red arrow indicates the position of the tuffite bed described by Bukowski (2011)

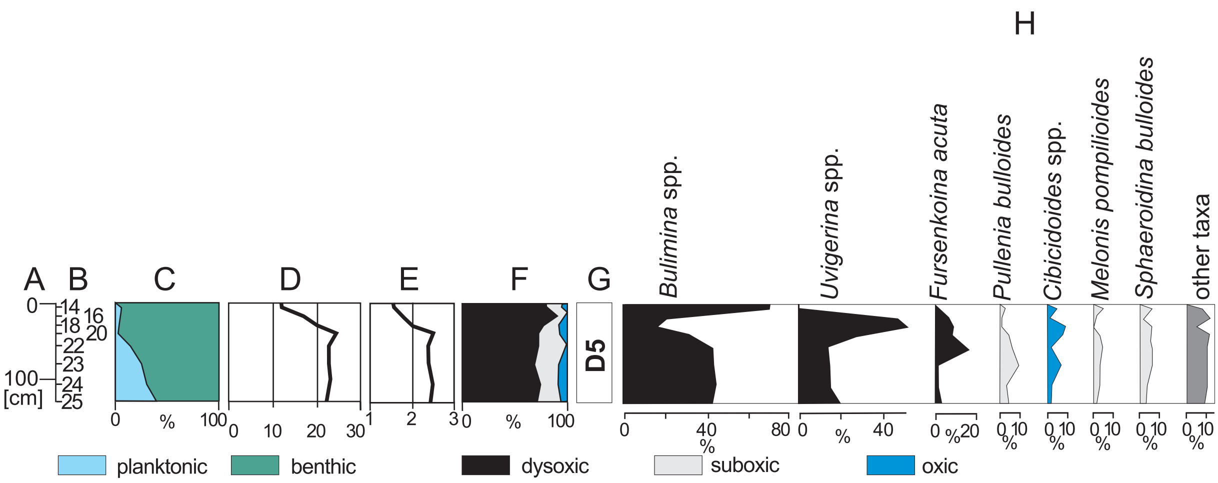

Fig. 11. The Leszcze section studied

A–H – for explanations see Figure 10

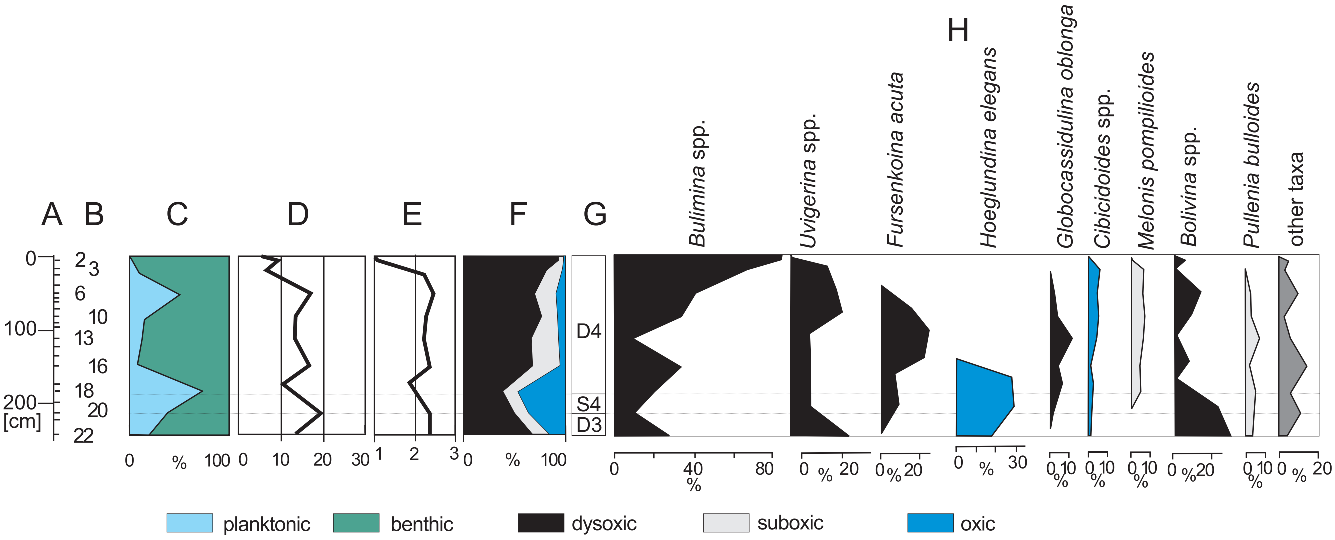

Fig. 12. The Borków section studied

A–H – for explanations see Figure 10

ative excursion of the $\delta^{13}C_b$ (Fig. 14). The planktonic oxygen isotope record also shows a similar trend of changes as the $\delta^{13}C_p$ record (Fig. 14).

LESZCZE

The benthic carbon isotope record ($\delta^{13}C_b$) in the Leszcze section shows a gradual decrease, from 0.15‰ 1.3 m below the gypsum to –0.85‰ 25 cm below the gypsum, and then it increases to 0.29‰, but just below the gypsum it shows a small fall (to 0.1‰). The planktonic carbon stable isotope record ($\delta^{13}C_p$) shows a very similar pattern – it decreases from 0.62‰ 1.3 m below the gypsum to –0.66‰ 25 cm below the gypsum and then it increases to 0.36‰ (there is no slight decrease occurring in the benthic record). The benthic oxygen isotope record ($\delta^{18}O_b$) shows quite a gradual decrease from the base of the section to 0.8 m below the gypsum, from ca. 3 to 0.5‰, and then it gradually increases to 2.72‰ at the topmost part, with the only excursion noted at the depth ca. 0.6 m below the gypsum where the $\delta^{18}O_b$ values reaches 4.08‰. The planktonic oxygen isotope record ($\delta^{18}O_p$) shows a very similar trend (except there is no excursion): from 2.15‰ at the base to –0.2‰ 25 cm below the gypsum, and then to ca. 1.1‰ at the top of the section (Fig. 15).

BORKÓW

The benthic carbon stable isotope record ($\delta^{13}C_b$) of the Borków section varies between –0.38 and 0.16‰, with a maximum recorded 1.8 m below the base of the gypsum. Minima are observed 1.6 and 2.0 m below the gypsum (Fig. 15). Two shifts towards more positive values (by ca. 0.5 and 0.4‰; Fig. 15) are

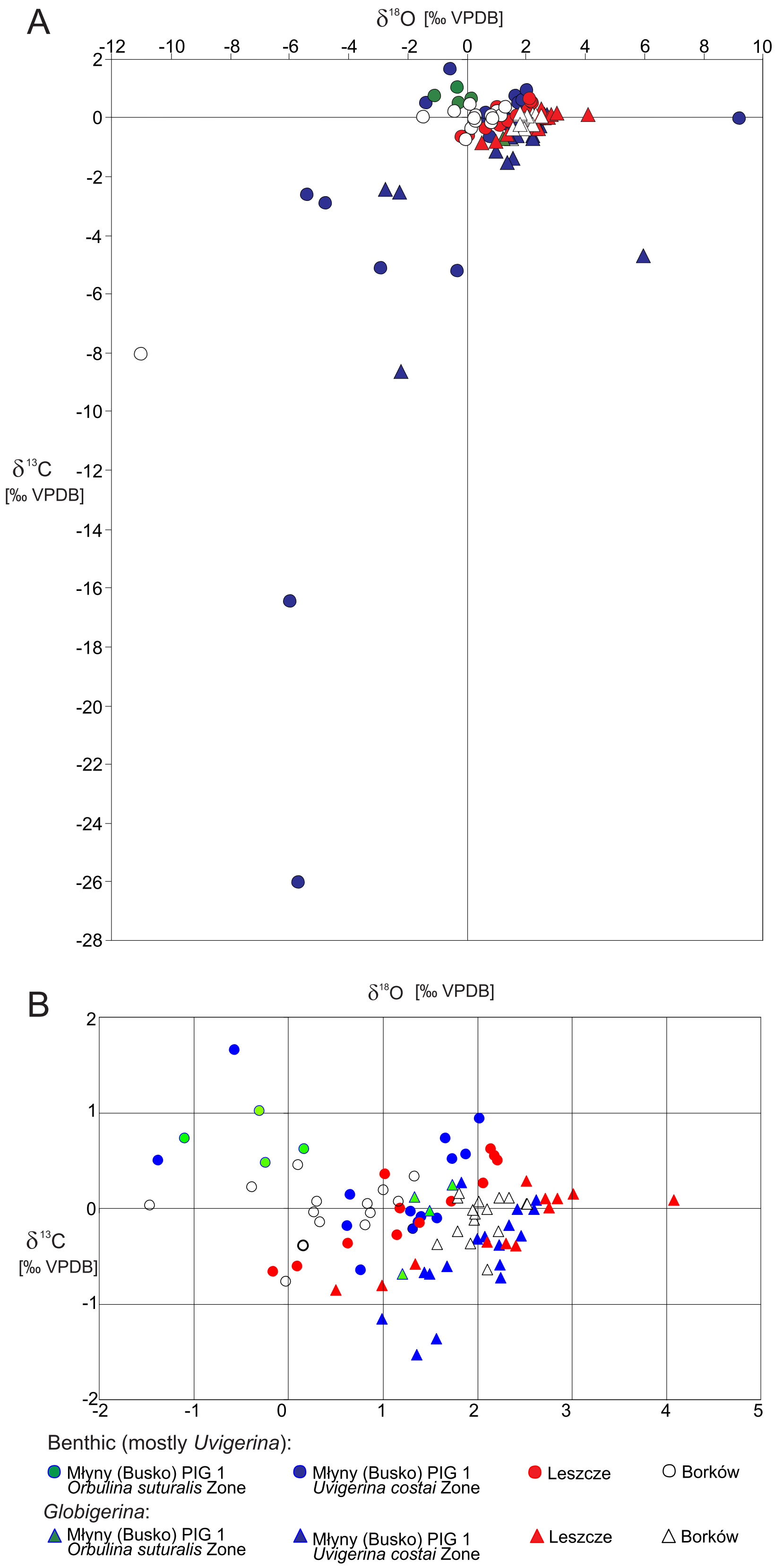

Fig. 13. Plot of δ^{13}C and δ^{18}O for all data (A) and for dataset ignoring abnormal values (B)

followed by a clear slightly increasing trend and then, in the uppermost part of the section, a decreasing trend of $\delta^{13}C_b$ values (Fig. 15). The planktonic carbon isotope record ($\delta^{13}C_p$) fluctuates between –0.77 and 0.46‰ and has a similar pattern as $\delta^{13}C_b$ except at 1.8 m below the gypsum where the negative shift (by 0.8‰) coincides with the positive shift (by 0.5‰) of $\delta^{13}C_b$. The benthic oxygen isotope record shows quite a gradual increase from the base of the section to 0.8 m below the gypsum, from ca. 1.7 to 2.5‰, and then it gradually decreases to 2.0‰ in the topmost part. In contrast to the δ^{13}C records, the planktonic δ^{18}O record shows a very different pattern except for the topmost part of the section (Fig. 15). The δ^{18}O values are ranging between –1.47 to 1.34‰ (Fig. 15).

INTERPRETATION AND DISCUSSION

The taxonomic composition of the foraminiferal assemblages makes it possible to distinguish two foraminiferal zones in the Młyny (Busko) PIG 1 borehole section: the *Orbulina suturalis* and *Uvigerina costai* zones (cf. Łuczkowska, 1964; Szczechura, 1984; Gonera et al., 2012; Fig. 10). The boundary between the two zones is located at a depth of 196.3 m. In Leszcze and Borków only the *Uvigerina costai* Zone was found.

The *Orbulina suturalis* Zone includes the lower part of the studied section of the Młyny (Busko) PIG 1 borehole comprising the interval contained between samples 41 to 33 (3.5 m thick) with an abundant warm water planktonic foraminiferal assemblage composed mainly of orbulinids and *Globigerinoides* spp. Rare *Globorotalia mayeri* and *G. siakensis* are also present. The upper boundary is placed at the level of the highest occurrence of *Orbulina suturalis*. The lower boundary of the zone has not been detected, due to the presence of *Orbulina suturalis* in the lowermost sample analysed.

It is commonly supposed that trends in the relative abundance of different foraminiferal taxa are likely to be responses to palaeoenvironmental changes (e.g., Buzas and Gibson, 1969; Murray, 1991, 2006) and it is the organic flux which influences by its amount, kind and quality not only the numbers of individuals but also the species composition of assemblages (Lutze and Coulbourn, 1984; Jorissen et al., 1995; Altenbach et al., 1999; Gooday et al., 2001). A high flux of organic matter to the sea-floor causes low oxygen concentrations within the sediment pore waters because oxygen is used in oxidation of the organic material. Infaunal species dominate in assemblages associated with relatively high organic-carbon fluxes and epifaunal ones in more oligotrophic environments (Corliss and Chen, 1988; Gooday, 1994; Thomas, 1990; Jorissen et al.,

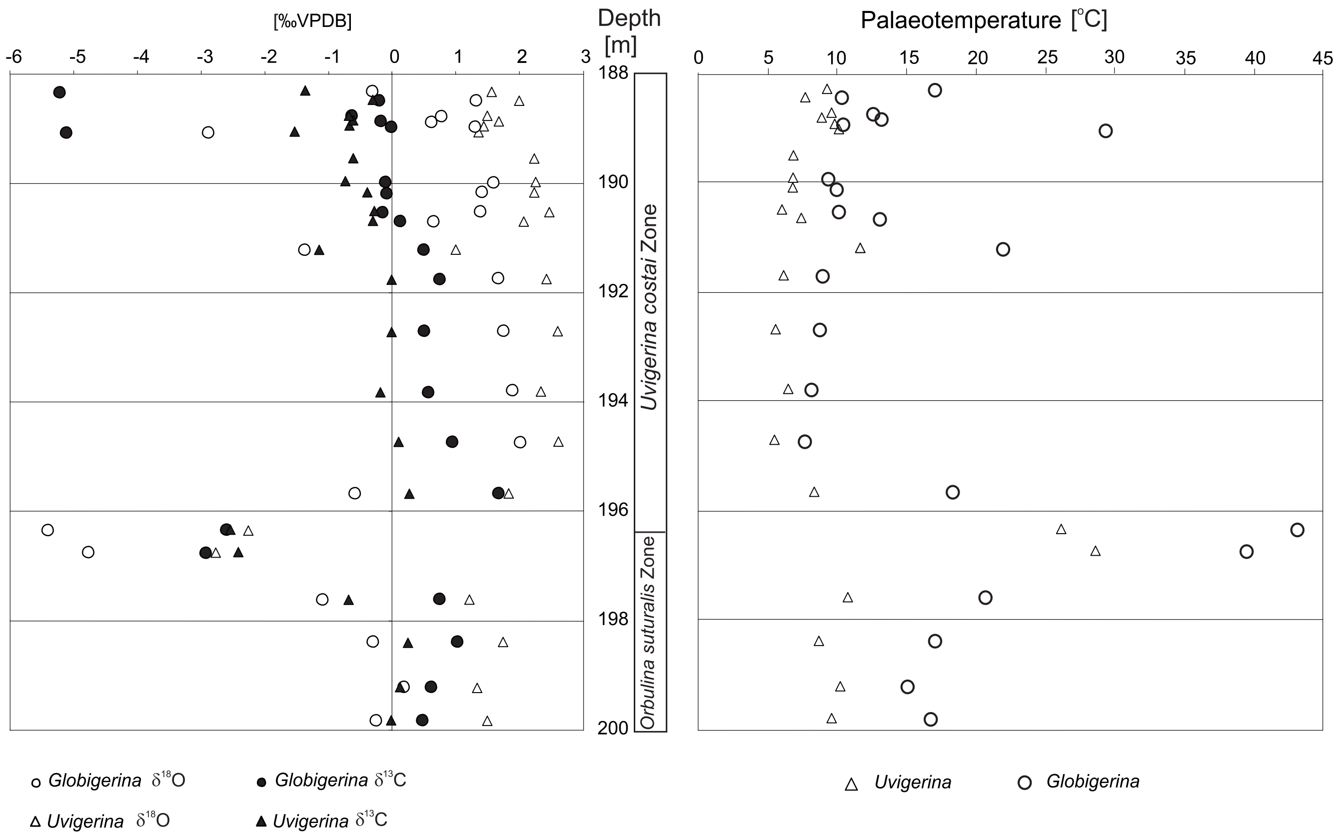

Fig. 14. Benthic and planktonic δ^{13}C and δ^{18}O isotope records for the Młyny (Busko) PIG 1 borehole section and calculated palaeotemperatures of ambient seawater

1995). Foraminiferal species diversity is much lower in stressed environments and assemblages are characterized by high dominance. The H(S) values below 2 indicate that the balance in the assemblages is distorted by high dominance of a few stress-tolerant taxa (Buzas and Gibson, 1969).

The benthic foraminiferal successions in the studied sections suggest oxygenation and productivity changes in the Carpathian Foredeep Basin prior to the Badenian salinity crisis. Four intervals of lowered oxygenation and/or elevated organic flux to the sea-floor alternated with intervals where oxygen stress was not so severe, are recognized in the most complete section studied (the Młyny section). *Buliminina* and *Uvigerina* are present continuously in the studied interval; in several places they dominate the assemblages; *Uvigerina* exceeds 60% while *Bulimina* even 80%. They are representatives of stress markers, as they are deep infaunally living organisms. In the material studied the deep infauna is represented also by *Bolivina* spp., *Fursenkoina acuta* and *Globocassidulina oblonga*. Of this group only *Fursenkoina acuta* briefly forms 25% of the assemblage in the uppermost part of the *Uvigerina costai* Zone. Oxic species in the studied interval are minor contributors to the assemblages. Their abundance fluctuates between 2 and 20%.

Intervals with benthic assemblages in which stress-tolerant taxa exceed 50% of the total and with high dominance [H(S) values are <2.2] are interpreted as having formed under conditions of lowered oxygen levels and high organic flux.

Eight assemblages have been distinguished in the Młyny section (Figs. 10 and 16).

Assemblage O1 occurs at the base of the section (depth 199.5–200.0 m). The assemblage is relatively highly diversified and with low dominance. The H(S) value is 2.8. Spiroplectamminids (*Spiroplectinella carinata*, *Vulvulina pennatula*), *Martinotiella communis*, *Melonis pompilioides, Sphaeroidina bulloides, Heterolepa dutemplei, Cibicidoides* spp.*, Hansenisca soldanii, Siphonina reticulata, Stilostomella* spp. and nodosariaceans (*Laevidentalina elegans*, *Lenticulina* spp.) are the common components of this assemblage. Stress markers (*Bulimina costata, Uvigerina aculeata* and *Bolivina* spp.) form only 14.4%, and oxic species (*Heterolepa dutemplei, Cibicidoides* spp., *Sigmoilinita tenuis*) 8.6% of the assemblage. The assemblage indicates a mesotrophic, close to oligotrophic, marine environment.

Assemblage D1 in the 0.7-m-thick interval (depth 198.8 to 199.5 m) is dominated by *Uvigerina* spp., which comprise up to 64% of the assemblage. Other stress markers: *Bulimina* (*B. costata, B. elongata*) and *Bolivina* (*Bol. dilatata*, *Bol. hebes*) form 5%. *Melonis pompilioides*, *Hansenisca soldanii*, nodosariaceans, and spiroplectamminids are common taxa. Oxic taxa form only 3% of the total assemblage. The H(S) value is 2.2. The high dominance of infaunal forms (*Uvigerina, Bulimina, Bolivina*), low H(S) value and low oxic component suggest low oxygen levels at the sea-floor caused by enhanced organic carbon flux and mesotrophic to eutrophic environment.

Assemblage S2 occurs in a 2.7-m-thick interval (depth 196.1 to 198.8 m). Two subassemblages (S2a and S2b) are recognized: S2a – with common *Bulimina* (23%), spiroplectamminids (20%), *Heterolepa dutemplei* (10%) and nodosariaceans (up to 19%), and the S2b subassemblage in which

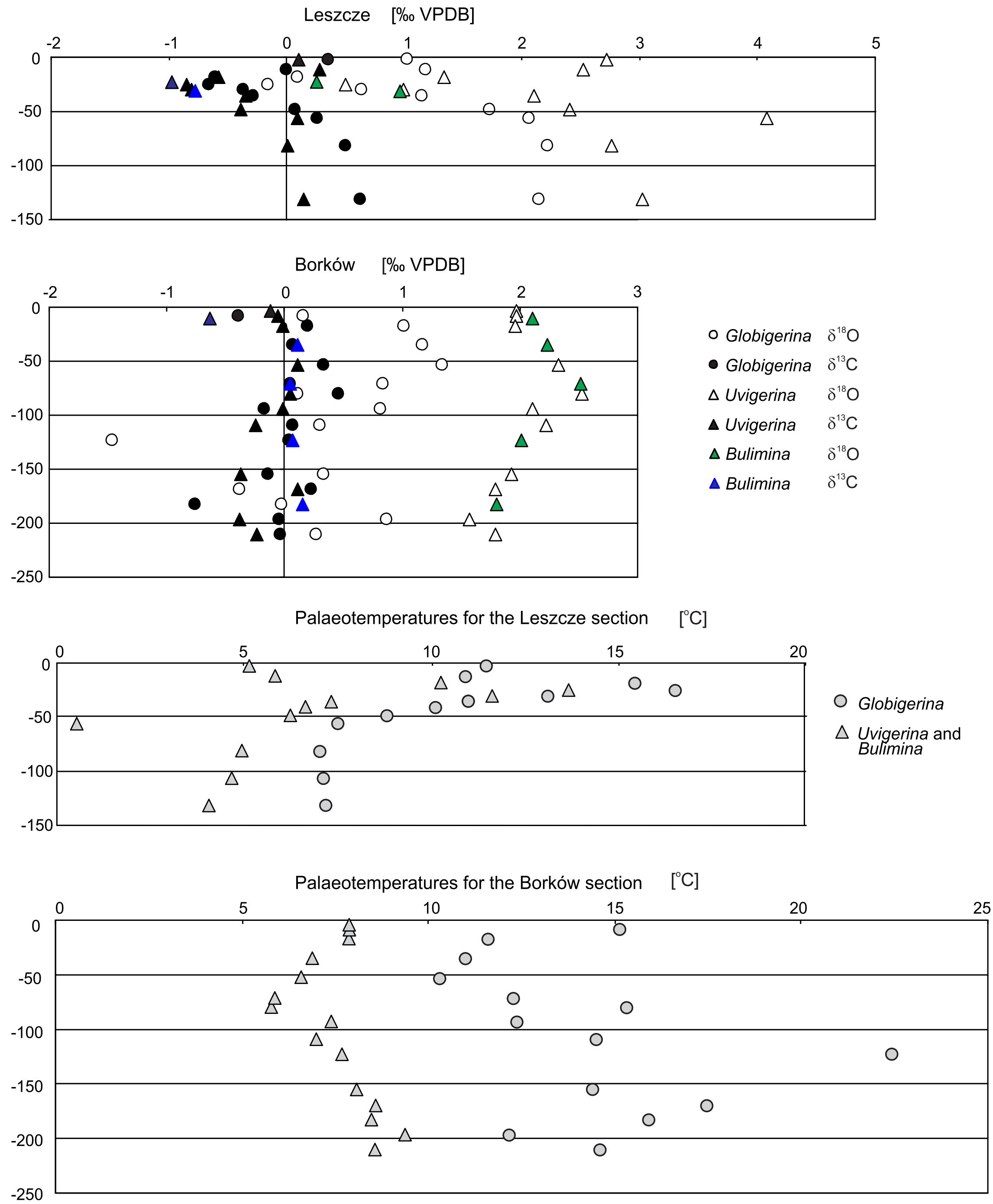

Fig. 15. Benthic and planktonic $\delta^{13}C$ and $\delta^{18}O$ isotope records for the Leszcze and Borków sections and calculated palaeotemperatures of ambient seawater

Uvigerina dominates and exceeds 30%, *Melonis pompilioides*, *Heterolepa dutemplei* and spiroplectamminids are common, and nodosariaceans are very rare or absent. *Nonion commune* in this subassemblage reaches 5%. The H(S) value in assemblage S2 reaches 2.72. Assemblage S2 reflects a return to mesotrophic, close to oligotrophic conditions in surface waters and lowered food supply, which resulted in good oxygenation at the sea-floor and relatively high diversities.

Assemblage D2 in the 3.4-m-thick interval (depth 192.7 and 196.1 m) is characterized by high contribution of stress markers which form from 50 to 91% of the assemblage. The H(S) values are between 2 and 2.2. Two subassemblages (D2a and D2b) are recognized: the D2a subassemblage with *Bulimina* (42%) and *Uvigerina* (24%). *Cibicidoides* spp., *Heterolepa dutemplei*, *Melonis pompilioides* and *Spiroplectinella carinata* are common species; oxic species (mainly *Cibicidoides* spp. and *Heterolepa duemplei*) form 19% of the total. The D2b subassemblage is dominated by *Uvigerina*, which reaches up to 61%; *Bulimina* is also common (up to 27%) and oxic *Heterolepa dutemplei* (10%). The oxic species compose 5 to 16% of the subassemblage.

Table 1

Summary of $\delta^{18}O$ and $\delta^{13}C$ statistics for each locality studied

Locality		n	Taxon	$\delta^{13}C$ [‰ VPDB]			$\delta^{18}O$ [‰ VPDB]		
				range	mean	SD	range	mean	SD
Młyny (Busko) PIG 1	total	21	U	–1.53 to 0.27	–0.42	0.5	0.99 to 2.62	1.88	0.49
		18	G	–0.65 to 1.66	0.36	0.56	–1.38 to 2.02	0.72	1.06
	U.c. Zone	17	U	–1.53 to 0.27	–0.50	0.50	0.99 to 2.62	1.97	0.48
		14	G	–0.64 to 1.66	0.26	0.60	–1.38 to 2.02	1.03	0.96
	O.s. Zone	4	U	–0.69 to 0.25	–0.09	0.41	1.21 to 1.74	1.44	0.23
		4	G	0.48 to 1.02	0.71	0.23	–1.10 to 0.17	–0.37	0.53
Leszcze		9	U	–0.85 to 0.15	–0.22	0.39	0.5 to 4.08	2.24	1.11
		12	G	–0.66 to 0.62	0.02	0.45	0.16 to 2.21	1.3	0.81
Borków		11	U	–0.38 to 0.11	–0.10	0.18	1.57 to 2.53	2.06	0.27
		14	G	–0.76 to 0.46	–0.01	0.31	–1.47 to 1.34	0.38	0.73
TOTAL		44	U		–0.31	0.43		1.99	0.64
		44	G		0.15	0.49		0.77	0.95

U – *Uvigerina*; G – *Globigerina*; *U.c.* Zone – *Uvigerina costai* Zone; *O.s.* Zone – *Orbulina suturalis* Zone

The foraminiferal record from the 8-m-thick marls underlying the gypsum indicates a longer period of high primary productivity and eutrophication of surface waters interrupted by a few short lasting periods with a return to mesotrophic, nearly oligotrophic conditions.

Assemblage D2 represents period of high primary productivity and low bottom-water oxygen content. The high dominance of *Uvigerina* and *Bulimina* and low content of oxic species confirm unfavourable conditions for the epifauna. The dominance of foraminiferal assemblages firstly by *Bulimina* over *Uvigerina* and then by *Uvigerina* over *Bulimina* may be probably explained by the different nutritional requirements of the two groups.

Assemblage S3 in the 0.7-m-thick interval at 192.0 to 192.7 m depth, is relatively highly diversified and shows low dominance. Stress markers do not reach 30%. Oxic species form 23% of the assemblage. Abundant is *Pullenia* (21%); common – *Melonis pompilioides* (5%). After a longer absence *Laevidentalina* spp. and *Stilostomella* spp. reappear in this assemblage. The H(S) value is 2.52. The low contribution of stress markers, low dominance, and relatively high diversity suggest mesotrophic conditions.

Assemblage D3 recorded in the 2-m-thick interval at a depth of 190.0 to 192.0 m is subdivided into three subassemblages: D3a, D3b and D3c. Subassemblage D3a (in the lower 0.7 m, at 191.3 to 192.0 m depth) is dominated by *Uvigerina* which reaches 50%; *Bulimina* forms only 6%. Suboxic *Melonis pompilioides* comprises up to 15% of the subassemblage. Oxic species are less common. *Cibicidoides* spp. do not exceed 8%. The H(S) value drops to 2. Subassemblage D3b (in the 0.9-m-thick interval at 190.4 to 191.3 m depth) differs from the previous subassemblage by the decrease in the abundance of *Uvigerina*. In subassemblage D3b, *Uvigerina* and *Bulimina* contribute in similar numbers and form 53% of the assemblage. *Melonis pompilioides* is other common species reaching 19%. Oxic markers are not abundant and form only 5% of the subassemblage. The H(S) value is 2.5. Subassemblage D3c in the upper 0.4 m, at 190.0 to 190.4 m depth, is dominated by *Uvigerina* which forms up to 53.5% of the subassemblage. *Bulimina* does not exceed 15%. *Melonis pompilioides*, *Sphaeroidina bulloides*, *Stilostomella* spp. are common taxa. Oxic species (mainly *Cibicidoides* spp.) form 6% of the total. The H(S) value is 2.2. The subassemblage D3c is recognized in the lowermost 0.3-m-thick part of the Borków section. At this site, however, *Bolivina*, along with *Bulimina* and *Uvigerina*, is an important contributor to the assemblage; its content exceeds 20%. Assemblage D3 reflects a longer period of eutrophic, close to mesotrophic conditions in surface waters and lowered oxygenation at the sea-floor.

Assemblage S4 occurs in the 0.4-m-thick interval (at 189.6 to 190.0 m depth) where stress markers form only 30%. The oxic species (mainly *Hoeglundina elegans* and *Cibicidoides* spp.) are present in similar proportions, forming up to 31% of the assemblage. *Melonis pompilioides, Lenticulina, Nodosaria*, and *Stilostomella* are also common in this assemblage. The H(S) value is 2.8. In the Borków Quarry, assemblage S4 is recorded 1.6 to 2.0 m below the gypsum. Assemblage S4 with its low contribution of stress markers, low dominance and relatively high diversity indicates a short-lived return to mesotrophic, close to oligotrophic, conditions.

Assemblage D4 recorded in the 1.6-m-thick interval at 188.0 to 189.6 m depth is subdivided into three subassemblages: D4a, D4b and D4c. Subassemblage D4a (in the 0.6-m–thick interval, at 189.0 to 189.6 m depth) is characterized by benthic foraminiferal assemblages where the contribution of stress markers is very high and varies insignificantly (75 to 83%). The H(S) values are between 1.9 and 2.6. *Uvigerina* and *Bulimina* dominate the assemblages. *Uvigerina* forms between 33 and 60% of the assemblages, and *Bulimina* 13 to 37%. Oxic species are minor contributors and do not exceed 7% of the assemblages. Subassemblage D4b occurs in the 0.3-m-thick interval (at 188.7–189.0 m depth) where stress markers form ca. 50% *Bulimina* – 37%, *Uvigerina* – 9%); *Pullenia miocenica*is abundant and reaches 25% in this assemblage. Oxic markers (mainly *Cibicidoides* and *Cibicides*) form 24% of assemblage. The H(S) values are between 2 and 2.4. Subassemblage D4c occurs in the uppermost 0.7-m-thick interval (at 188.0–188.7 m depth) just below the gypsum and is dominated by *Bulimina*; its contribution varies from 57 to 80%, while *Uvigerina* becomes a minor component and drops to less than 2%. *Fursenkoina acuta* reaches 25% in the lower part. The H(S) values are 1.8 to 1.9.

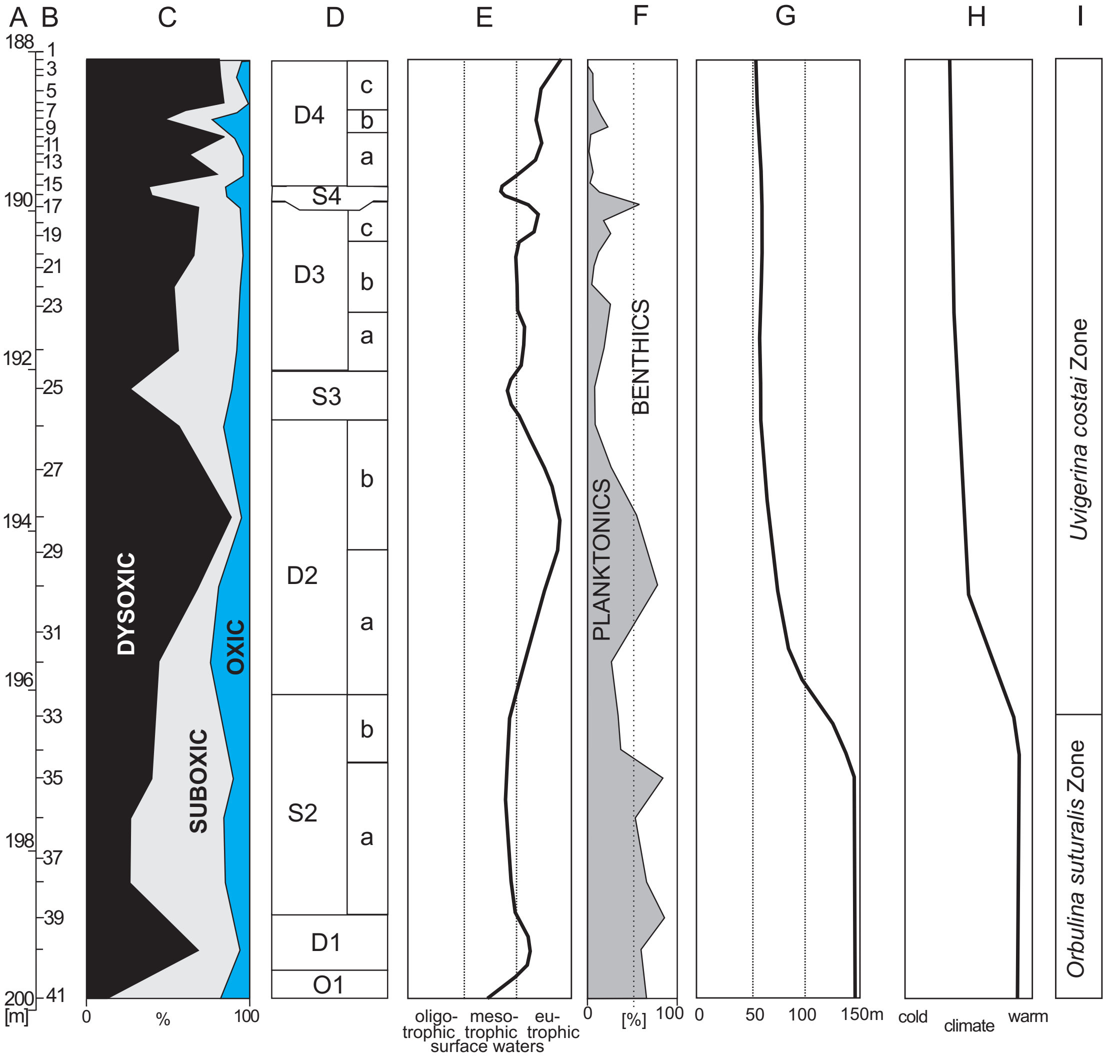

Fig. 16. Summary of environmental changes prior to the Badenian Salinity Crisis in the northern part of the Polish Carpathian Foredeep Basin inferred from changes in foraminiferal assemblages in the Młyny (Busko) PIG 1 borehole

A – depth; B – sample number; C – proportion of dysoxic, suboxic and oxic forms in benthic foraminiferal assemblages; D – benthic foraminiferal assemblages (see the text for explanation); E – relative changes in eutrophication of surface waters; F – abundance fluctuation of planktonic and benthic forms in foraminiferal assemblages; G – sea level changes; H – climatic changes; I – foraminiferal zones

Assemblage D4 occurs in a 1. 6-m-thick marl underlying the gypsum in the Borków Quarry and in a 1.2-m-thick marl below the gypsum outcropping in the Leszcze Quarry.

Assemblage D4 reflects again a period with high primary productivity and eutrophic conditions in surface waters and highly dysoxic waters at the seafloor. The youngest subassemblage D4c with very high dominance of *Bulimina* indicates probably not only very low oxygen levels at the sea-floor causing stress for benthic life, but probably also increased salinity as *Bulimina* is tolerant of both dysoxia and high bottom-water salinity (Verhallen, 1991). The H(S) diversity index is used as a measure of the stability of the environment. In open-marine outer shelf to slope environments, the H(S) value is about 3 (Murray, 1991; Drinia et al., 2007). Decreasing values of H(S) suggest increasing environmental stress and increased dominance and low diversity in populations. The H(S) values <2 indicate a high dominance of a few tolerant taxa. In upwelling areas with high primary productivity foraminiferal diversity is reduced. The depth in the sediment down to which organisms can live is determined by oxygen availability, and in the presence of oxygen, the vertical distribution of organisms is controlled by food availability (Jorissen et al., 1992). High rates of primary production at the surface lead to anaerobic bacterial blooms in the oxygen minimum zone of mid-waters and on the sea-floor beneath. In eutrophic regions deep infaunal species dominate assemblages under dysaerobic conditions (Corliss and Chen, 1988; Jorissen et al., 1995). *Bulimina, Bolivina, Uvigerina* are calcareous foraminifers that proliferate in such environments (Bernhard, 1986; Perez-Cruz and Machain-Castillo, 1990). Fluctuations of abundances of stress markers in the assemblages reflect changes in oxygenation and the preservation of organic matter at the sea-floor. Assemblages D1, D2–D4 and with low values of H(S) (<2.2) represent periods with high organic flux and dysoxic conditions at the sea-floor.

The *Bulimina* and *Uvigerina* groups are taxa with high tolerance to dysoxia and increased salinity (van der Zwaan, 1982, 1983; Lutze and Colbourn, 1984; Verhallen, 1991; Jorissen et al., 1992; Loubère, 1994, 1996). However, alternations of peak abundances of the two groups may be related to the amount, kind and quality of organic matter input to the sea-floor (Lutze and Coulbourn, 1984; Jorissen et al., 1995; Altenbach et al., 1999; Gooday et al., 2001; Peryt et al., 2002) especially if the two groups have specific and different nutritional requirements (van der Zwaan, 1982).

Assemblages S2–S5 characterize periods of ameliorated oxygenation conditions at the sea floor (suboxic environments). In these assemblages taxa tolerant for suboxic environments form 37 to 50% of the assemblages, and the H(S) value is >2.2. Spiroplectamminids, *Lenticulina*, *Laevidentalina*, *Pullenia*, *Melonis pompilioides*, *Sphaeroidina bulloides*, *Nonion commune* are common; in places they form up to 25% of the assemblage (e.g., *Pullenia miocenica* at depths of 192.2 and 188.65 m). Oxic species represented by *Heterolepa dutemplei*, *Cibicidoides* spp. and *Hoeglundina elegans* rarely reach 20%.

Assemblage O1 is composed of several species that are equally abundant. The H(S) values are >2.8. Dysoxic taxa form only 13.5% of this assemblage. Oxic species form 12%. The largest component consists of species that live as shallow infauna and are tolerant to suboxic environments. They form up to 75% of the assemblage. This assemblage reflects the period of highest oxygenation level at the sea-floor in the entire studied section.

Planktonic foraminifera are present throughout the Młyny section except in the topmost 0.2 m thick bed below the gypsum where this group is practically absent. In the lower part of the section (i.e., most of the *Orbulina suturalis* Zone) the P/B ratio values are high (60–85%). At the *Orbulina suturalis*/*Uvigerina costai* boundary interval the P/B decreases to 30–50% and again increases up to 80% in the middle part of the *Uvigerina costai* Zone. The upper part of the zone is characterized by low P/B values.

Warm-water planktonic foraminifera (i.e. *Orbulina* and *Globigerinoides*) dominate planktonic foraminiferal assemblages in the *Orbulina suturalis* Zone. Minor contributors to the assemblages are *Paragloborotalia mayeri* and *P. siakensis* – also indicators of oligotrophic warm-waters. Planktonic foraminiferal assemblages from the *Uvigerina costai* Zone are characterized by the high dominance of *Globigerina bulloides.*

Globigerinoides is a surface-dweller common in warm, oligotrophic waters of the mixed layer with highest abundances in regions where there is a permanent vertical stratification of the water column (Hemleben et al., 1989; Di Stefano et al., 2010). *Orbulina* – an intermediate water dweller living mainly at 50–100 m – is usually associated with relatively warm and oligotrophic surface waters (Hemleben et al., 1989; Armstrong and Brasier, 2005). *Globigerina bulloides* is a mixed-layer, cold-water dweller adapted to more eutrophic waters, tolerant for a wide range of typical oceanic salinities (Pujol and Vergnaud-Grazzini, 1995; Majewski, 2003; Majewski and Bohaty, 2010). *Globorotalia* is a deeper water dweller living mainly below 100 m, adapted to cooler, more eutrophic waters (Armstrong and Brasier, 2005).

The upsection decrease in the proportion of planktonic foraminifers reflects the shallowing of the basin accompanied by a decrease in the temperature gradient between the upper (warmer) and deeper (colder) waters. The replacement of intermediate warm water planktonic foraminiferal assemblages by assemblages dominated by *Globigerina* (mainly *G. bulloides*) is related to the Middle Miocene climate transition. This event was widely recorded in the middle Badenian of the Paratethys area (e.g., Gonera et al., 2000; Gonera, 2001; Hudáčková and Spezzaferri, 2002; Böhme, 2003; Jiménez-Moreno et al., 2005; Báldi, 2006; Harzhauser and Piller, 2007). It should be mentioned that already Szczechura (1982) interpreted the replacement of the assemblage of planktonic foraminifers with *Globigerinoides* spp. and orbulinids by the assemblage with *Globigerina* spp. (mainly *G. bulloides*) and *Globorotalia bykovae* as due to the climate cooling; consequently, she distinguished the occurrence of two ecozones below the evaporites: a *Globigerinoides* ecozone and a *Globigerina* ecozone.

$\delta^{13}C$ and $\delta^{18}O$ values of foraminifers are commonly applied for palaeoenvironmental interpretations of the Central Paratethys in the Badenian (e.g., Durakiewicz et al., 1997; Gonera et al., 2000; Báldi, 2006; Báldi and Hohenegger, 2008; Kováčová and Hudáčková, 2009; Kováčová et al., 2009; Peryt and Gedl, 2010; Bukowski, 2011; Holcová and Demeny, 2012; Gonera and Bukowski, 2012). The earlier studies have shown large variabilities which, as indicated by Holcová and Demény (2012), indicate sample inhomogeneity even in well-preserved foraminiferal samples, due to primary environmental variation and postmortem mixing of tests of various populations and sources. Total foraminiferal samples reported in this paper had a mean $\delta^{13}C$ value ca. 0‰ (–0.31 ± 0.43‰ for *Uvigerina* and 0.15 ± 0.49‰ for *Globigerina*). Accordingly, the $\delta^{13}C$ values of *Uvigerina* are lower than those of *Globigerina* (Table 1) which is the normal case, since an increased flux of organic matter to the sea-floor results in an increase in light carbon in infaunal benthic foraminifera (McCorkle et al., 1990); hence bottom waters contain depleted $\delta^{13}C$ (Broecker and Peng, 1982). The same is characteristic for the Upper Silesia Basin where Gonera and Bukowski (2012) reported a similar mean value for *Uvigerina* (0.07 ± 0.11‰ in IIC and –0.42 ± 0.46‰ in IID) and a slightly higher mean value for *Globigerina* (0.53 ± 0.28‰ for IIC and 0.29 ± 0.4‰ for IID); very similar values were recorded in the Młyny (Busko) PIG 1 borehole (Table 1). However, this is not the case in Moravia (Holcová and Demeny, 2012, fig. 11) and Vienna Basin (Kováčová and Hudáčková, 2009; Kováčová et al., 2009) where *Globigerina* has lighter $\delta^{13}C$ values than the benthic taxa. The foraminiferal samples from the Połaniec Trough had a mean $\delta^{18}O$ value of 1.99 ± 0.64‰ for *Uvigerina* and 0.77 ± 0.95‰ for *Globigerina*. In Upper Silesia, *Uvigerina* shows a similar mean $\delta^{13}O$ value (2.06 ± 0.72‰ for IIC and 2.54 ± 0.27‰ for IID; Gonera and Bukowski, 2012). In contrast, *Globigerina* shows a slightly higher mean $\delta^{13}O$ value in Upper Silesia (1.28 ± 1.11‰ in IIC and 1.88 ± 0.19‰ in IID; Gonera and Bukowski, 2012) than in the Młyny (Busko) PIG 1 section (Table 1). The average $\delta^{18}O$ value of *Globigerina* in the Vienna Basin (0.25‰ according to Kováčová and Hudáčková, 2009) is lower than in the Młyny (Busko) PIG 1 section and Upper Silesia; a still lower value (ca. –1‰; see Holcová and Demény, 2012, fig. 11) is recorded in Moravia.

For calculation of palaeotemperatures, various equations are used but all generally follow the original equation established by Epstein et al. (1953). However, due to various corrections the final temperature values can differ substantially (Appendix 4) although the trends of temperature changes based on calculations with various equations remain stable. All temperature equations take into account the isotopic composition of the seawater where the carbonate was precipitated, which is unknown. In addition, the possible effect of salinity increase has to be taken into account when interpreting the fossil records in the intervals prior to evaporite deposition (see discussion in Peryt and Gedl, 2010). For simplicity it was accepted, during the first approximation, that the Paratethys was an epicontinental sea of slightly elevated seawater salinity ($\delta^{18}O_{water}$ = 0.1‰ SMOW as

Table 2

Range of and mean palaeotemperatures for *Uvigerina* and *Globigerina* assuming that $\delta^{18}O_{water}$ was –1‰, 0‰, 0.1‰ and +1‰.

Locality	Taxon	Range of palaeotemperatures [°C] assuming that $\delta^{18}O_{water}$ was			
		–1‰ SMOW	0‰ SMOW	0.1‰ SMOW	1‰ SMOW
Młyny (Busko) PIG 1	U	1.8 to 7.4	5.2 to 11.3	5.5 to 11.7	11.2 to 15.4
	G	3.8 to 17.0	7.3 to 21.5	7.7 to 22.0	11.2 to 26.3
Leszcze	U	-2.6 to 9.3	0.3 to 13.3	0.6-13.7	3.6 to 17.5
	G	3.1 to 10.6	6.6 to 14.7	7.0 to 15.1	10.4 to 19.1
Borków	U	2.1 to 5.3	5.5 to 9.0	5.8 to 9.4	9.2 to 13.0
	G	6.2 to 17.4	9.9 to 22.0	10.3 to 22.4	13.9 to 26.8
TOTAL	U	1.7 to 5.8	5.1 to 9.6	5.4 to 9.9	8.7 to 13.6
	G	4.8 to 12	8.4 to 16.1	8.8 to 16.6	12.4 to 20.6
		Mean palaeotemperatures [°C] assuming that $\delta^{18}O_{water}$ was			
		–1‰ SMOW	0‰ SMOW	0.1‰ SMOW	1‰ SMOW
Młyny (Busko) PIG 1	U	4.3	7.8	8.2	11.7
	G	8.5	12.4	12.8	16.6
Leszcze	U	2.8	6.3	6.7	10.1
	G	6.3	10.1	10.5	14.1
Borków	U	3.6	7.2	7.6	11
	G	9.8	13.8	14.2	18.1
TOTAL	U	3.7	7.3	7.6	11.1
	G	8.3	12.2	12.6	16.4

Palaeotemperatures calculated with the formula given by Epstein et al. (1953)

indicated by relict water occurring in strata below the Badenian evaporites – see discussion in Bukowski, 2011). Figures 14 and 15 show the interpreted palaeotemperature in three sections studied, assuming $\delta^{18}O_{water}$ = 0.1‰ SMOW, and Table 2 shows the ranges of palaeotemperatures for two taxa assuming various $\delta^{18}O_{water}$ values: –1, 0, 0.1 and 1‰. For the palaeotemperature calculation of the total set of samples, the range of maximum and minimum values was established taking into account main values and the standard deviation (plus or minus).

In their study of Badenian foraminifera from the Vienna Basin Kováčová et al. (2009) assumed a $\delta^{18}O_{water}$ of 0‰, and calculated palaeowater temperatures, if the equation of Epstein et al. (1953) is applied, would be 6.3–8.5°C for benthic foraminifers (mostly *Uvigerina*) and 9.7 to 17.7°C for *Globigerina*. Those values are similar to the results from this study. When $\delta^{18}O_{water}$ of 0‰ is used for the calculation of palaeowater temperature, the ranges of mean values would be 6.3–7.8°C for *Uvigerina* and 10.1–13.8°C for *Globigerina*, and they increase to 11–11.7°C for *Uvigerina* and 10–18°C for *Globigerina* when a $\delta^{18}O_{water}$ of 1‰ is used in calculations. In the modern Mediterranean $\delta^{18}O_{water}$ = 1‰ was recorded (Pierre, 1999), and in the Red Sea it is still higher (2‰; Craig, 1966) while the Black Sea has a value of –3‰ (Latal et al., 2006). Taking into account the geological context the existence of local variations of the $\delta^{18}O_{water}$ in the Central Paratethys both in time and space casts no doubt.

However, there is a clear temporal change as far as the palaeotemperature of water in which foraminifers lived is concerned, at the boundary between the *Orbulina suturalis* and *Uvigerina costai* zones (Fig. 14; cf. Table 1). The average palaeotemperature of water based on the $\delta^{18}O$ of *Uvigerina* decreased by ca. 2°C (from 9.9°C in the *Orbulina suturalis* Zone to 7.9°C in the *Uvigerina costai* Zone when $\delta^{18}O_{water}$ = 0.1‰ SMOW, and from 13.5 to 11.4°C when $\delta^{18}O_{water}$ = 1‰ SMOW). An even greater decrease (ca. 6°C) is characteristic for *Globigerina* (from 17.4 in the *Orbulina suturalis* Zone to 11.5°C in the *Uvigerina costai* Zone when $\delta^{18}O_{water}$ = 0.1‰ SMOW, and from 21.5 to 15.2°C when $\delta^{18}O_{water}$ = 1‰ SMOW). In the Młyny (Busko) PIG 1 section only the uppermost part of the *Orbulina suturalis* Zone was available to study, so the earlier benthic oxygen isotope record remains enigmatic. In the Mediterranean Sea, this record shows a gradual trend toward heavier values between ~14.95 and 13.95 Ma (Mourik et al., 2011; cf. Miller et al., 1991). As indicated by Mourik et al. (2011), between ~14.0 and 13.9 Ma, open ocean records show a short interval characterized by relatively light benthic $\delta^{18}O$ values associated with a warm phase, although this signal seems to be absent in the Mediterranean. In turn, no similar trend is observed in the planktonic $\delta^{18}O$ record (Mourik et al., 2011). The global Middle Miocene cooling is reflected in the benthic oxygen isotope record, showing a ~0.6‰ increase between ~13.95 and 13.76 Ma. Mourik et al. (2011) concluded that bottom water temperature in the Mediterranean did not change significantly at that time. Much stronger changes in the water palaeotemperature as indicated by both the benthic and planktonic $\delta^{18}O$ records in the Młyny (Busko) PIG 1 section (Fig. 14) are in concert with the stronger signal of the Badenian cooling trend in the Carpathian Foredeep assumed by Bicchi et al. (2003) and Báldi (2006).

Below the gypsum, the $\delta^{18}O$ values of both benthic and planktonic foraminifers show quite large variations (Figs. 14 and 15), which is possibly due to the salinity increase (see Peryt and Gedl, 2010, for discussion).

On the basis of sedimentological analyses, coastal upwelling has been repeatedly suggested for Central Paratethys during the Early Miocene (Grunert et al., 2010, with references therein) and the Middle Miocene (e.g., Gonera, 2001; Key et al., 2013).

Foraminifers that calcify in an upwelling environment yield higher $\delta^{18}O$ values and lower $\delta^{13}C$ values (e.g., Faul et al., 2000; Peeters et al., 2002). Upwelling causes higher $\delta^{18}O$ values in response to mixing with upwelled deeper, colder waters, and lower $\delta^{13}C$ values result from mixing with upwelled deeper, more nutrient-rich waters containing older dissolved inorganic carbon with low $\delta^{13}C$ values (Key et al., 2013, with references therein). Foraminiferal samples reported in this paper had a mean $\delta^{13}C$ value of –0.31‰ (*Uvigerina*) and 0.15‰ (*Globigerina*) and a mean $\delta^{18}O$ value of 1.99‰ (*Uvigerina*) and 0.77‰ (*Globigerina*), and thus $\delta^{13}C$ values are clearly lower than the range in mean global values (ca. 1.6‰ about 14 to 13.8 Ma; Zachos et al., 2001). The $\delta^{13}C$ results can be interpreted as support for upwelling, and Key et al. (2013) suggested that there could have been upwelling along the northern margin of Carpathian Foredeep if the dominant winds were out of the west, as they could have caused upwelling due to the Coriolis effect (cf. Grunert et al., 2010). Contrary to expectations, the $\delta^{18}O$ values of foraminifers determined in this study do not show the predicted higher values: the mean $\delta^{18}O$ value for *Uvigerina* is around the mean global value (ca. 1.6 to 2.0‰ from 14 to 13.8 Ma; Zachos et al., 2001), and accordingly, I do not use isotope data from foraminifera to argue for upwelling in the studied part of Central Paratethys during the Middle Miocene.

CONCLUSIONS

1. Seventy-four samples of marls occurring below the mid-Badenian gypsum in three sections from the northern part of the Połaniec Trough, northern Polish Carpathian Foredeep Basin: Młyny (Busko) PIG 1 borehole section and Leszcze and Borków quarries, yielded rich foraminiferal assemblages. In the Młyny (Busko) PIG 1 borehole, sixty-seven benthic and twenty-one planktonic taxa were found.

2. Benthic foraminiferal assemblages (mostly calcareous forms; agglutinated foraminifera are represented only by four species) of the studied interval (12 m thick) in the Młyny borehole are characterized by the dominance of *Bulimina* and *Uvigerina*. Planktonic foraminifers are composed mainly of warm-water orbulinids (*Orbulina suturalis* and *O. bilobata*) and *Globigerinoides* spp. in the lower part of the section and by cool-water *Globigerina* spp. in the upper part.

3. Taxonomic composition of foraminiferal assemblages makes it possible to distinguish two foraminiferal zones in the Młyny borehole: *Orbulina suturalis* and *Uvigerina costai.* The boundary between the two zones is located at a depth of 196.3 m. In the Leszcze and Borków quarries only the *Uvigerina costai* Zone is accessible.

4. The foraminiferal record from the *Uvigerina costai* Zone of the Młyny section indicates a longer period of high primary productivity and eutrophication of surface waters interrupted by a few short lasting periods with a return to mesotrophic or nearly oligotrophic conditions.

5. The benthic foraminiferal successions in the studied interval suggest oxygenation and productivity changes in the Carpathian Foredeep Basin prior to the Badenian salinity crisis. Four intervals of dysoxic conditions alternated with intervals with good oxygenation at the sea-floor, and eight assemblages have been distinguished in the Młyny section.

6. The upsection decrease in the proportion of planktonic foraminifers reflects the shallowing of the basin accompanied by a decrease in the temperature gradient between the upper (warmer) and deeper (colder) waters. The replacement of intermediate warm-water planktonic foraminiferal assemblages by *Globigerina*-dominated assemblages (mainly *G. bulloides*) is related to the Middle Miocene climate transition widely recorded in the middle Badenian of the Paratethys area.

7. The $\delta^{18}O$ and $\delta^{13}C$ ratios of two foraminiferal taxa: *Globigerina* (in most cases, *G. bulloides*) and *Uvigerina* (mostly *U*. ex gr. *peregrina*), were studied in 52 samples. Total foraminiferal samples reported in this paper had a mean $\delta^{13}C$ value of –0.31 ± 0.43 for *Uvigerina* and 0.15 ± 0.49‰ for *Globigerina*, and a mean $\delta^{18}O$ value of 1.99 ± 0.64‰ for *Uvigerina* and 0.77 ± 0.95‰ for *Globigerina*. There is a clear change in the palaeotemperature of water in which foraminifers lived at the boundary between the *Orbulina suturalis* and *Uvigerina costai* zones. The average palaeotemperature of water based on the $\delta^{18}O$ of *Uvigerina* decreased by ca. 2°C and based on the $\delta^{18}O$ of *Globigerina* by ca. 6°C. The observed changes in the water palaeotemperature are in concert with the stronger signal of the Badenian cooling trend in the Carpathian Foredeep assumed previously by Bicchi et al. (2003) and Báldi (2006).

8. Below the gypsum, the $\delta^{18}O$ values of both benthic and planktonic foraminifers show quite large variations that are possibly due to the salinity increase.

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