Palaeoenvironmental changes preceding the Middle Miocene Badenian salinity crisis in the northern Polish Carpathian Foredeep Basin (Borków quarry) inferred from foraminifers and dinoflagellate cysts

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Peryt D. and Gedl P. (2010) – Palaeoenvironmental changes preceding the Middle Miocene Badenian salinity crisis in the northern Polish Carpathian Foredeep Basin (Borków quarry) inferred from foraminifers and dinoflagellate cysts. Geol. Quart., **54** (4): 487–508. Warszawa.

 Study of foraminiferal and dinoflagellate cyst assemblages and palynofacies occurring in 2 m-thick marls cropping out beneath a giant gypsum intergrowth unit in the Borków gypsum quarry in Southern Poland, one of the key Badenian evaporite sections in the Polish Carpathian Foredeep Basin, has shown the presence of 49 species of benthic foraminifers and 11 species of planktonic ones, and 51 dinoflagellate (including 8 redeposited ones). The composition of the foraminiferal fauna and its isotopic signal indicate temperature-stratified, nutrient-rich and thus less-oxygenated marine water. Changes in the relative abundance of epifaunal and infaunal species indicate a clear environmental change during the deposition of the marls. A middle to outer shelf marine, well-ventilated environment with moderate primary productivity existed during the deposition of the bottom part of the marls. Subsequently, infaunal bottom-dwellers became dominant due to a massive increase in food supply to the sea bottom and shallowing of the sea to inner – middle shelf depths, and than a decreasing trend of a relative abundance of the infaunal morphogroups is observed until the top of the marls that were deposited in an inner shelf environment with moderate primary productivity. The calculated palaeotemperatures for particular foraminifer taxa (*Globigerina* spp., *Cibicidoides* and *Bulimina elongata*) show a slight upsection decrease and a decrease in the temperature differences between the bottom and intermediate water beds. Palynofacies are composed of elements of mixed origin, including terrestrial, marine (mainly dinoflagellate cysts) and elements of uncertain derivation (structureless organic matter). The palynological content of most samples indicates their deposition in an open-marine marine environment, in the stable marine conditions of an open shelf basin with no salinity fluctuations. The sample just below the gypsum contains no dinoflagellate cysts, perhaps due to a drastic change in the photic zone leading to a complete collapse of the dinoflagellate flora. Very rare occurrence of planktonic foraminifers in that sample suggest the shallowing of the basin accompanied by a decrease in the temperature gradient between the upper (warmer) and lower (colder) water beds. A shallow, cold water marine environment is indicated for the topmost foraminiferal assemblage.

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INTRODUCTION

The Paratethys developed as a large epicontinental sea, with several connections to other marine provinces and subject to the repeated occurrence of isolation and reopening of oceanic pathways (Rögl, 1998). The multiple stages of isolation resulted, among other effects, in salinity crises. The Middle Miocene salinity crisis in the Central Paratethys resulted in the deposition of evaporites in the Carpathian region (Fig. 1). In addition, evaporites were deposited in several other places in the Eastern Paratethys as well as in the Red Sea and the Middle East (Popov *et al.*, 2004). In the Carpathian Foredeep Basin,

the evaporites are late Badenian (Serravallian) in age (Fig. 2) and are underlain by deep-water deposits in more central basin locations. The earlier studies suggested that the onset of evaporite deposition was sudden but not synchronous in all facies zones: the evaporites deposited in the basin center preceded the beginning of evaporite sedimentation in the marginal basin that extended into the foreland (see Peryt, 2006, with references therein). The range of evaporite drawdown was estimated as a few tens of metres of the northern margin of the Carpathian Foredeep in Poland (B bel, 2004) and 50–100 m in its axial part (Oszczypko, 1998). Isotopic studies of Badenian foraminifers occurring below evaporites suggest that the interrupted communication of the Paratethys with the ocean was a
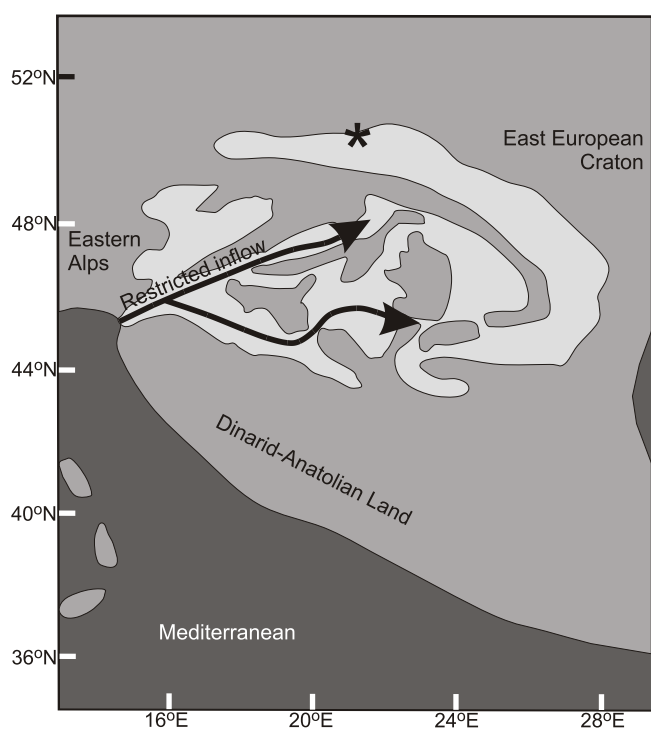
Fig. 1. Simplified palaeogeographic reconstruction of Central Paratethys (light grey) *ca*. **13.8 Ma (after de Leeuw** *et al*.**, 2010, modified after Rögl, 1998); star marks location of the the Borków quarry**
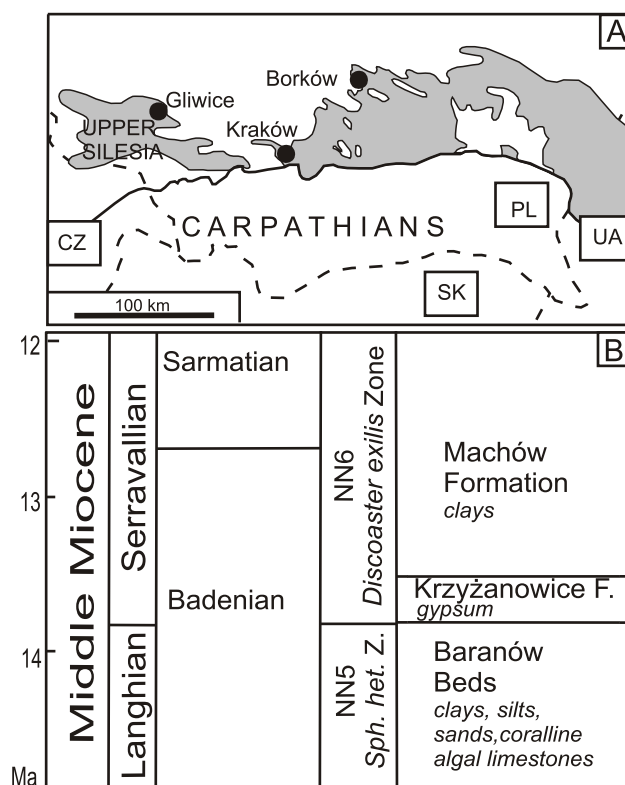

Fig. 2A – location of the Borków quarry; grey – Miocene deposits of the Carpathian Foredeep Basin located north of the Carpathian Overthrust (thick line); B – stratigraphy of the Miocene strata in the Borków region. The Miocene time scale after Hilgen *et al*. (2009), partly recalibrated and correlated 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 *Sphenolithus heteromorphus* Zone

consequence of eustatic sea level fall, possibly related to climatic cooling (Gonera *et al.*, 2000), and it was coupled with a tectonic closure of connection with the Tethys (Peryt, 2006). The deposition of evaporites and of the underlying strata occurred during the cooling interval (between 14.0 and 13.5 Ma) when the mean annual temperature dropped more than 7°C, to temperatures around 14.8–15.7°C, in Central Europe (Böhme, 2003). A major step in Middle Miocene global cooling occurred at 13.82 ±0.03 Ma (Abels *et al.*, 2005) and it triggered a significant drop (~60 m) in global sea level that hindered the exchange of water through the gateway to the Mediterranean, consequently setting off the Badenian salinity crisis shortly after 13.81 Ma (de Leeuw *et al.*, 2010).

The aim of this paper is to provide information on foraminiferal and dinoflagellate cyst assemblages and palynofacies occurring in marls underlying a giant gypsum intergrowth unit in the Borków gypsum quarry in Southern Poland (Fig. 3) and to present the implications which are crucial to resolve questions concerning the transition from marine to evaporitic conditions (e.g., Orszag-Sperber *et al.*, 2009).

GEOLOGICAL SETTING

The Badenian marine deposits of the northern part of the Carpathian Foredeep Basin lie transgressively on eroded Cretaceous and Jurassic strata (Radwański, 1969) and are included into the Pińczów Formation, including various carbonate and siliciclastic rock units up to several tens of metres thick (Czapowski, 2004). The Badenian marls of the Baranów Beds constituting the upper member of the Pińczów Formation are typically several metres thick in the Borków area but in some

places the marls are lacking and the gypsum of the Krzyżanowice Formation covers coralline algal limestones of the Pińczów Formation, as indicated by archival data of the Borków quarry. The marls used to be exposed at the entrance to the Borków quarry (e.g., Bąbel, 1999*a*: plate II, fig. 1) but now they are covered, yet the lower surface of the lowest gypsum unit (unit a – according to local lithostratigraphical subdivision by Wala, 1962), reveals convexities (Fig. 3B) which are interpreted by Bąbel (1999*b*) as resulted from sinking of the growing gypsum crystals into muddy substrate. Recent excavation at the bottom of the quarry exposed the 2 m-thick marls occurring below the lowest gypsum unit (Fig. 3C). This unit, *ca*. 5.3 m thick and described in detail by Bąbel (1987), consists of giant gypsum intergrowths and is overlain by bedded selenites with intercalations of alabastrine and stromatolitic gypsum, followed by sabre gypsum (Fig. 3A). The upper part of the gypsum sequence consists primarily of various facies of clastic gypsum (Fig. 3A; Bąbel, 1991; Kasprzyk, 1993; Peryt and Jasionowski, 1994). Giant gypsum intergrowths originated from density-stratified brines (Pawlikowski, 1982). This density stratification possibly started during the deposition of the Ervilia Bed, locally occurring below gypsum in the marginal part of the Carpathian Foredeep Basin, a thin layer (usually 10–15 cm) containing fauna adapted to increased salinity and low oxygen levels (Peryt, 2006, with references therein).
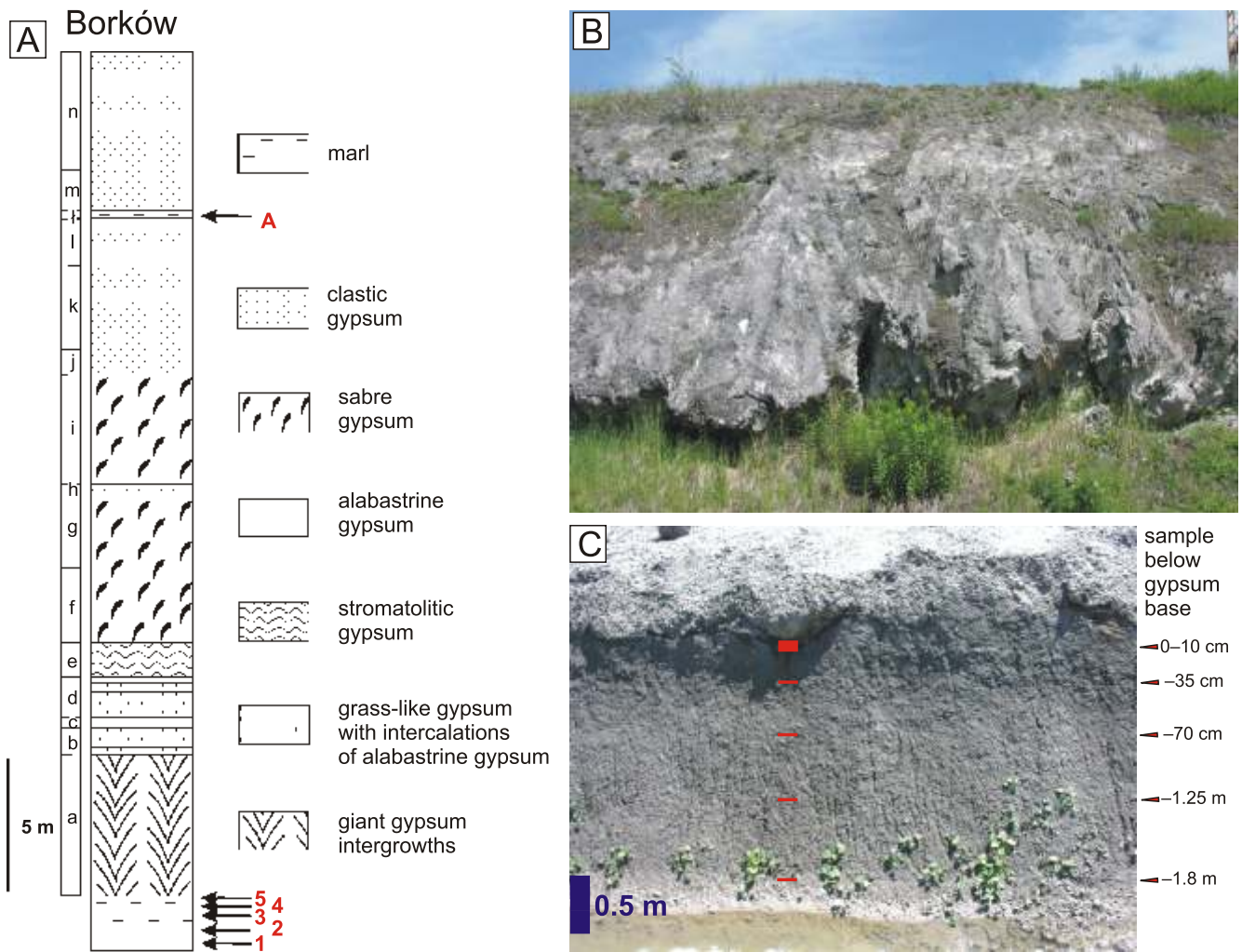
Fig. 3A – the Borków quarry section (after Peryt and Jasionowski, 1994), showing the location of the samples studied; left column of the lithological section shows gypsum units (a–n after Wala, 1962); B – field photo (June 2009) shows the giant gypsum intergrowth unit (*ca*. 5 m thick) near the entrance to the quarry; notice the convexities below the giant gypsum intergrowths; C – field photo shows the location of samples 1–5 (in red) in the excavation; sample A comes from the upper part of the gypsum succession

MATERIAL AND METHODS

Five samples from the excavation have been studied for foraminifers and dinoflagellate cysts. Their location is shown in Figure 3. For comparison, one sample (designated as A) from the upper part of the gypsum succession (Fig. 3A) has been studied for dinoflagellate cysts; previously, in this gypsum unit, planktonic foraminifers have been reported (Peryt *et al.*, 1994).

The samples for palynology were processed in the Micropalaeontological Laboratory of the Institute of Geological Sciences, Polish Academy of Sciences, Kraków. The standard palynological procedure applied included 38% hydrochloric acid (HCl) treatment, 40% hydrofluoric acid (HF) treatment, heavy liquid ($ZnCl_2$ + HCl; density 2.0 g/cm^3) separation, ultrasound for 10–15 s and sieving at 15 μm on a nylon mesh. No nitric acid (HNO_3) treatment was applied. The quantity of rock processed was approximately 20 g for each sample. Microscope slides were made from each sample using glycerin jelly as a mounting medium. The rock samples, palynological residues and slides are stored in the collection of the Institute of Geological Sciences, Polish Academy of Sciences, Kraków.

Washed residues for foraminiferal study were obtained from the marls by disaggregation using Na_2SO_4. An aliquot of about 200–300 specimens of foraminifers from the 100–600 μm size fraction was picked for the faunal analyses. Taxonomy of the foraminifers follows Loeblich and Tappan (1988), Odrzywolska-Bie kowska and Olszewska (1996) and Cicha *et al.* (1998). Foraminiferal taxa were allocated to morphogroups according to Jones and Charnock (1985) and Corliss and Chen (1988). The relative abundance of infaunal and epifaunal forms and the relative abundance of infaunal and epifaunal morphogroups within benthic foraminiferal assemblages were calculated. The figured specimens are deposited in the Institute of Palaeobiology, Polish Academy of Sciences, Warsaw (ZPAL F. 59).

It is commonly supposed that trends in relative abundance of different taxa are likely to be responses to palaeoenvironmental changes (e.g., Jorissen, 1999; Drinia *et al.*, 2007), and therefore the Shannon-Weaver heterogeneity index H(S) and relative percentages of benthic foraminifer species within benthic foraminiferal assemblages as well as the percent of planktonic foraminifers within total foraminiferal assem-

Recent environmental requirements of genera recorded in the marls occurring below gypsum at Borków quarry (after Murray, 1991, 2006)

Genus	Mode of live	Substrate	Salinity	Temperature	Depth, environment
Bolivina	infaunal–epifaunal	muddy sediment	marine	cold to warm	inner shelf-bathyal
Bulimina	infaunal	mud to fine sand	marine	cold-temperate	inner shelf-bathyal
Cibicides	epifaunal	hard substrates	marine	cold-warm	0 to >2000 m; lagoons, shelf-bathyal
Cibicidoides	epifaunal	hard substrates	marine	cold	shelf-bathyal
Discorbis	epifaunal	firm substrates, coarse sand	marine	temperate-warm	0–50 m; inner shelf
Elphidium – keeled	epifaunal	sand	marine (35–70‰)	temperate-warm	0–50 m; inner shelf
Elphidium – non-keeled	infaunal	mud, sand	brackish-hypersaline marshes and lagoons (35–70‰)	temperate-warm	inner shelf
Fursenkoina	infaunal	mud	30–35‰		0–1200 m; lagoons, shelf, upper bathyal
Globobulimina	infaunal	mud	marine	temperate-cold	shelf-bathyal
Globocassidulina	infaunal	mud	marine	temperate-cold	shelf-bathyal
Heterolepa	epifaunal	hard substrates	marine	cold	shelf-bathyal
Hoeglundina	infaunal	mud	marine	cold	middle shelf-bathyal
Lenticulina	infaunal	mud	marine	cold	shelf-bathyal
Melonis	infaunal	mud, silt	marine	<10°C	shelf-bathyal
Pullenia	infaunal	mud	marine	cold	shelf-bathyal
Pyrgo	epifaunal, free or clinging	plants or sediment	marine	cold	shelf-bathyal
Rosalina	epifaunal, clinging or attached	firm substrates	marine	temperate-warm	0–100 m; lagoons, inner shelf
Spiroloculina	epifaunal, free or clinging	sediment or plants	marine-hypersaline	temperate-warm	0–40 m; lagoons, inner shelf
Triloculina	epifaunal, free or clinging	mud, sand, plants	marine-hypersaline 32–55‰	cold	0–40 m; inner shelf, some bathyal species
Quinqueloculina	epifaunal, free or clinging	plants or sediment	marine-hypersaline32–65‰	cold-warm	0–40 m; shelf, rarely bathyal
Uvigerina	mainly infaunal, some epifaunal, free	muddy sediment	marine	cold	100 to >4500 m; shelf-bathyal

Salinity: brackish – 0–32‰; marine – 32–37‰; hypersaline – >37‰; temperature (of the bottom water) cold, temperate, warm (even in tropical areas water deeper than ≈ 100 m is temperate or cold); environment: shelf – 0–180 m, bathyal – 180 to ≈ 4000 m, abyssal – greater than ≈ 4000 m; the data relate to the main occurrence of each genus and exclude rare occurrences in other environments

blages (P/B ratio) were calculated. Foraminiferal species diversity is much lower in stressed environments, and when the Shannon-Weaver index is below 2, the balance in the assemblages is distorted by high dominance of a few stress-tolerant taxa (Drinia *et al.*, 2007). Palaeobathymetry was estimated on the basis of benthic fauna characteristics and the P/B ratio. The percentage of planktonic foraminifers is one of the most consistent proxies to assess palaeowater depth (Drinia *et al.*, 2007, with references therein). The palaeoenvironmental interpretation based on foraminifers applies the requirements of present-day representatives of recorded taxa (Table 1).

One of the most important factors controlling the distribution of foraminifers is temperature (Schiebel and Hemleben, 2005). To calculate absolute water temperature, $\delta^{18}O$ ratios of selected foraminifer species were used: planktonic *Globigerina* spp., infaunal *Bulimina elongata* and epifaunal *Cibicidoides*. In addition, epifaunal *Hoeglundina elegans* was analysed. 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 Palaeobiology, 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‰. For calculation of palaeotemperatures, the equations developed by Epstein *et al.* (1953), Shackleton (1974), Erez and Luz (1983), and Bemis *et al.* (1998) were used.

Five samples from Borków quarry (four samples from section I and sample A) were subject to X-ray Diffraction (XRD) study using a *Philips X'Pert PW 3020* spectrometer at the Central Chemical Laboratory of the Polish Geological Institute. The wavelength used was K-Alpha1 and the peak search parameter set was PC-APD.

RESULTS

FORAMINIFERS

The study of foraminifers showed the presence of 49 benthic species and 11 planktonic species. The preservation of

foraminifers is good to moderate. In most cases it allows determination to species level. In some cases, however, e.g. in samples 1 and 5, the foraminiferal tests show traces of corrosion and/or mechanical damage that may indicate resedimentation. Agglutinated foraminifers have been only found in sample 1. The number of species in particular samples varied from 14 to 22. The list of taxa identified is shown in Appendix. The dominant and common species are illustrated in Figures 4–6.

The following species recorded in the material studied are interpreted to be stress (deep infaunal, dysoxic) markers: *Bulimina elongata*, *B. insignis*, *B. aculeata*, *Bolivina dilatata*, *B. spathulata*, *Uvigerina aculeata*, *U. semiornata*, *Praeglobobulimina pyrula*, *Globocassidulina oblonga*, *Fursenkoina acuta* and *Melonis pompilioides* (e.g., Spezzaferri *et al.*, 2002; Báldi, 2006; Báldi and Hohenegger, 2008). *Cibicidoides austriacus*, *C. ungerianus*, *C. pseudoungerianus*, *Lobatula lobatula*, *Sigmoilinita tenuis*, *Triloculina* spp., *Pyrgo* spp., *Elphidium* spp. and *Hoeglundina elegans* are interpreted to be epifaunal or oxyphilic markers (e.g., Báldi, 2006; Báldi and Hohenegger, 2008). *Pullenia bulloides* and *Sphaeroidina bulloides,* interpreted as stress markers by some authors (van der Zwaan *et al.*, 1990; van Hinsbergen *et al.*, 2005; Báldi and Hohenegger, 2008), are considered by van Kouwenhoven and van der Zwaan (2006) as oxyphilic species. In the present paper the two species are interpreted as inbenthic forms. Increased percentages of miliolids are a proxy of increased ventilation in bottom and pore waters (den Dulk *et al.*, 2000).

Hoeglundina elegans is an epifaunal species (Jorissen *et al.,* 1998), widespread in recent oceans at depths ranging from 42 to 4300 m (van Morkhoven *et al.*, 1986). On the mud platform north of Trinidad, *H. elegans* ranges from 50 to 140 m; the highest frequencies occur between 70 and 110 m (van Morhoven *et al.*, 1986). Elphidiids live at their greatest abundances in paralic or shelf depths (shallower than 50 m) (Murray, 1991, 2006; Hayward *et al.,* 1997).

Planktonic foraminifers are often used as palaeoclimatic indicators. *Globigerina bulloides*, *G. praebulloides*, *G. concinna*, *G. druryi, G. tarchanensis* are interpreted as cool indices; *Globorotalia bykovae* as cool-temperate and *G. mayeri* as warm-temperate indices (Szczechura, 1982; Spezzaferri *et al.,* 1992, Bicchi *et al.*, 2003).

Sample 1 (–1.8 m). The benthic foraminiferal assemblage of sample 1 is moderately diverse and dominated by large, thick-walled *Hoeglundina elegans* which forms 50% of the total. *Cibicidoides* spp. form 13.5% of the assemblage. Less common is *Uvigerina* which participates in 9% to the assemblage; *Bolivina* is almost 5%. *Pullenia bulloides* and *Globocassidulina oblonga* are minor components and form 3.5 and 2.5% of the assemblage, respectively. Single specimens of polymorphinids and glandulinids were also recorded. The only agglutinated species, *Pseudotriplasia elongata*, forms more than 6%. Stress marker species form about 25% of the benthic foraminiferal assemblage. The P/B ratio is about 70%, and H(S) is 1.83. Planktonic foraminifers are very abundant, small and include specimens of *Globigerina bulloides, G. praebulloides, G. tarchanensis, G. druryi* and *Globigerinita uvula*.

Sample 2 (–1.25 m). The benthic foraminiferal assemblage of sample 2 is very well-preserved. *Bulimina* spp. and *Fursenkoina acuta* dominate. Each of them exceeds 36% of the

assemblage. The third most abundant component of the assemblage is *Globocassidulina oblonga* which makes up more than 16%. Two more species, *Bolivina dilatata* and *Pullenia bulloides*, contribute more 3% to the assemblage. A few planktonic foraminifera: *Globorotalia bykovae*, *Globigerina subcretacea* and *G.* sp., occur. Stress marker species exceed 90% of the assemblage. The P/B ratio is 17%, and H(S) is 1.9.

Sample 3 (–70 cm). In sample 3 foraminiferal tests are very well-preserved. *Bulimina* spp. form 40% of the benthic foraminiferal assemblage. *Uvigerina* is the second most abundant genus in this assemblage and its contribution exceeds 13%. *Cibicidoides* spp. form 10% of the assemblage, *Melonis* – 7%. *Fursenkoina acuta*, *Pullenia bulloides* and *Sphaeroidina bulloides* are less common components of the assemblage. Their contribution comprises between 3 to 4.5%. Stress marker species form about 75% of the benthic foraminiferal assemblage. The P/B ratio is 32%, and H(S) is 2. *Globigerina* spp., *Globorotalia bykovae* and *G. mayeri* represent planktonic foraminifers.

Sample 4 (–35 cm). The benthic foraminiferal assemblage of sample 4 is well-preserved, dominated by buliminids (*Bulimina elongata, B. aculeata, B. insignis, B.* sp.) which form, as in sample 0–10 cm, 60% of the assemblage. Small-sized *Bolivina* species are abundant in the smallest fraction. *Elphidium* is very rare in this assemblage while *Melonis* exceeds 12%. *Cibicidoides* forms about 5% of the assemblage. *Globocassidulina oblonga*, *Uvigerina (U. aculeata, U. pudica)*, *Fursenkoina acuta* and *Pullenia bulloides* – not present in sample 5 – contribute to this assemblage from 3.0 to 4.5% each. *Sigmoilinita tenuis* is a minor component and forms 2.5% of the assemblage. Stress marker species form about 80% of the assemblage. The P/B ratio is 9% and H(S) is 1.96. Planktonic foraminifers are represented by *Globigerina bulloides*, *G. praebulloides* and *Globigerina* sp.

Sample 5 (0–10 cm). The benthic foraminiferal assemblage of sample 5 is dominated by biserial forms represented mainly by *Bulimina* spp. (Fig. 7). They form almost 60% of the assemblage. *Bolivina* is very rare in the fraction size studied. In the smallest size fraction <125 μm very small *Bolivina* tests dominate. The second most common group in this assemblage represents *Elphidium*. Keeled representatives of this genus – *Elphidium crispum*, *E. macellum*, *E. aculeatum*, *E. argenteum* and *Elphidium* sp. – form more than 10% of the assemblage. However, some of these are damaged, which may indicate a re-working origin. *Cibicidoides* and *Lobatula* are less common and their contribution does not exceed 5% of the assemblage. Single specimens of *Globulina*, *Glandulina*, *Lagena*, *Reussoolina* and *Guttulina* occur in this assemblage. Hauerinids and nonionids are other minor components of the assemblage. Planktonic forms are represented by single specimens of *Globigerina*. A single specimen of the Cretaceous planktonic foraminfer *Heterohelix* recorded in this sample indicates that some reworked material may contribute to the assemblage. The P/B ratio is 3.5%, and H(S) is 2. Stress marker species form more than 60% of the benthic foraminiferal assemblage.

The results of all isotopic measurements of selected foraminifer taxa are shown in Figures 8 and 9. The δ^{13}C values for *Globigerina* vary between –0.76 and 0.07‰, for *Bulimina elongata* between –0.63 and 0.16‰, and for *Cibicidoides* be-
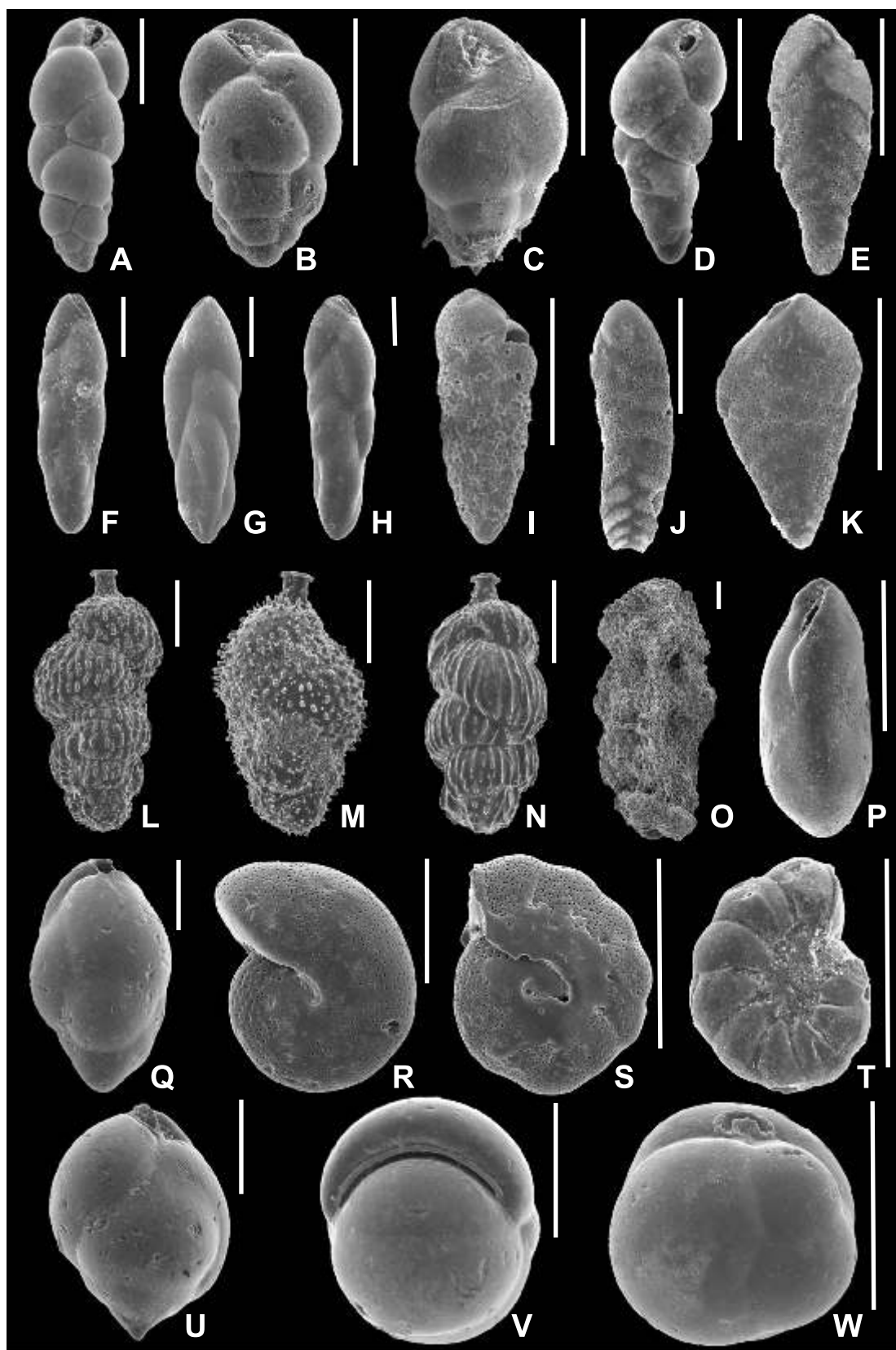
Fig. 4. Benthic foraminifers (infaunal species) from marls of the Borków quarry
(M, W – sample 1; A, D–H, J, K, P, Q, U, V – sample 2; L, N, S, T – sample 3; I, R – sample 4; B, C – sample 5)

A, **D** – *Bulimina elongata*; **B** – *Bulimina* sp.; **A**, **C** – *Bulimina aculeata*; **E** – *Bolivina maxima*; **F–H** – *Fursenkoina acuta*; **I** – *Bolivina plicatella*; **J** – *Bolivina antiqua*; **K** – *Bolivina dilatata*; **L** – *Uvigerina pudica*; **M** – *Uvigerina aculeata*; **N** – *Uvigerina pygmea*; **O** – *Pseudotriplasia elongata*; **P** – *Globocassidulina oblonga*; **Q** – *Praeglobobulimina pupoides*; **R** – *Melonis pompilioides*; **S** – *Astrononion perfossum*; **T** – *Porosononion martkobi*; **U** – *Praeglobobulimina pyrula*; **V** – *Pullenia bulloides*; **W** – *Sphaeroidina bulloides*; scale bar is 200 μm
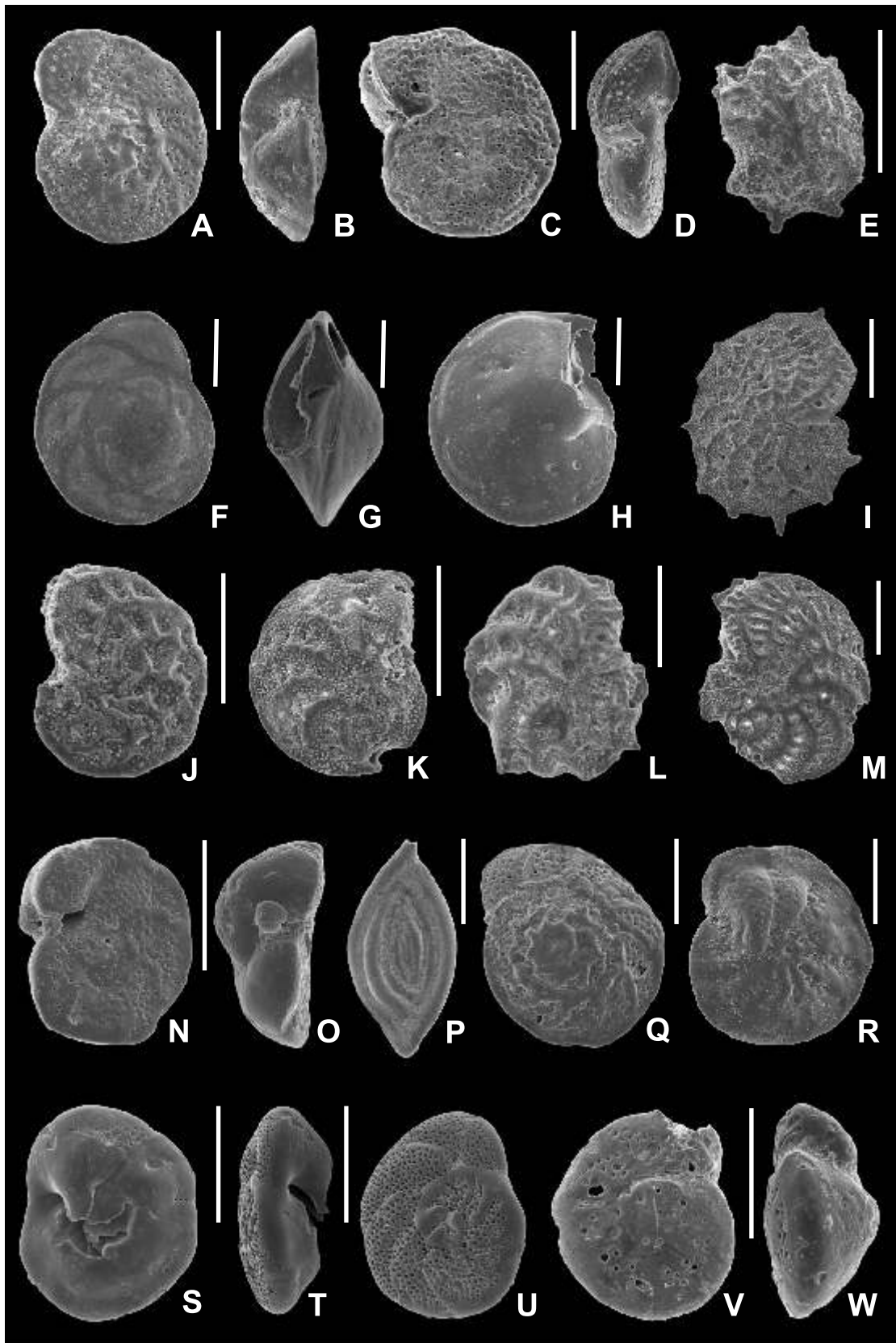
Fig. 5. Benthic foraminifers (epifaunal species) from marls of the Borków quarry
(F–H, P–U – sample 1; A–D – sample 2; N, O – sample 4; E, I–M, V, W – sample 5)

A, B – *Cibicidoides austriacus*; **C, D** – *Anomalinoides badenensis*; **E** – *Elphidium aculeatum*; **F–H** – *Hoeglundina elegans*; **I** – *Elphidium aculeatum*; **J** – *Elphidium* sp.; **K** – *Elphidium argenteum*; **L** – *Elphidium aculeatum*; **M** – *Elphidium macellum*; **N, O** – *Lobatula lobatula*; **P** – *Sigmoilinita tenuis*; **Q, R** – *Cibicidoides ungerianus*; **S, T, U** – *Rosalina*? sp.; **V, W** – *Cibicidoides lopjanicus*; scale bar is 200 µm
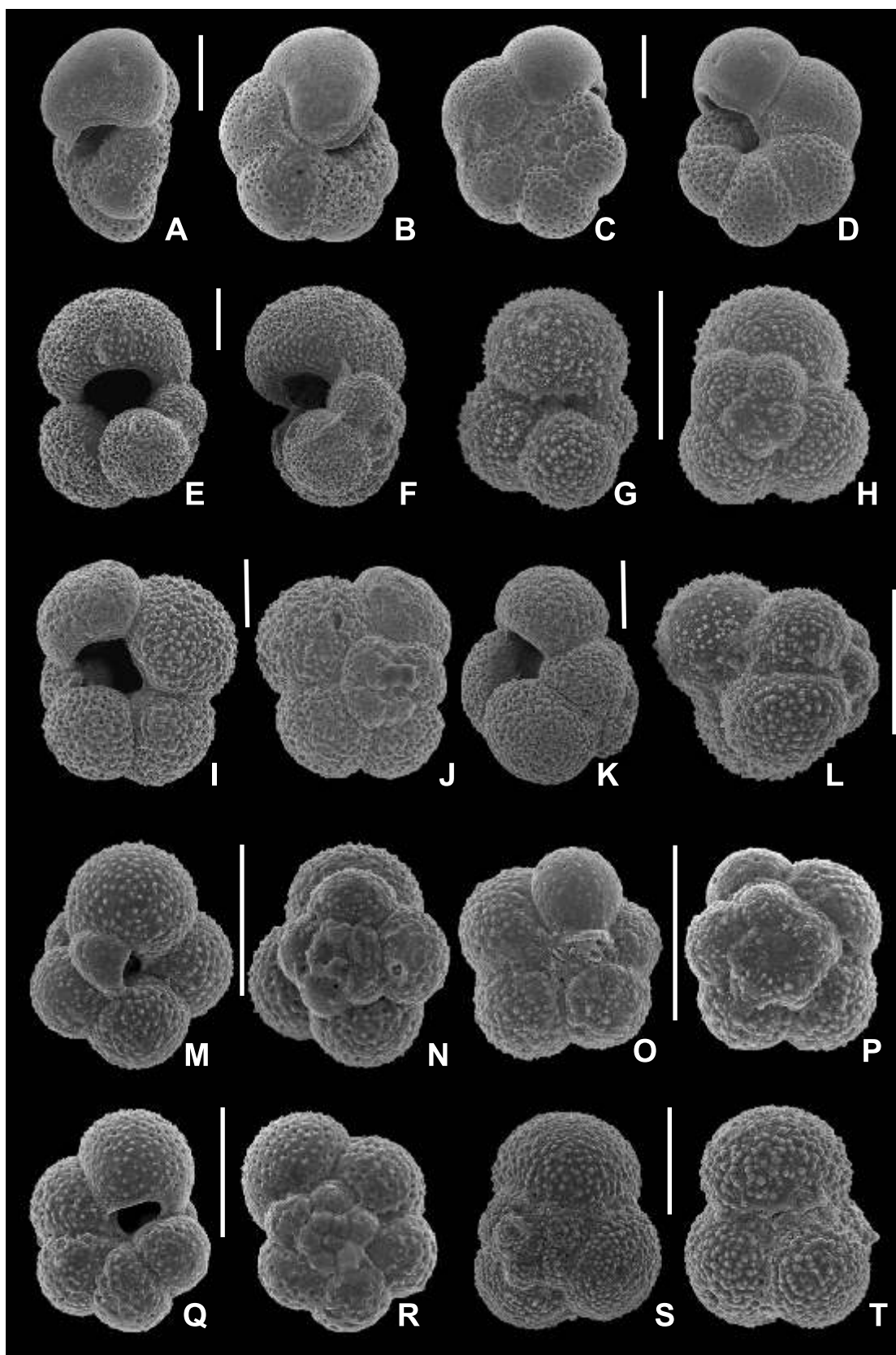
Fig. 6. Planktonic foraminifers from marls of the Borków quarry
(A, B, G, H, L, O–R – sample 1; C–F, I, J, M, N, S, T – sample 3; K – sample 4)

A, **B** – *Globorotalia bykovae*; **C**, **D** – *Globorotalia mayeri*; **E**, **F** – *Globigerina bulloides*; **G**, **H** – *Globigerina praebulloides*; **I**, **J** – *Globigerina concinna*; **K** – *Globigerina druryi*; **L** – *Globigerinita uvula*; **M**, **N** – *Globigerinoita* sp.; **O**, **P** – *Globigerina tarchanensis*; **Q**, **R** – *Globigerina subcretacea*; **S**, **T** – *Globigerina?* sp.; scale bar is 100 μm
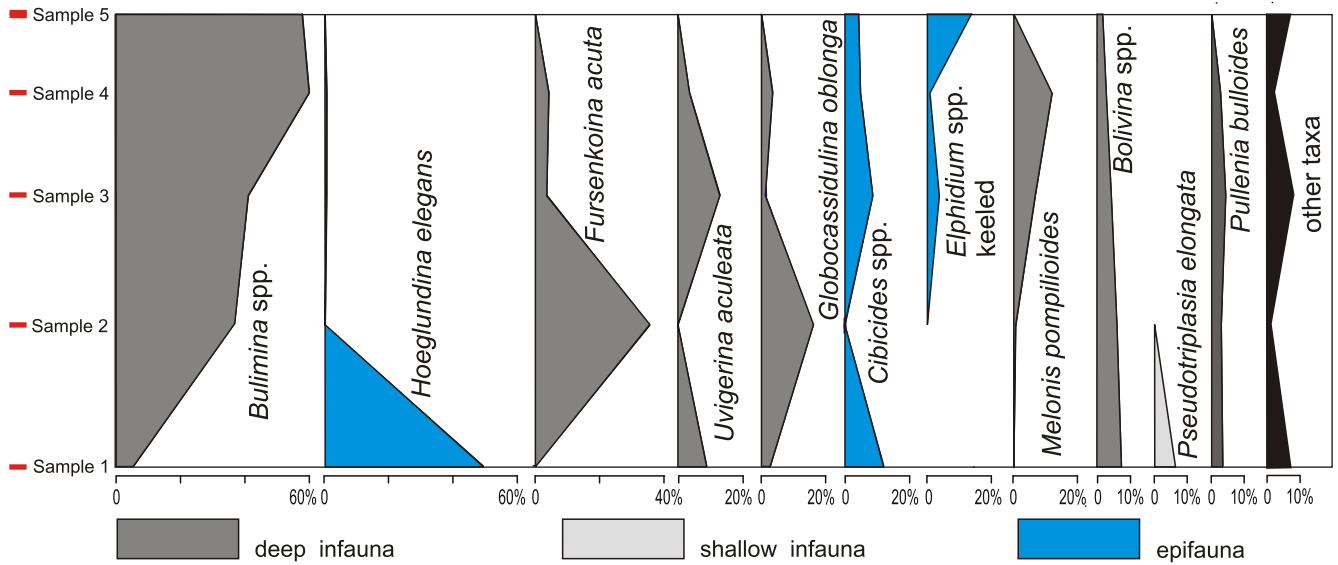
Fig. 7. Relative abundances of dominant and common benthic foraminiferal species within assemblages in the marls below the gypsum at Borków

tween –0.17 and 0.9‰; thus the range of $\delta^{13}C$ values for particular taxa is 0.83, 0.79 and 1.07‰, respectively (Figs. 8 and 9). In the section, *Bulimina elongata* shows a slight upward decrease in $\delta^{13}C$ values, and *Cibicidoides* and *Globigerina* show slight increases in $\delta^{13}C$ values (Fig. 8). The $\delta^{18}O$ values for *Bulimina elongata* and *Cibicidoides* show the same pattern: first the values increase upwards and then slightly decrease (Fig. 8), and *Bulimina elongata* invariably shows higher values than co-occurring *Cibicidoides* (the offset of *Bulimina elongata* is 0.82 to 0.98‰). In the section, *Globigerina* first shows a decrease in $\delta^{18}O$ values and then a clear increase

(Fig. 8). $\delta^{18}O$ values for *Globigerina* vary between –1.47 and 1.17‰, for *Bulimina* between 1.8 and 2.52‰, and for *Cibicidoides* between 0.98 and 1.8‰; thus the range of $\delta^{13}C$ values for *Globigerina* is distinctly greater (2.64‰) than for *Bulimina elongata* (0.72‰) and *Cibicidoides* (0.82‰; Figs. 8 and 9). In particular samples, the $\delta^{18}O$ values for benthic taxa are always higher than the values for *Globigerina* (Fig. 8) and for the total set of samples, $\delta^{18}O$ values for *Globigerina* are distinctly lower than the values for benthic taxa (Fig. 9). Both $\delta^{13}C$ and $\delta^{18}O$ values for the total of *Bulimina elongata* are slightly higher than for the total of *Cibicidoides* (Fig. 9). *Hoeglundina*
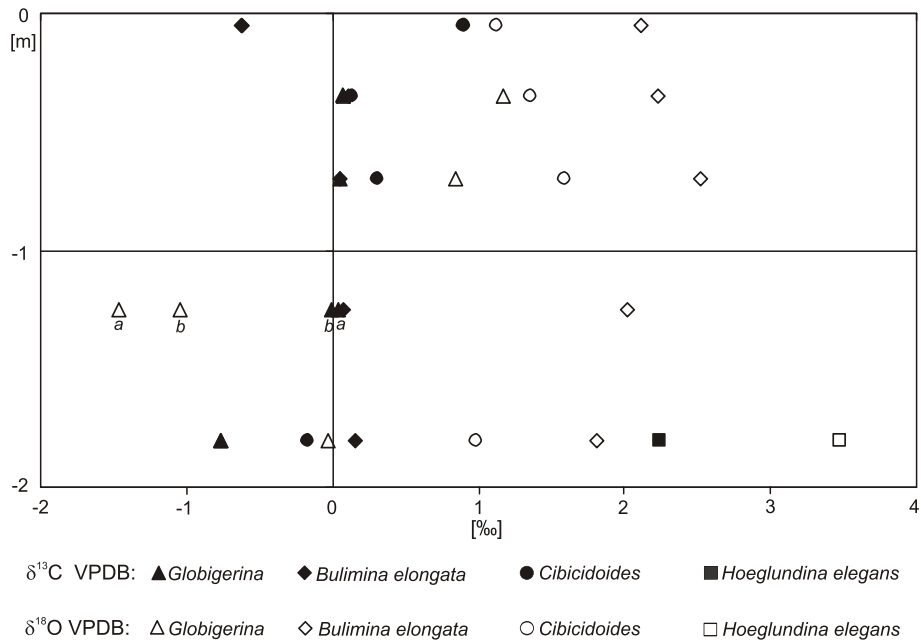

Fig. 8. Isotope profiles of foraminifers from Badenian marls of Borków quarry

Two sets of specimens of *Globigerina* from sample 4 have been measured;
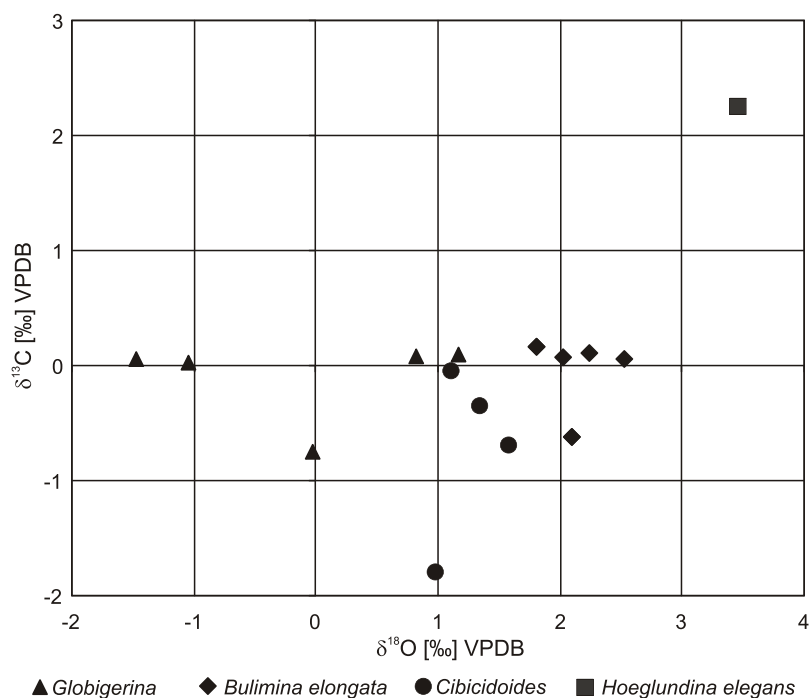they are indicated by the letters *a* and *b*

Fig. 9. Plot of $\delta^{13}C$ and $\delta^{18}O$ values of Badenian foraminifers from marls below the gypsum of Borków quarry

elegans shows high $\delta^{13}C$ (2.24‰) and $\delta^{18}O$ (3.47‰) values (Fig. 9). High $\delta^{13}C$ values are characteristic for Badenian *H. elegans* in general (see e.g., Báldi and Hohenegger, 2008), but the $\delta^{18}O$ values exceed the recorded values, which results in unrealistically low palaeotemperatures (see Table 2); however, the state of preservation of this taxon indicates that some forms can be reworked.

The results of temperature calculations based on $\delta^{18}O$ values of foraminifers are shown in Table 2. All temperature equations take into account the $\delta^{18}O$ composition of the surrounding seawater, that is unknown. The calculations were done for $\delta_w = 0$‰ (value characteristic for recent mean seawater), $\delta_w = -1$‰ (value characteristic of recent mean seawater mixed with freshwater), and $\delta_w = +1$‰ (value characteristic of recent concentrated seawater). However, δ_w are not constant in time, and Lear *et al.* (2000, fig. 1D) calculated that during the Badenian evaporite deposition a global δ_w was lower than today by *ca*. 0.5‰.

T a b l e 2

Palaeotemperatures (in °C) in particular samples calculated with the equations established by Epstein *et al*. (1953) [equation 1], Shackleton (1974) [equation 2], Erez and Luz (1983) [equation 3], and Bemis *et al*. (1998) [equation 4], depending on $\delta^{18}O_w$

$\delta^{18}O_w$	Equation	Taxon																	
		Bulimina elongata					*Cibicides*				*Hoeglundina elegans*	*Globigerina*				
+1‰	1	11.9	11.4	10.3	12.3	13.1	16.0	14.0	14.0	16.6	6.7	15.8	17.2	28.1	25.9	20.1
+1‰	2	12.2	11.6	10.5	12.6	13.4	16.4	15.4	14.4	17.0	6.7	16.2	17.6	28.1	26.2	21.5
+1‰	3	12.0	11.5	10.2	12.4	12.4	16.4	15.5	14.4	17.1	7.0	16.2	17.7	28.3	26.3	21.7
+1‰	4	8.1	7.6	6.4	8.5	9.4	12.6	11.4	10.4	13.3	2.8	12.4	14.0	26.9	24.3	18.5
0‰	1	8.0	7.6	6.6	8.4	9.2	11.8	9.9	10	12.4	3.3	11.7	12.9	23.1	21.1	16.6
0‰	2	8.1	7.6	6.5	8.5	9.3	12.1	11.1	10.2	12.7	2.9	11.9	13.4	23.4	21.6	17.0
0‰	3	7.6	7.1	5.8	8.0	7.9	12.0	11.0	9.9	12.6	1.7	11.8	13.2	23.7	21.7	17.1
0‰	4	4.1	3.6	2.6	4.4	5.2	8.0	7.1	6.1	8.6	−0.5	7.8	9.3	21.0	18.6	13.3
−1‰	1	4.5	4.1	3.1	4.8	5.5	8.0	6.1	6.3	8.5	0.3	7.4	9.1	18.5	16.7	12.4
−1‰	2	4.2	3.8	2.7	4.6	5.4	8.1	7.1	6.2	8.6	−0.6	7.9	9.2	19.0	17.1	12.7
−1‰	3	3.2	2.7	1.6	3.6	3.6	7.6	6.6	5.5	8.2	−2.6	7.3	8.8	19.1	17.2	12.6
−1‰	4	0.6	0.2	−0.7	0.9	1.6	4.2	3.2	2.3	4.6	−2.9	3.9	5.1	15.5	13.4	8.7
Sample		1	2	3	4	5	1	2	3	5	5	2	3	4a	4b	5

Because two sets of specimens of *Globigerina* from sample 4 have been measured and they differ slightly, the palaeotemperatures calculated for those two sets (termed samples 4a and 4b) are shown separately (see Fig. 8)

DINOFLAGELLATE CYSTS AND PALYNOFACIES

All samples studied contain palynological organic matter. Palynomorphs show very good preservation. Both terrestrial and marine palynomorphs are pale-coloured; their wall structure is intact. The list of taxa identified is shown in Appendix. The occurrence of dinoflagellate cysts is shown in Table 3. Selected taxa are illustrated in Figures 10 and 11. Ratio changes of particular dinoflagellate cyst taxa related to specific environments are shown in Figure 12. Palaeoenvironmental preferences of particular dinoflagellate cyst taxa are based on literature data (Morzadec-Kerfourn, 1976, 1977, 1983; Wall *et al.*, 1977; Biffi and Grignani, 1983; Harland, 1983; Bradford and Wall, 1984; Brinkhuis, 1994; Gedl, 1996, 1997, 1999; Rochon *et al.*, 1999; Vink *et al.*, 2000; Marret and Zonneveld, 2003).

Dinoflagellate cysts from samples 2–4 and from sample A commonly occur coated in delicate structureless organic matter. Marine palynomorphs from other samples are devoid of such coats. The samples studied yielded infrequent specimens of dinoflagellate cysts recycled from older, Paleogene strata. There are both Eocene (*Areosphaeridium diktyoplokum*) and Oligocene (*Chiropteridium* sp.) taxa. Their excellent state of preservation suggests that they derive from epicontinental Paleogene strata rather than from coeval Carpathian ones (see Gedl, 2005).

Samples collected from most of the section (except for the topmost sample) yielded palynofacies composed of elements of mixed origin, including terrestrial, marine (mainly dinoflagellate cysts) and elements of uncertain derivation (structureless organic matter). The bulk of palynological organic matter of these samples consists of land-derived palynodebris and sporomorphs represented mainly by bisaccate pollen grains. The former include black and dark brown phytoclasts (dominant in samples 1, 3 and 4), cuticle particles (most frequent in sample 4), and hyalinous particles,

which most likely are of resin origin (their ratio is high in sample 4, much lower in sample 3). Sporomorph assemblages dominated by bisaccate pollen grains occur in all samples; their ratio varies from several percent (samples 2 and 3) to 30% (samples 1 and 4).

Samples 1–4 contain also dinoflagellate cysts (from a few percent up to 10% of sampled palynofacies). Their assemblages are taxonomically fairly diverse, although almost each one shows minor domination of particular taxa. The assemblage from sample 1 shows slight enrichment in specimens of *Batiacasphaera sphaerica*, *Spiniferites* spp., and *Hystrichokolpoma rigaudiae*. Relatively common are also *Systematophora placacantha* and *Operculodinium* spp. Sample 2 yielded an assemblage dominated by *Palaeocystodinium golzowense* and *Batiacasphaera sphaerica*, with frequent *Systematophora placacantha* and *Spiniferites* spp. The former two species are also common in sample 4, associated with frequent *Operculodinium* spp. Sample 3 contains low amounts of palynological organic matter; hence, its dinoflagellate cyst assemblage consists of infrequent specimens. The distribution of all dinoflagellate cysts from the excavation is shown in Table 3. Samples 1–4 yielded also organic linings of foraminifera and acritarchs (Figs. 10 and 11); they are most common in the lowest sample (1).

Two lower samples (1 and 2) yielded dinoflagellate cysts recycled from Paleogene strata. These are single specimens of the genus *Wetzeliella* (found in sample 2), and *Deflandrea heterophlycta*, *Charlesdowniea* sp., *Areosphaeridium diktyoplokum* (sample 1). Single specimens of the genus *Homotryblium* have been found (*Homotryblium tenuispinosum* – sample 2, and *H. floripes* – sample 1). It is not certain if either species occur in situ, or they are recycled (see Gedl, 2005).
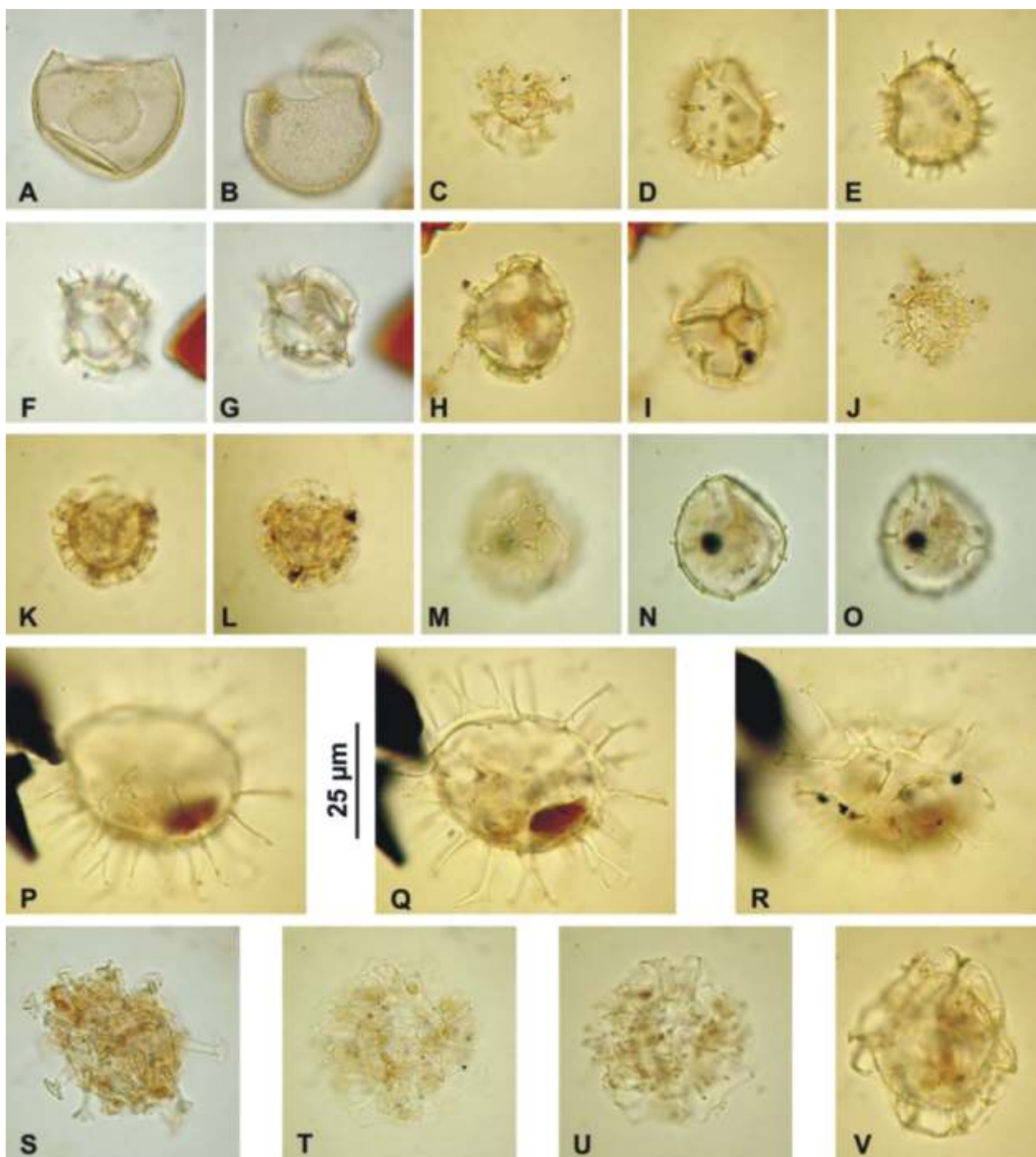
The top sample (5) contains no marine palynomorphs, being dominated by sporomorphs (mainly bisaccate pollen

Table 3

**Occurrence of dinoflagellate cysts in the marls below the gypsum at Borków**

Lithostratigraphy	Sample	1 *Areosphaeridium diktyoplokum**	2 *Batiacasphaera sphaerica*	3 *Cerebrocysta poulsenii*	4 *Charlesdowniea sp.**	5 *Cordosphaeridium minimum*	6 *Dapsilidinium sp.*	7 *Deflandrea heterophlycta**	8 *Heterosphaeridium? sp.*	9 *Homotryblium floripes*	10 *Hystrichokolpoma rigaudiae*	11 *Imperfectodinium? sp.*	12 *Labyrinthodinium truncatum*	13 *Lejeunecysta sp.*	14 *Lingulodinium machaerophorum*	15 *Melitasphaeridium choanophorum*	16 *Nematosphaeropsis labyrinthus*	17 *Operculodinium centrocarpum*	18 *Operculodinium pieseckii*	19 *Operculodinium sp.*	20 *Pentadinium laticinctum*	21 *Spiniferites pseudofurcatus*	22 *Spiniferites ramosus*	23 *Spiniferites sp.*	24 *Systematophora placacantha*	25 *Unipontidinium aquaeductum*	26 *Dapsilidinium pseudocolligerum*	27 *Homotryblium sp.*	28 *Palaeocystodinium golzowense*	29 *Wetzeliella sp.**	30 *Imperfectodinium septatum*	31 *Pyxidiniopsis sp.*	32 *Impagidinium sp.*	33 *Operculodinium israelianum*	34 *Polysphaeridium zoharyi*	35 *Selenopemphix nephroides*	acritarch (Svenkodinium)
Baranów Beds	5																																				
	4		16								3				7		1	24		11			7	3	5	3		1	21				5	2	3	1	2
	3									3								5		1	5		7	2	9	2					2	1					
	2		46								5				5	2	2	11		5	3		18	6	19	4	9	2	53	1							3
	1	1	15	1	1	4	3	1	1	2	12	1	5	1	7	5	2	7	1	3	2	2	12	5	9	2											2

Asterisked are redeposited (Paleogene) forms

Fig. 10. Dinoflagellate cysts and acritarchs from Borków quarry
(A–L, P, R, U, V – sample 1; M–O – sample 3; S, T – sample 2)

A, **B** – *Batiacasphaera sphaerica*; **C** – *Cordosphaeridium minimum*; **D**, **E** – *Operculodinium piaseckii* (the same specimen, various foci); **F–I** – *Cerebrocysta poulsenii* (F, G and H, I – same specimens, various foci); **J** – *Svenkodinium* sp. (acritarch); **K**, **L** – *Labyrinthodinium truncatum* (same specimen, various foci); **M–O** – *Imperfectodinium septatum* (same specimen, various foci); **P–R** – *Systematophora placacantha* (same specimen, various foci); **S** – *Melitasphaeridium choanophorum*; **T**, **U** – *Nematosphaeropsis labyrinthus* (same specimen, various foci); **V** – *Unipontidinium aquaeductum*; scale bar refers to all microphotographs
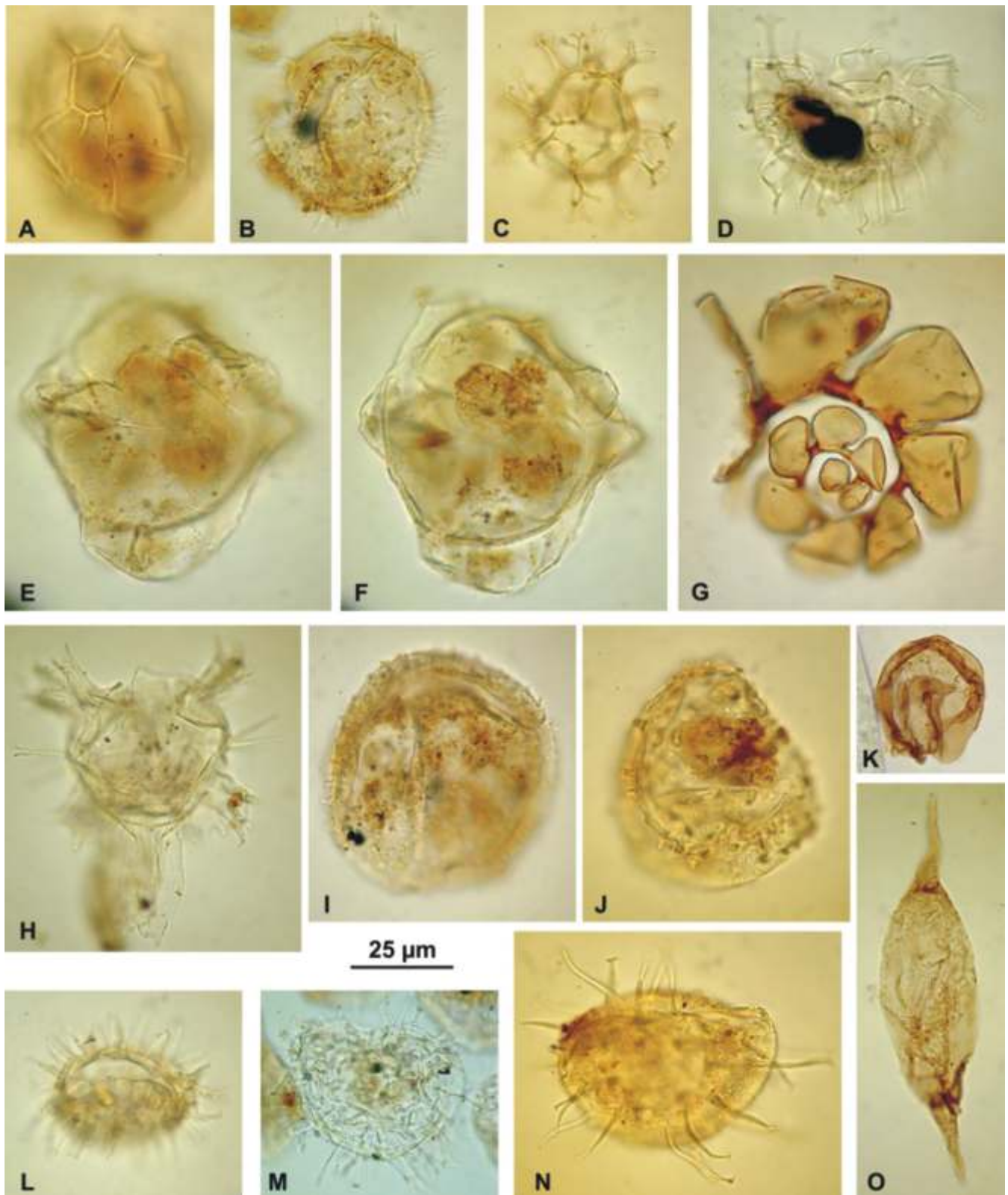
Fig. 11. Dinoflagellate cysts and foraminifer organic lining from the Borków quarry
(A, E–G, I–K, N – sample 3; B, O – sample 2; C, D, H, L – sample 1; M – sample A)

A – *Impagidinium* sp.; **B** – *Operculodinium centrocarpum*; **C** – *Spiniferites ramosus*; **D** – *Systematophora placacantha*; **E**, **F** – *Pentadinium laticinctum* (same specimen, various foci); **G** – foraminifer organic lining; **H** – *Hystrichokolpoma rigaudiae*; **I**, **J** – *Operculodinium* sp.; **K** – *Selenopemphix nephroides*; **L** – *Lingulodinium machaerophorum*; **M** – *Systematophora* cf. *placacantha*; **N** – *Operculodinium* sp. (*O. microtriainum*?); **O** – *Palaeocystodinium golzowense*; scale bar refers to all microphotographs
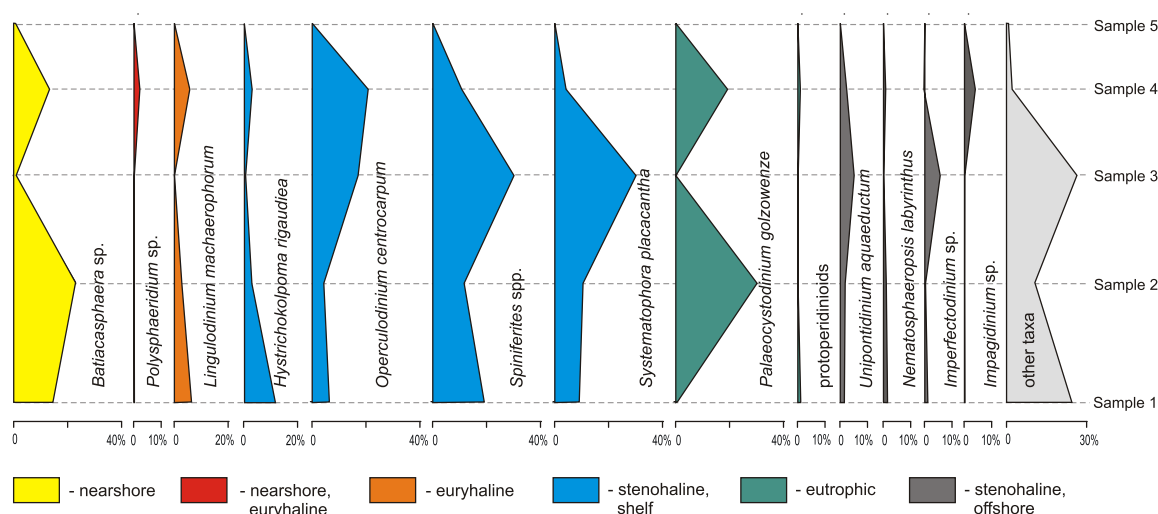
Fig. 12. Ratio changes of particular dinoflagellate cyst taxa related to specific environments in the marls below the gypsum at Borków

grains), and lesser amounts of cuticle remains. Highly dispersed structureless organic matter also occurs.

Sample A contains much higher amounts of palynological organic matter than samples from below the gypsum and its palynofacies is different. It consists almost exclusively of pollen grains, with a very minor addition of dark brown phytoclasts and cuticle particles (up to 5%). Dinoflagellate cysts are very rare. Several specimens of *Spiniferites* sp., *Systematophora placacantha*, *Systematophora* cf. *placacantha*, and a single specimen of *Lingulodinium* sp. have been found. Dinoflagellate cysts are well-preserved, but often they are covered with an organic coat. Much more frequent are ovoid palynomorphs, which most likely represent Prasinophytea resembling the genus *Leiosphaeridia*.

CLAY MINERALS

The results of XRD study of samples from the Borków quarry show that except for sample 5, the composition of the marls underlying the gypsum and sample A is very similar when

Table 4

The results of XRD study of samples from Borków quarry

Sample designation	Main components	Clay minerals
A	gypsum, quartz, calcite, feldspar, pyrite, clay minerals	smectite, illite, kaolinite, chlorite
5	quartz, gypsum, calcite, clay minerals	smectite, illite
4	quartz, calcite, pyrite, gypsum, feldspar, clay minerals	smectite, illite, kaolinite, chlorite
2	quartz, calcite, pyrite, feldspar, clay minerals	smectite, illite, kaolinite, chlorite
1	quartz, calcite, gypsum, feldspar, clay minerals	smectite, illite, kaolinite, chlorite

the major minerals are taken into account. Sample 5 shows a poorer assemblage of clay minerals as only smectite and illite occur. In addition, the sample is lacking feldspars and pyrite that occur in the underlying rocks (and in sample A; Table 4).

INTERPRETATION AND DISCUSSION

Foraminifers, dinoflagellate cysts, palynofacies and clay minerals occurring in marls below the Badenian gypsum at Borków indicated a clear environmental change during the deposition of marls (Fig. 13). The planktonic/benthic (P/B) ratio of foraminifers varies between 70% (in the lowermost sample) and 3% (in the topmost sample) indicating a shelf environment with tendency to shallowing of the sea through time. Rich and diverse dinoflagellate cyst assemblages and in particular the occurrence of offshore taxa such as *Impagidinium* (rare) and more frequent *Nematosphaeropsis* (e.g., Morzadec-Kerfourn, 1977; Wall *et al.*, 1977; Harland, 1983; Dale, 1996; Rochon *et al.*, 1999; Vink *et al.*, 2000) also indicate an open marine environment (Fig. 12). The dinoflagellate cyst assemblages consist generally of cosmopolitan species typical for a shelf environment (e.g., *Spiniferites ramosus*, *Operculodinium centrocarpum*). On the other hand there are *Polysphaeridium* specimens, the motile-stage of which is believed to have inhabited near-shore waters, frequently with increased salinity (e.g., Wall and Dale, 1969; Dale, 1976; Wall *et al.*, 1977; Harland, 1983; Morzadec-Kerfourn, 1983) are very rare or lacking, and also other dinoflagellate cysts species tolerant of reduced or increased salinity like *Lingulodinium machaerophorum* (e.g., Williams, 1971; Morzadec-Kerfourn, 1976, 1977; Reid and Harland, 1977) show no increased ratio. Palynofacies analysis indicates a high, gradually increasing upwards, frequency of pollen grains. The clay mineral association in the marls studied (Table 4) and in particular the dominance of the illite-chlorite association, suggests altitude-controlled, well-drained source
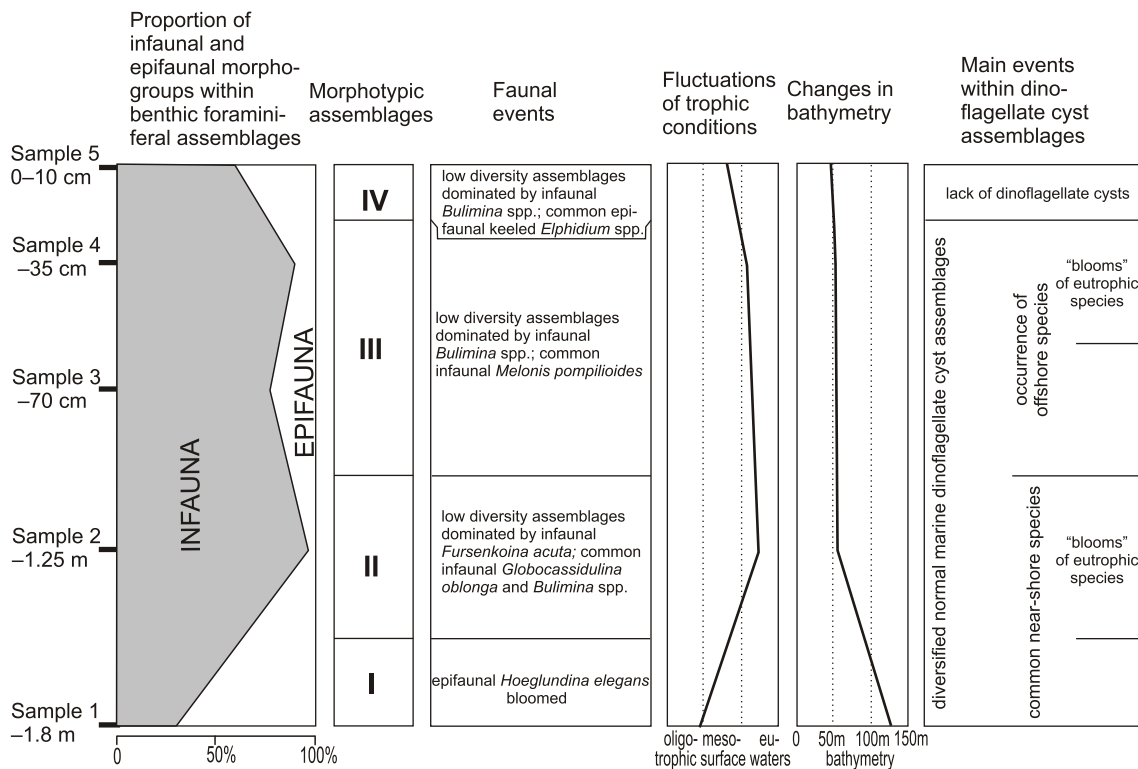
Fig. 13. Summary diagram of proportion of infaunal and epifaunal morphogroups within benthic foraminiferal assemblages, morphotypic assemblages, faunal events, fluctuations of trophic conditions, changes in bathymetry, and main events within dinoflagellate cyst assemblages during deposition of marls below the gypsum at Borków

areas, and rapid transportation of the terrigenous supply (Eslinger and Pevear, 1988). The lack of kaolinite in the topmost sample (Sample 5) may be related to climate change as kaolinite points to intense hydrolysis under warm and humid climate. In the Badenian evaporite basin of Transylvania, kaolinite is dominant in marginal areas, whereas illite, chlorite and smectite become significant phases towards the basin (Bican-Bri an and Hosu, 2006).

Sample 5 appeared barren as far as dinoflagellate cysts are concerned, which might indicate a drastic change in the photic zone leading to a complete collapse of the dinoflagellate flora. Ultimately, the lack of dinoflagellate cysts may be related to post-depositional factors, e.g., higher oxidation at the clay/gypsum boundary due to increased water flow, but it is remarkable that sample A contains dinoflagellate cysts; thus the lack seems to be a primary feature that finds its expression in the foraminiferal assemblage recorded in that part of the section.

Using information on present morphotypes of benthic foraminifera (Jones and Charnock, 1985; Corliss and Chen, 1988), four assemblages have been recognized (I–IV) which reflect changes in the relative abundance of epifaunal and infaunal species (Fig. 13). Assemblage I (sample 1) is interpreted to represent a middle to outer shelf marine, well-ventilated environment with moderate primary productivity. A flux of organic detritus is sufficient to sustain infaunal bottom-dwellers. Somewhere between samples 1 and 2 an important change in the structure of benthic foraminiferal assemblages took place, and assemblage II (sample 2) is composed

almost entirely of infaunal species (90% of the assemblage). This assemblage, dominated by infaunal bottom-dwellers, reflects a massive increase in food supply to the sea bottom and shallowing of the sea to inner – middle shelf depths. Assemblage III (samples 3 and 4) is characterized by a small decrease in the abundance of infaunal forms, and it indicates mesotrophic conditions at inner – middle shelf depths. The trend of decreasing relative abundance of the infaunal morphogroups continued in assemblage IV (sample 5), where the contribution of this group decreases to 60%. Assemblage IV is interpreted to represent an inner shelf environment with moderate primary productivity.

A rapid change in the benthic foraminiferal assemblage is seen in samples taken from the lower part of the interval studied. The assemblage recorded in sample 1, dominated by the epifaunal species *Hoeglundina elegans*, an oxyphilic marker, suggesting well-oxygenated bottom water, is replaced in sample 2 by an assemblage where *H. elegans* is almost absent and deep infaunal, stress-tolerant taxa represented mainly by *Bulimina elongata, B. aculeata, B. insignis, Bolivina dilatata, Fursenkoina acuta, Globocassidulina oblonga* and *Melonis pompilioides* dominate, suggesting oxygen deficiency at the sediment-water interface. This change in the composition of benthic foraminiferal assemblages may reflect change of the marine environment from close to oligotrophic to mesotrophic or eutrophic conditions. A high flux of organic matter to the sea floor causes low oxygen concentrations within the sediment pore waters because the oxygen is used in oxidation of the or-

ganic material. Infaunal species dominate in benthic foraminiferal assemblages associated with relatively high organic-carbon fluxes (e.g., Corliss and Chen, 1988; Jorissen *et al.*, 1995; Peryt *et al.*, 2002), and epifaunal ones in more oligotrophic environments (Thomas, 1990; Gooday, 1994; Jorissen *et al.*, 1995). In highly oligotrophic regions all food particles will be consumed or oxidised at the sediment surface and the underlying sediment will contain only small quantities of organic matter, which cannot sustain an abundant infaunal population.

Significant number of specimens of *Hoeglundina elegans* in sample 1 are more or less damaged which may suggest that some of them are resedimented, suggesting that the indigenous assemblage is not so strongly epifauna-dominated and thus reflects a normal marine mesotrophic environment. Accordingly, the change would be less drastic – from meso- to eutrophic conditions in the near-surface waters. It was probably caused by shallowing as indicated by the upsection decrease in the share of planktonic foraminifers within the total foraminifer assemblage up to their very rare occurrence in the topmost sample. This shallowing, resulted from sea level fall, could induce increased erosion by incised rivers and thus an influx of abundant nutrients causing the eutrophication of near-surface waters and the oxygen deficit in bottom waters. The assemblages of planktonic foraminifers are dominated by representatives of genus *Globigerina* that are cool water indices. Warm-temperate indices such as *Globorotalia mayeri* are rare in sample 3. A shallow, cold water marine basin is indicated for the assemblage of sample 5 (*cf.* Table 1).

The recorded δ^{13}C values of benthic foraminifers, and in particular the consistently lower values of infaunal *Bulimina elongata* compared to epifaunal *Cibicidoides* and *Hoeglundina* support the concept of microhabitat effects on test composition (McCorkle *et al.*, 1990). McCorkle *et al.* (1990) concluded that δ^{13}C differences between species with similar vertical distribution in the sediments and interspecific δ^{18}O differences indicate that taxon-specific vital effects also influence test composition, and vital effects are thought to be reflected in the heavy δ^{18}O values of *Hoeglundina elegans* (Fig. 9) and the offset toward the higher δ^{18}O values in *Cibicidoides* compared to *Bulimina elongata* (Fig. 9; *cf.* Fig. 14). However, the foraminiferal δ^{18}O values are close to isotopic equilibrium and thus they can be used for reliable palaeotemperature calculation (McCorkle *et al.*, 1990). There is some difference between the calculated values depending on the equations used (Table 2). The calculations based on equations developed by Epstein *et al.* (1953), Shackleton (1974), and Erez and Luz (1983) gave very similar results, whereas the calculated values with the use of equation developed by Bemis *et al.* (1998) are lower by 3–4‰. This difference was noticed by Grunert *et al.* (2010) in the case of the Lower Miocene of the North Alpine Foreland Basin and explained by Shackleton's (1974) equation having been derived from benthic uvigerinids, and so its application to planktonic foraminifers being inappropriate. Bemis *et al.* (1998) concluded that the existing palaeotemperature equations overestimate temperatures by 3–5°C relative to *Globigerina bulloides* equations when ambient temperature varies from 15–25°C.

However, the same difference was noted in the case of other taxa (Table 2). The data published by Durakiewicz *et al.* (1997) indicate that the palaeotemperatures calculated with the use of equations proposed by Shackleton (1974) are very close to, or identical with, the values resulting from equations based on planktonic foraminifers (Erez and Luz, 1983) and molluscs (Epstein *et al.*, 1953). In Figure 14 we show the variation of palaeotemperatures in the Borków section calculated with the use of equations established by Shackleton (1974) and Bemis *et al.* (1998) for δ^{18}O$_w$ of +1‰, 0 and –1‰. In all these cases the palaeotemperature shows a slight upward decrease (Fig. 14), and the differences in palaeotemperatures calculated for particular taxa indicate that the water column showed a temperature gradient (Table 2) which decreased through time (Fig. 14). Differences between the bottom and intermediate water temperature during the deposition of the strata studied were 3.8°C (sample 4) – 7.7°C (sample 1), and the temperature decreased in this interval by 1.7°C for the bottom water layer and 5.1°C for the intermediate water layer if the equation proposed by Shackleton (1974) is applied (Table 2). Very similar δ^{18}O curves and palaeotemperatures calculated for bottom (U*vigerina* sp.) and intermediate water (*Globigerina bulloides*) foraminifers were found in the DNV section (Slovakia) of the Vienna Basin around the NN5–NN6 boundary (Ková ová *et al.*, 2009, fig. 8).

However, the possible effect of salinity increase has to be taken into account. The foraminifer assemblage of sample 1 indicates normal seawater conditions. During Badenian times the δ_w was *ca.* 0.5‰ lower than today (*cf.* Lear *et al.*, 2000) and thus we assume that the δ_w was first –0.5‰, and then *ca.* 0‰ during deposition of sample 2 (Fig. 15). Subsequently, it could increase by up to +0.5‰ during deposition of sample 3 and +1.0‰ (or more) during the deposition of the upper samples (4 and 5); the δ^{18}O$_w$ = +1‰ was recorded, for example, in the Mediterranean (Pierre, 1999), and in the Red Sea it is still higher (+2‰; Craig, 1966). In such a scenario, the actual palaeotemperature curves for *Bulimina elongata* and *Cibicidoides* would be close to linear, increasing upsection. The curve for *Globigerina* is more complex because of a clear excursion towards higher values in sample 2. The sudden increase of palaeotemperature for *Globigerina* in this sample (Figs. 14 and 15) is interpreted as an artifact, possibly related to reworked specimens in the sample analysed. Consequently, the palaeotemperature curves for *Globigerina* would be also close to linear, very slightly increasing upsection (Fig. 15). There was a difference in temperature between the upper water layer and the lower water layer as indicated by curves for *Bulimina elongata* and *Globigerina* (Fig. 15); for *Globigerina,* two curves are shown that are based on different equations (Shackleton, 1974; Bemis *et al.*, 1998) because, as raised by Grunert *et al.* (2010, p. 138), the equation established by Shackleton (1974) has been derived from benthic uvigerinids and hence its application to planktonic foraminifers seems inappropriate. These palaeotemperature curves show that the difference between the water layers gradually decreased, and at the end of the deposition of the marls was negligible (if at all present). At the same time the salinity of water was slightly increasing (Fig. 15), as is otherwise to be expected considering the anti-estuarine circulation pattern in the Central Paratethys
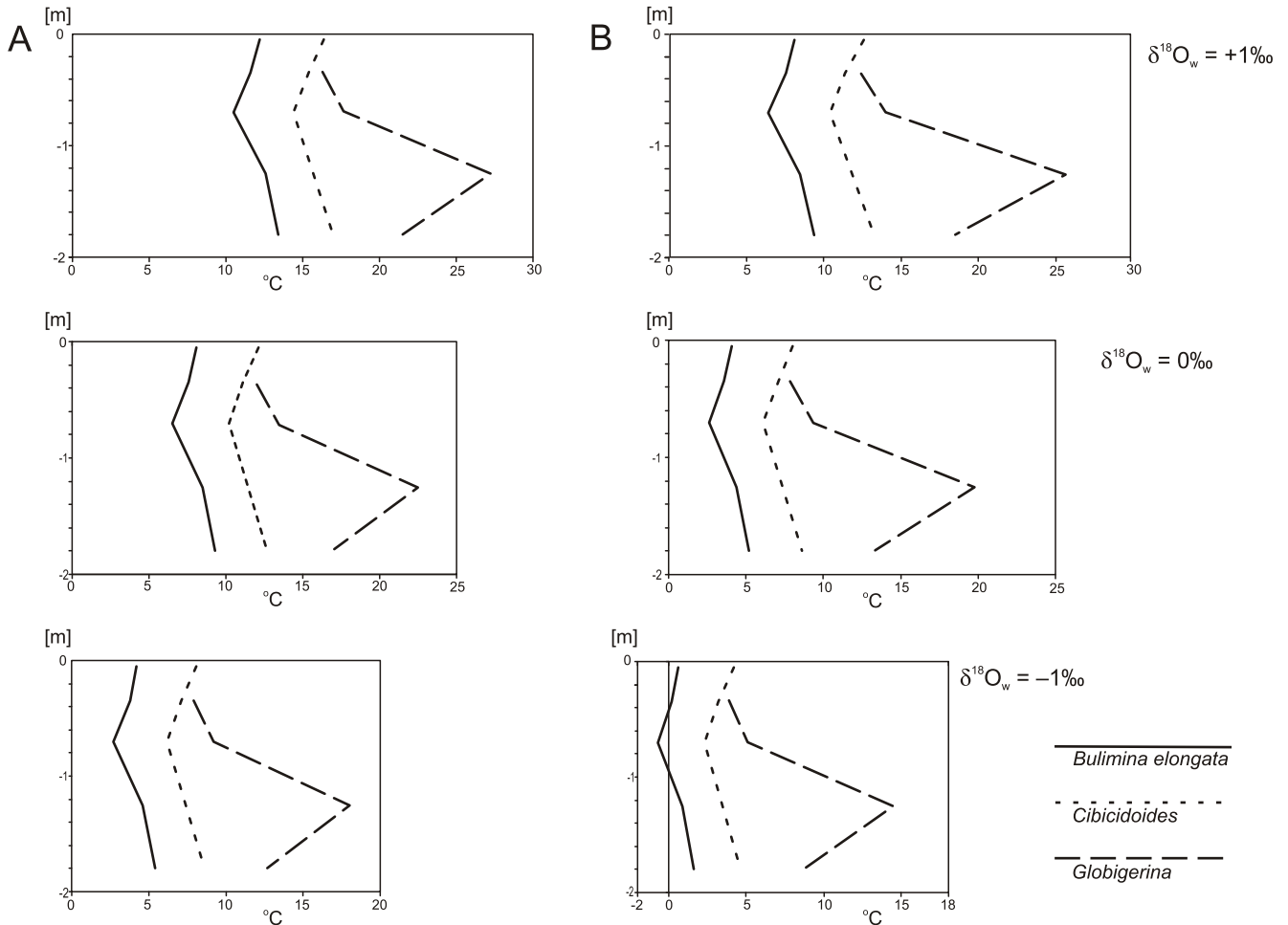
Fig. 14. Palaeotemperature curves for foraminifer taxa in the Borków marls calculated with the equations established by Shackleton (1974) (A) and Bemis *et al.* (1998) (B), depending on $\delta^{18}O_w$ = +1‰, 0‰ or –1‰

(Gonera, 2001) combined with the occurrence of silled basins such as the Carpathian Foredeep (Báldi, 2006).

Based on these assumptions and using the equation proposed by Shackleton (1974), temperature estimates for *Bulimina elongata* and *Globigerina* vary from *ca.* 7°C and *ca.* 15°C in sample –1.8 m to 12°C and *ca.* 17°C in the top sample, respectively (for the top sample we applied the projection from the earlier trend shown by *Globigerina*). When, however, the equation established by Shackleton (1974) is used for *Bulimina elongata* only and the equation proposed by Bemis *et al.* (1998) is used for globigerinids (see Grunert *et al.*, 2010, for discussion), the temperature for *Globigerina* would rise from *ca.* 11 to *ca.* 13°C in the interval studied, and the difference between the lower and the upper water beds would thus fall from 4 to 1°C (*cf.* Fig. 15).

The recorded trends in $\delta^{13}C$ and $\delta^{18}O$ values of the foraminifer taxa studied from Borków is in accordance with the long-term trends observed by Gonera *et al.* (2000) in *Globigerina bulloides* and *Uvigerina* spp. in the Badenian strata below evaporites in Upper Silesia. Durakiewicz *et al.* (1997) and Gonera *et al.* (2000) used the $\delta^{18}O$ values of calcite from foraminifer tests in the interpretation of palaeo-temperatures and concluded that the trend observed in Upper Silesia indicates a temperature decrease. This decline in tem-
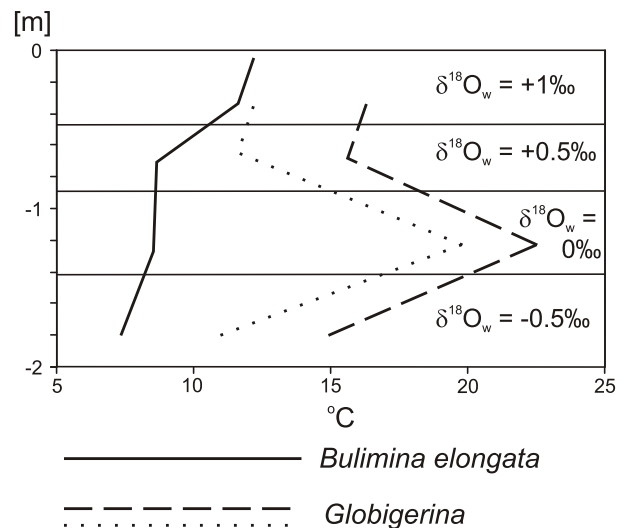
Fig. 15. Palaeotemperatures of *Bulimina elongata* (calculated with the equation established by Shackleton, 1974) and *Globigerina* (calculated with the equation established by Shackleton, 1974 – dashed line, and by Bemis *et al.*, 1998 – dotted line) assuming changes of $\delta^{18}O_w$ (see text for discussion)

perature has been documented by the displacement of warm-water planktonic foraminiferal assemblages and the expansion of the cool-water populations (Gonera *et al.*, 2000; Bicchi *et al.*, 2003). The replacement of warm-water planktonic foraminifers by cold-water assemblages is also documented in the middle/upper Badenian of the Vienna Basin (Hudá ková and Spezzaferi, 2002; Ková ová and Hudá ková, 2009). The effect of possible increased salinity prior to the deposition of evaporites which would result into an increase in $\delta^{18}O$ values was ignored because no evidence of an important environmental change in terms of salinity was found (Gonera *et al.*, 2000, p. 235). However, it was suggested that foraminifer species occurring in the strata underlying evaporites were tolerant to increased salinity (Gonera *et al.*, 2000; *cf.* Gonera, 2001).

The most outstanding feature of the dinoflagellate cyst assemblages is an increase of peridinioids in samples 2 and 4 (Fig. 12). The very frequent occurrence of *Palaeocystodinium* and, less common, protoperidinioids may be related to nutrient-rich (eutrophic) waters (e.g., Wall *et al.*, 1977; Biffi and Grignani, 1983; Bujak, 1984; Duffield and Stein, 1986). So far, no such peridinioid-rich assemblage has been described from Miocene strata of the Carpathian Foredeep (Gedl, 1996, 1997, 2005). This increase of nutrient availability cannot be rather related to freshwater influx, since we observe no enrichment in palynodebris that should occur in the case of increased river activity. This phenomenon might be related to a particular water stratification leading to the development of the water density gradient preventing organic matter sinking and leading to its concentration in the photic zone. Palynofacies analysis and in particular a high, gradually increasing upwards, frequency of pollen grains indicates that a large proportion of the terrestrial particles were transported into the basin by wind or floated on the sea surface, which is typical for high sea level phases. No direct influx of land-derived particles can be detected. Similar pollen-grain domination has been noted from evaporites and underlying strata from other localities of the Carpathian Foredeep (Gedl, 1997, 1999, 2004; Peryt *et al.*, 1997).

IMPLICATIONS

The foraminiferal record of environmental changes leading to the Messinian salinity crisis (MSC) showed that the planktonic foraminifera disappear first, and the last occurrence of benthic foraminifers marks the onset of the MSC (Gennari *et al.*, 2009). In some sections of the Mediterranean Messinian, the onset of the MSC predates the onset of gypsum precipitation by about 60 000 years (Lozar *et al.*, 2010). At the Borków site there is a clear upsection decrease in 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. It is reasonable to conclude that the time duration between the onset of the Badenian salinity crisis and the onset of gypsum precipitation was much shorter than in the Messinian of the Mediterranean.

The pattern of changes in the Badenian is somewhat different due to two factors. The first factor is expressed in the various general geographical positions of evaporite basins in the

Badenian and the Messinian which occurred in peripheral parts of the Badenian basin (and thus were subject to greater local control) in contrast to the Messinian where evaporites were mostly basin-centred. This, in turn, implies that various circulation patterns of water masses occurred in both basins. The second factor is the difference in scale – the Badenian basin of the Carpathian Foredeep was much smaller in area than the Messinian basin of the Mediterranean. The environmental changes in the Badenian pre-evaporite and evaporite basins of the Carpathian Foredeep had a step-like nature, in contrast to the gradual environmental changes in the Messinian.

Despite those fundamental differences, there are also some similarities. In the Messinian, foraminifers in the pre-evaporite unit show significant changes in bottom-water oxygenation (Goubert *et al.*, 2001). Agglutinated foraminifers are extremely rare in the pre-evaporite levels that are characterized by high frequencies of buliminaceans and bolivinaceans. Foraminiferal assemblages of the uppermost part of the pre-evaporite unit indicate a shallowing trend (Goubert *et al.,* 2001). In the Messinian, stratification of the water column, resulting in dysoxic bottom water and oligotrophic, normal salinity waters at the surface, occurred (Goubert *et al.*, 2001). In the Messinian of the Mediterranean, questions concerning the transition from marine to evaporitic conditions still remain (see Orszag-Sperber *et al.*, 2009, with references therein) although recent study in Cyprus demonstrates that a significant drop in water level occurred that predated the deposition of the lower gypsum, and this event is variously represented in several other basins of the Mediterranean (Orszag-Sperber *et al.*, 2009). The same conclusion results from study of the marls underlying the gypsum in the Borków section.

CONCLUSIONS

Four foraminiferal assemblages have been recognized in marls occurring below the Badenian gypsum in the northern Carpathian Foredeep Basin; the assemblages reflect changes in the relative abundance of epifaunal and infaunal species (Fig. 13). Assemblage I (the oldest one) is interpreted to represent a middle to outer shelf, well-ventilated environment with moderate primary productivity. A flux of organic detritus is sufficient to sustain the infaunal bottom-dwellers. Subsequently, an important change in the structure of the benthic foraminiferal assemblages took place, and assemblage II is composed almost entirely of infaunal species, being dominated by infaunal bottom-dwellers and thus reflecting a large increase in food supply to the sea bottom and shallowing of the sea to inner – middle shelf depths. Assemblage III is characterized by a small decrease in abundance of infaunal forms, and it indicates mesotrophic conditions at inner – middle shelf depths. The trend of decreasing relative abundance of the infaunal morphogroups continued in assemblage IV (occurring just below the gypsum in the section studied) that is interpreted to represent an inner shelf environment with moderate primary productivity.

Palynological data, in turn, show no major change of palaeoenvironment during the time directly preceding chemical sedimentation in the Borków section. Environmental conditions within the photic zone were stable, fully marine condi-

tions of an open shelf basin without salinity fluctuations. Neither climatic nor water temperature changes were inferred. The only instability may refer to fluctuation of trophic conditions in the photic zone. Particular samples yielded dinoflagellate cyst assemblages enriched in peridinioids, which commonly appear in eutrophic environments. Their "blooms" were presumably initiated by nutrient accumulation associated with water stratification. There is no sign of freshwater influx: land influences seem to be limited to air-borne transportation of pollen grains (possibly also floated). Therefore, the observed changes of benthic foraminifera assemblages may be related to fluctuations of primary productivity within the photic zone, whereas land-derived organic matter influx was rather stable. Periods of increased eutrophication leaded to deposition of increased amounts of organic matter at the bottom, causing thus worsening of living conditions at the floor, which favoured the infaunal dwellers. Another consequence of surface water eutrophication might have been a decrease in planktonic foraminifers, recorded in the upper part of the section.

The composition of the foraminiferal fauna in the marls preceding the gypsum precipitation and its isotopic signal indicate temperature-stratified, nutrient-rich and thus less-oxygenated marine water. The upsection decrease of share of planktonic foraminifers within the total foraminiferal assemblage up to their very rare occurrence in the topmost sample reflects the shallowing of the basin during the deposition of the interval studied that was accompanied by a decrease in temperature gradient between the upper (warmer) and lower (colder) water layers. The assemblages of planktonic foraminifers are dominated by the representatives of genus *Globigerina* that are cool water indices. A shallow, cold water marine environment is concluded for the topmost foraminiferal assemblage. The composition of foraminiferal assemblages does not allow for unequivocal conclusions regarding an increase in water salinity during the deposition of the uppermost part of the marls studied, but an eventual salinity increase would imply an increase in water temperature as well (*cf*. Figs. 14 and 15).

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APPENDIX

Faunal reference list of the identified foraminifers and dinoflagellate cysts. Taxonomy of the Foraminifera follows Cicha *et al.* (1998); their descriptions and representative illustrations can be found in the same publication. Dinoflagellate cyst full taxonomic citations are given in Fensome and Williams (2004); asterisked are redeposited (Paleogene) forms.

FORAMINIFERA

Anomalinoides badenensis (d'Orbigny, 1846) (Fig. 5C, D)
Astrononion perfossum (Clodius, 1922) (Fig. 4S)
Bolivina antiqua d'Orbigny, 1846 (Fig. 4J)
Bolivina dilatata Reuss, 1850 (Fig. 4K)
Bolivina plicatella Cushman, 1930 (Fig. 4I)
Bolivina maxima Cicha and Zapletalova, 1963 (Fig. 4E)
Bulimina aculeata d'Orbigny, 1846 (Fig. 4C)
Bulimina elongata d'Orbigny, 1846 (Fig. 4A, D)
Bulimina insignis Łuczkowska, 1953
Bulimina sp. (Fig. 4B)
*Cibicidoides austriacus (*d'Orbigny, 1846) (Fig. 5A, B)
Cibicidoides lopjanicus (Myatlyuk, 1950) (Fig. 5V, W)
Cibicidoides pseudoungerianus (Cushman, 1922)
Cibicidoides ungerianus (d'Orbigny, 1846) (Fig. 5Q, R)
Elphidium aculeatum (d'Orbigny, 1846) (Fig. 5E, I, L)
Elphidium argenteum Parr, 1945 (Fig. 5K)
Elphidium crispum (Linné, 1758)
Elphidium macellum (Fichtel et Moll, 1798) (Fig. 5M)
Elphidium sp. (Fig. 5J)
Eponides repandus (Fichtel et Moll, 1798)
Fursenkoina acuta (d'Orbigny, 1846) (Fig. 4F–H)
Fursenkoina pauciloculata (Brady, 1884)
Glandulina ovula d'Orbigny, 1846
Guttulina communis d'Orbigny, 1826
Globocassidulina oblonga (Reuss, 1850) (Fig. 4P)
Globulina punctata d'Orbigny, 1826
*Heterolepa dutemplei (*d'Orbigny, 1846)
Hoeglundina elegans (d'Orbigny, 1826) (Fig. 5F–H)
Lagena striata (d'Orbigny, 1839)
Lobatula lobatula (Walker et Jacob, 1798) (Fig. 5N, O)
Melonis pompilioides (Fichtel et Moll, 1798) (Fig. 4R)
Nonion tumidulus Pishvanova, 1960
Porosononion martkobi (Bogdanowicz, 1947) (Fig. 4T)
Praeglobobulimina pyrula (d'Orbigny, 1846) (Fig. 4Q, U)
Pseudotriloculina consobrina (d'Orbigny, 1846)
Pseudotriplasia elongata Małecki, 1954 (Fig. 4O)
Pullenia bulloides (d'Orbigny, 1826) (Fig. 4V)
Pyrgo sp.
Reussoolina apiculata (Reuss, 1851)
Riminopsis boueanus (d'Orbigny, 1846) (Fig. 5V)
Rosalina? sp. (Fig. 5S–U)
Sigmoilinita tenuis (Czjzek, 1848) (Fig. 5P)
Spiroloculina tenuissima Reuss, 1867
Sphaeroidina bulloides d'Orbigny, 1826 (Fig. 4W)
Triloculina sp.
Uvigerina aculeata d'Orbigny, 1846 (Fig. 4M)
Uvigerina pudica Łuczkowska, 1955 (Fig. 4L)
Uvigerina pygmea d'Orbigny, 1826 (Fig. 4N)
Valvulineria bradyana (Fornasini, 1900)
Globigerina bulloides d'Orbigny, 1826 (Fig. 6E, F)
Globigerina concinna Reuss, 1850 (Fig. 6I, J)

Globigerina druryi Akers, 1960 (Fig. 6K)
Globigerina praebulloides Blow, 1959 (Fig. 6G, H)
Globigerina subcretacea (Łomnicki, 1901) (Fig. 6Q, R)
Globigerina tarchanensis Subbotina et Chutzieva, 1950 (Fig. 6O, P)
Globigerina? sp. (Fig. 6S, T)
Globigerinita uvula (Ehrenberg, 1862) (Fig. 6L)
Globigerinoita sp. (Fig. 6M, N)
Globorotalia bykovae (Aisenstat, 1960) (Fig. 6A, B)
Globorotalia mayeri Cushman et Ellisor, 1983 (Fig. 6C, D)

DINOFLAGELLATE CYSTS

*Areosphaeridium diktyoplokum** (Klumpp, 1953) Eaton, 1971
Batiacasphaera sphaerica Stover, 1977 (Fig. 10A, B)
Cerebrocysta poulsenii de Verteuil et Norris, 1996 (Fig. 10F–I)
Charlesdowniea sp.*
Cordosphaeridium minimum (Morgenroth, 1966) Benedek, 1972 (Fig. 10C)
Dapsilidinium pseudocolligerum (Stover, 1977) Bujak *et al.*, 1980
Dapsilidinium sp.
*Deflandrea heterophlycta** Deflandre et Cookson, 1955
Heterosphaeridium? sp.
Homotryblium floripes (Deflandre et Cookson, 1955) Stover 1975
Homotryblium sp.
Hystrichokolpoma rigaudiae Deflandrea et Cookson, 1955 (Fig. 11H)
Impagidinium sp. (Fig. 11A)
Imperfectodinium septatum Zevenboom et Santarelli, 1995 (Fig. 10M–O)
Imperfectodinium? sp.
Labyrinthodinium truncatum Piasecki, 1980 (Fig. 10K, L)
Lejeunecysta sp.
Lingulodinium machaerophorum (Deflandre et Cookson, 1955) Wall, 1967 (Fig. 11L)
Melitasphaeridium choanophorum (Deflandre et Cookson, 1955) Harland et Hill, 1979 (Fig. 10S)
Nematosphaeropsis labyrinthus (Ostenfeld, 1903) Reid, 1974 (Fig. 10T, U)
Operculodinium centrocarpum (Deflandre et Cookson, 1955) Wall, 1967 (Fig. 11B)
Operculodinium israelianum (Rossignol, 1962) Wall, 1967
Operculodinium piaseckii Strauss et Lund, 1992 (Fig. 10D, E)
Operculodinium sp. (Fig. 11I, J, N)
Palaeocystodinium golzowense Alberti, 1961 (Fig. 11O)
Pentadinium laticinctum Gerlach, 1961 (Fig. 11E, F)
Polysphaeridium zoharyi (Rossignol, 1962) Bujak *et al.*, 1980
Pyxidiniopsis sp.
Selenopemphix nephroides (Benedek, 1972) (Fig. 11K)
Spiniferites pseudofurcatus (Klumpp, 1953) Sarjeant, 1970
Spiniferites ramosus (Ehrenberg, 1838) Mantell, 1854 (Fig. 11C)
Spiniferites sp.
Systematophora placacantha (Deflandre et Cookson, 1955) Davey *et al.*, 1969 (Figs. 10P R and 11D)
Systematophora cf. *placacantha* (Deflandre et Cookson, 1955) Davey *et al.*, 1969 (Fig. 11M)
Unipontidinium aquaeductum (Piasecki, 1980) Wrenn, 1988 (Fig. 10V)
Wetzeliella sp.*