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# Marine transgression(s) to evaporite basin: The case of middle Miocene (Badenian) gypsum in the Central Paratethys, SE Poland

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## Abstract

The middle Miocene Badenian evaporite basin of the Carpathian Foredeep Basin was a saline lake, separated by a barrier from the sea and supplied with seawater seeping through the barrier or overflowing it occasionally in the form of short-lived marine transgressions. Such transgressions could leave behind marine microfossils in marly clay intercalations. One of them (2.3 m thick) occurs in the uppermost part of the sulphate sequence, in the unit 'o', in the Babczyn 2 borehole section. It contains marine palynomorphs (dinoflagellate cysts) and foraminiferal assemblages indicating a marine environment. The low-diversity benthic foraminiferal assemblages are dominated by opportunistic, shallow infaunally living species, preferring muddy or clayey substrate for thriving, brackish to normal marine salinity, and inner shelf environment. Dinoflagellate cyst assemblages, although taxonomically impoverished, consist of marine species; euryhaline forms that tolerate increased salinity are missing. Relatively common microfossils found in clay intercalations within gypsum have important palaeogeographical implications: they strongly suggest that there existed an additional inflow channel supplying the Polish Carpathian Basin from the south during the evaporite deposition and afterwards.

**Keywords:** Evaporite basins, Transgression, Microfossils, Badenian, Palaeogeography, Paratethys

## 1 Introduction

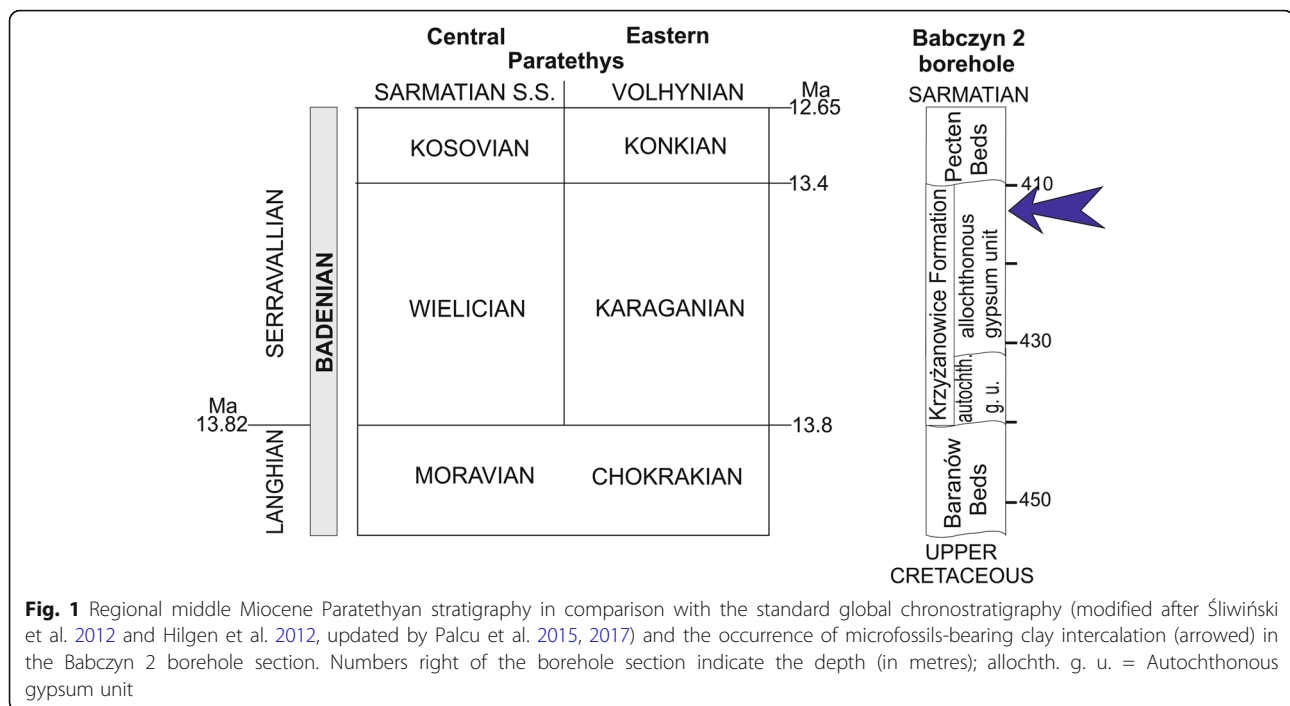
The Paratethys was an epicontinental sea that developed as a relic of the Tethys. It existed between early Oligocene and late middle Miocene times and constituted a system of marine basins extending from the Alpine-Carpathian region to the modern Aral Sea during Oligocene to Miocene times. They were periodically connected with the Mediterranean, Indo-Pacific and Atlantic oceans (Rögl 1998). The Paratethys is divided into three segments: Western, Central and Eastern, and the regional time scale, based mostly on endemic fossil assemblages, is applied for particular parts of the

Paratethys (Fig. 1). Water circulation in the Paratethys was strongly controlled by two shallow and narrow gateways: the Slovenian (Trans-Tethyan Trench) corridor (Rögl 1998; Kováč et al. 2017) and the Bârlad Strait in Romania (Palcu et al. 2015) connecting the Central and Eastern Paratethys. Both gateways were located in tectonically active regions (Simon et al. 2019) and controlled the recorded palaeoenvironmental changes in these basins, although the exact mechanisms are still poorly understood (Palcu et al. 2017). At 13.8 Ma, the global climate cooled, triggering a glaciation, which led to a global sea-level fall of ~ 50–70 m (John et al. 2011; Simon et al. 2019), which drastically reduced the Trans-Tethyan Strait to a very shallow depth and disconnected the two Paratethyan basins (Fig. 2). The Badenian Salinity Crises ended before  $13.32 \pm 0.07$  Ma (de Leeuw

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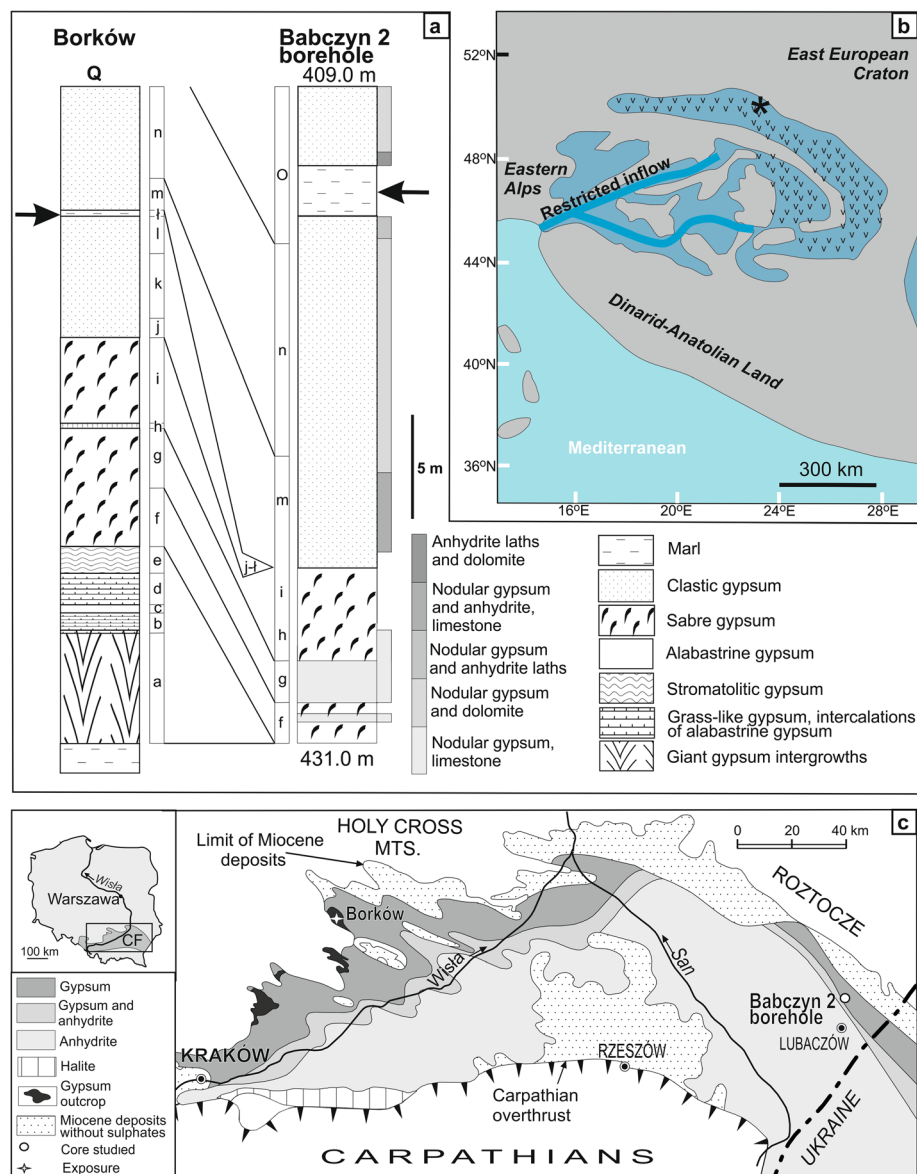
et al. 2018). A transgression that re-installed normal marine conditions in the Carpathian Foredeep Basin resulted from reconnection of the basin with the Mediterranean and Eastern Paratethys, primarily by tectonic modification of the interconnecting gateways, i.e. tectonic lowering of the barriers between the Central Paratethys and the neighbouring basins (de Leeuw et al. 2018).

The system of middle Miocene Badenian evaporite basins of the Central Paratethys (Fig. 2), which started to form at some 13.81 Ma, gained occasional connections with the Mediterranean marine reservoir through the Slovenian (Trans-Tethyan Trench) corridor or with the Eastern Paratethys (low-salinity water reservoir – Palcu et al. 2017) through the Bârlad Strait. Barred evaporite basins are sourced mostly by seepage (Kendall 2010; Warren 2016). When overflow happens, then depending on the volume of seawater inflow and the overflow duration, the brines of barred basin may be eventually replaced by seawater. One eminent connection of barred evaporite basin of the Carpathian Foredeep Basin with an open-sea reservoir was previously recognized in the middle part of the gypsum sequence of southern Poland where a marly clay intercalation sandwiched between the gypsum contains benthic and planktonic foraminifera indicating a short-lived inflow of marine water (Peryt 2013a; Fig. 2). The foraminifer-bearing clay intercalation in southern Poland occurs in the middle of the upper part of the gypsum sequence, i.e. at the same stratigraphic position as other foraminifer-bearing clay intercalations in the gypsum sequence, which were

recorded by Odrzywolska-Biełkowska (1975) in SE Poland (cf. Pawłowski et al. 1985; Kos in Kasprzyk 1989; Kubica 1992). In this paper, we report the foraminiferal and dinoflagellate cysts assemblages from the clay intercalation of the topmost part of the gypsum sequence in the Babczyn 2 borehole (SE Poland; Fig. 2). These assemblages indicate marine invasion into the Central Paratethys prior to the termination of the evaporite stage that occurred 13.36 Ma when the Central Paratethys returned to open-marine conditions, and the Eastern Paratethys remained more brackish (Simon et al. 2019).

## 2 Geological setting

Badenian sulphate deposits occur in most of the northern and northeastern Carpathian Foredeep Basin from Moravia in Czech Republic in the west through southern Poland and western Ukraine to the Ukrainian-Romanian borderland and Moldova (Peryt 2006, 2013b). Sulphate deposits in southeastern Poland consist of a sequence of lithofacies grouped into 18 lithostratigraphic units (from 'a' to 'r'; Kasprzyk 1993) or seven lithosomes (from 'A' to 'G'; Kubica 1992, 1994; Bąbel 2005). In SE Poland, in the Lubaczów area located close to the Polish-Ukrainian border (Fig. 2), the primary gypsum is partly or completely replaced by anhydrite and secondary gypsum (Kasprzyk 1995). In the Cieszanów 1 borehole, units 'a'–'o' have a total thickness of 44.8 m (Kasprzyk 1995), and in the Babczyn 2 borehole the gypsum sequence (32 m thick, depth 409–441 m) consists of units 'a'–'l' and 'm'–'o' (the upper part of the sequence is shown in Fig. 2, after Peryt and Kasprzyk 1992). Unit 'm' is composed



**Fig. 2** Geological setting. **a** Sections of Badenian gypsum of the Borków quarry (after Peryt and Jasionowski 1994) and Babczyn 2 borehole (middle and upper parts, after Peryt and Kasprzyk 1992; lower part is not shown); black arrows show the intercalations of microfossils-bearing clays described by Peryt (2013a) and this paper, respectively; alabastrine gypsum – alabastrine gypsum originated due to recrystallization of fine-grained gypsum precipitated in association with microbial mats (cf. Orti Cabo et al. 1984) and then transported during storms (cf. Kwiatkowski 1972); sabre gypsum – gypsum type composed of curved gypsum crystals resembling sabres which grew upwards and simultaneously curved laterally, thus most crystals are inclined and curved in the same direction (Bąbel 1986); **b** Simplified palaeogeographic reconstruction of Mediterranean–Paratethys connection during Badenian Salinity Crisis interval (modified after de Leeuw et al. 2010); star marks location of the Babczyn 2 borehole; **c** Location map of the Babczyn 2 borehole (after Peryt and Kasprzyk 1992) and the sulphate lithofacies of the Polish Carpathian Foredeep (after Kasprzyk 2005 and Bukowski 2011: fig. 10)

of laminated and bedded microcrystalline gypsum that contains layers and irregular bodies of gypsiferous, occasionally brecciated, microbial-peloidal carbonate, while unit 'n' consists of thinly laminated gypsum with three beds of carbonate-gypsum breccias in the middle part. Unit 'o' is nodular gypsum intercalated by a 2.3 m layer of marly clays (depth: 413–415.3 m) rich in plant

remains and carbonate lithoclasts (Pawłowska and Kubica: Karta otworu wiertniczego Babczyn 2, unpublished) as well as crushed mollusc (*Modiolus?*) shell fragments (Śliwiński et al. 2012). Interpretation by Peryt and Kasprzyk (1992) assumed that, following a sea-level drop after the deposition of unit 'n', very shallow subaqueous and subaerial conditions prevailed during deposition of

unit 'o' (Peryt and Kasprzyk 1992). Accordingly, this marly clay is younger than unit 'T' in which Peryt (2013a), in the Borków quarry section (Fig. 2), recorded previously the benthic foraminifer assemblages composed of pioneer, opportunistic, r-selected species dominated by elphidiids.

### 3 Material and methods

For the foraminiferal study, all samples of approximately 200 g were disaggregated in Glauber's salt, cleaned in an ultrasonic bath, dried and sieved into a  $\geq 63 \mu\text{m}$  size fraction. An aliquot of about 200–300 specimens of foraminifers was picked for the faunal analysis. The classification scheme used follows Loeblich Jr. and Tappan (1987), Cicha et al. (1998), Pawłowski et al. (2013) and Dubicka (2019). The palaeoenvironmental interpretation was based on foraminifers and the requirements of present-day representatives of recorded taxa (e.g. Walton and Sloan 1990; Verhallen 1991; Murray 1991, 2006; Jorissen et al. 1992; Sen Gupta and Machain-Castillo 1993; Kaiho 1994; Hayward et al. 1997; Loubere 1997; Alve and Murray 1999; Bernard and Sen Gupta 1999; Vaniček et al. 2000; Buzas-Stephens et al. 2003; Fiorini 2004; Kouvenhoven and van der Zwaan 2006; Debeney et al. 2009; Kaminski 2012; Schiebel and Hemleben 2017). The figured specimens are deposited in the Institute of Paleobiology, Polish Academy of Sciences, Warszawa (ZPAL F. 68).

The samples for the palynological study were processed following the procedure including 38% hydrochloric acid (HCl) dissolution, 40% hydrofluoric acid (HF) dissolution, heavy liquid ( $\text{ZnCl}_2 + \text{HCl}$ ; density  $2.0 \text{ g/cm}^3$ ) separation, and sieving at  $15 \mu\text{m}$  on a nylon mesh in ultrasounds for 10–15 s. No oxidation in nitric acid ( $\text{HNO}_3$ , fuming) was applied. The quantity of each rock sample processed was 10 g. Two slides from each sample were made using glycerine jelly as a mounting medium. Dinoflagellate cysts were qualitatively determined up to 300 specimens using a Zeiss AxioLab microscope; the remaining specimens were scanned for their taxonomy only. Palynofacies for each sample were calculated based on 500 particles. The unprocessed rock samples, palynological residues and slides are stored in the collection of the Institute of Geological Sciences, Polish Academy of Sciences, Research Centre in Kraków.

### 4 Results

Low-diversity foraminiferal assemblages are recorded in the interval studied (Table 1; Figs. 3, 4 and 5). Their preservation is poor to moderate. Foraminiferal tests are mostly recrystallized and often broken. The benthic foraminiferal assemblages consist entirely of calcareous species of very small and tiny tests. They are dominated by

3 taxa, i.e. *Nonion parvus*, *Haynesina depressula* and *Ammonia* spp. (mainly *A. parkinsoniana*; also common transitional forms from *parkinsoniana* to *tepida* and *A. tepida*). They form 60% to 80% of the assemblages (Fig. 6). *Elphidium* spp. is also a common and persistent contributor to the assemblages (6%–20%). Minor components are *Rosalina obtusa* and hauerinids (*Quinqueloculina* sp., *Triloculina* sp., *Pseudotriloculina consobrina*, and *Sigmoilinita tenuis*) forming up to 5% of the assemblages. *Nonion parvus* and *Ammonia* spp. fluctuate significantly throughout the interval. Relative abundance of *Ammonia* spp. varies between 6% and 62%; *Nonion parvus* accounts for 9% to 64%. Foraminiferal assemblages from samples 2 and 4 represent near-monospecific faunas (Hayward 2014). In sample 2, *Ammonia* spp. makes 62% of the assemblage; other components do not exceed 10% each. In sample 4, *Nonion parvus* makes up 64% of the assemblage, while the contribution of *Ammonia* spp. drops to 6% (Fig. 6).

The species show small sizes compared to usual dimensions. Planktonic foraminifera are scarce. They are represented mainly by small-sized *Globigerina* (*G. tarchanensis*), *Trilobatus* (*T. altospiralis*), *Globoturborotalita* cf. *druryi*, *Tenuitellinata* sp. Redeposited Eocene and Cretaceous foraminifers are quite common.

The 2.3-m-thick layer of marly clays yielded high amounts of palynological organic matter composed chiefly of terrestrial elements – mainly dark brown and black phytoclasts and pollen grains, the proportions of which oscillate between 80% and 90%. Marine elements that are present throughout the whole interval – dinoflagellate cysts, other algae and subordinate foraminifera organic linings, are up to a few per cent. Amorphous organic matter (AOM) is also present in the whole interval; except for sample 3, where it does not exceed 10% (Fig. 6).

Dinoflagellate cysts are well to moderately preserved, being all light-coloured (Table 1; Figs. 7, 8 and 9). Their assemblages are dominated by three taxa: *Spiniferites* (mainly *S. ramosus*), *Operculodinium* and *Systematophora placacantha* (Table 2). Proportions of these taxa fluctuate slightly, but generally *Spiniferites* is most common in all these samples; *Systematophora placacantha* is most frequent in basal samples, and becomes rarer in the upper part of the interval. They are accompanied by subordinate *Lingulodinium machaerophorum*, *Pentadinium laticinctum*, *Labyrinthodinium truncatum*, *Melitasphaeridium choanophorum* and *Pyxidiniopsis*. A characteristic feature of the dinoflagellate cyst assemblages is almost complete lack of peridinioids. There are no *Palaeocystodinium* (known from older Badenian strata of the Carpathian Foredeep). Rare specimens of *Lejeunecysta* may be reworked.



**Table 1** Identified taxa (asterisked are reworked species)**BENTHIC FORAMINIFERA**

*Ammonia parkinsoniana* (d'Orbigny 1839)  
*Ammonia tepida* (Cushman 1926)  
*Ammonia* sp.  
*Asterigerinata planorbis* (d'Orbigny 1846)  
*Bolivina plicatella* Cushman 1930  
*Bolivina pokornyi* Cicha & Zapletalova 1963  
*Bolivina* sp.  
*Elphidium aculeatum* (d'Orbigny 1846)  
*Elphidium* cf. *joukovi* Serova 1955  
*Elphidium* sp.  
*Favulina hexagona* (Williamson 1848)  
*Haynesina depressula* (Walker & Jacob 1798)  
*Haynesina* sp.  
*?Haynesina* sp.  
*Lobatula lobatula* (Walker & Jacob 1798)  
*Nonion parvus* Bogdanovich 1950  
*Pseudotriloculina consobrina* (d'Orbigny 1846)  
*Quinqueloculina* sp.  
*Rosalina obtusa* d'Orbigny 1846  
**PLANKTONIC FORAMINIFERA**  
*Globigerinelloides* sp.  
*Globigerina bulloides* d'Orbigny 1826  
*Globigerina tarchanensis* Subbotina & Khutsieva 1950  
*Globoturbotalita* cf. *druryi* (Akers 1955)  
*Tenuitellinata?* sp. A  
*Tenuitellinata?* sp. B  
*Trilobatus altospiralis* Spezzaferi 2018  
*Trilobatus* sp.

**DINOFLAGELLATE CYSTS**

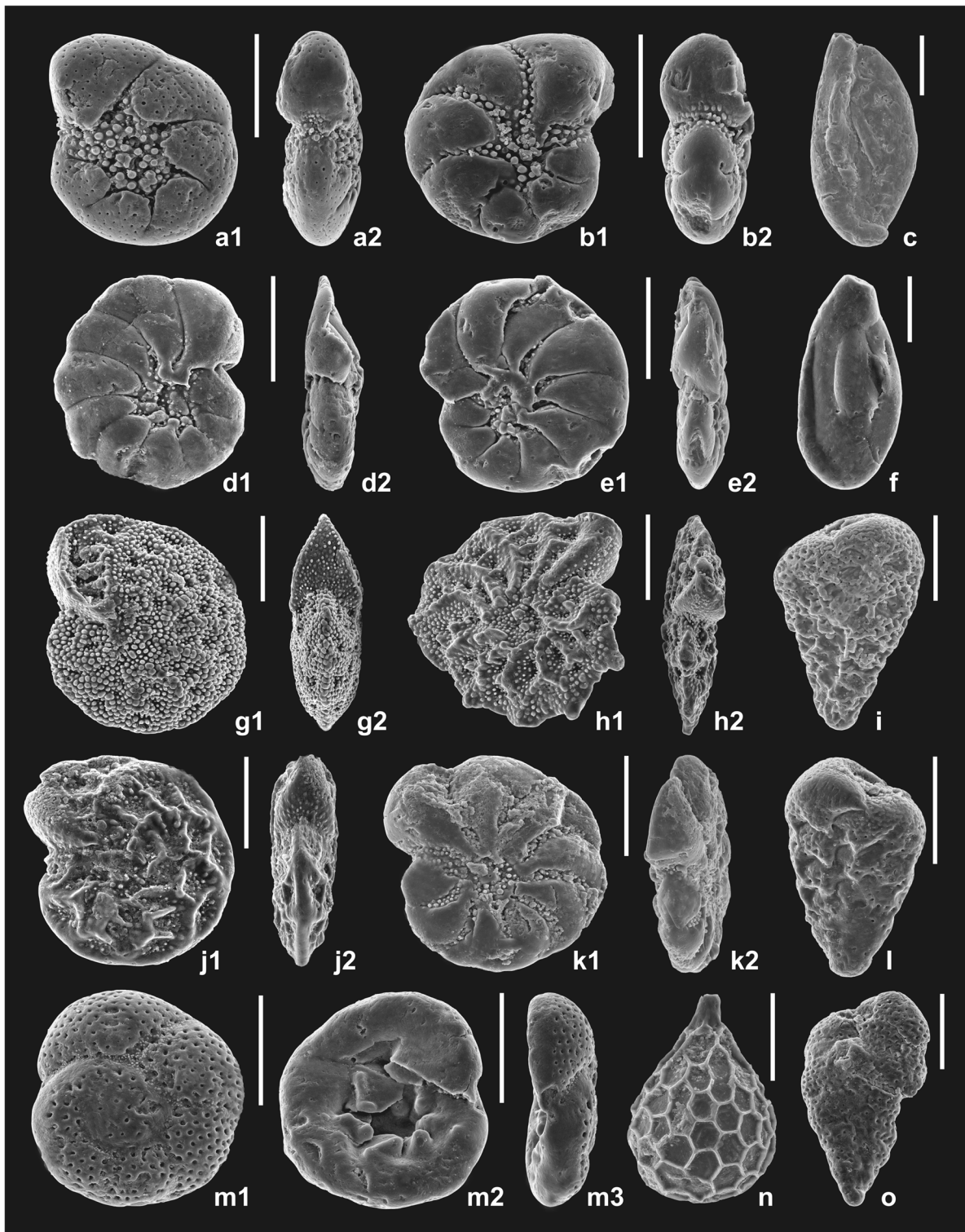
*Achomosphaera* sp.  
*Alisogymnium euclaense*\* (Cookson & Eisenack 1970) Lentin & Vozzhennikova 1990  
*Alterbidinium?* sp.\*  
*Areoligera* sp.\*  
*Areosphaeridium diktyoplokum*\* (Klumpp 1953) Eaton 1971  
*Areosphaeridium michoudii*\* Bujak 1994  
*Cerodinium* sp.\*  
*Charlesdowniea* sp.\*  
*Chiropteridium?* sp.\*  
*Circulodinium* sp.\*  
*Cordosphaeridium minimum* s.l. (Morgenroth 1966) Benedek 1972  
*Cordosphaeridium* sp.\*  
*Dapsilidinium* sp.  
*Deflandrea* sp.\*

**Table 1** Identified taxa (asterisked are reworked species)  
(Continued)

*Dinogymnium* sp.\*  
*Enneadocysta arcuata*\* (Eaton 1971) Stover & Williams 1995  
*Enneadocysta* sp.\*  
*Florentinia* sp.\*  
*Glaphyrocysta semitecta*\* (Bujak in Bujak et al. 1980) Lentin et Williams 1981  
*Glaphyrocysta* sp.\*  
*Homotryblium abbreviatum*\* Eaton 1976  
*Homotryblium floripes*\* (Deflandre & Cookson 1955) Stover 1975  
*Homotryblium plectilum*\* Drugg & Loeblich Jr. 1967  
*Homotryblium tenuispinosum*\* Davey & Williams 1966  
*Hystriocholpoma* spp.  
*Hystriochosphaeropsis obscura* Habib 1972  
*Impagidinium?* *aculeatum* (Wall 1967) Lentin & Williams 1981  
*Impagidinium* spp.  
*Labyrinthodinium truncatum* Piasecki 1980  
*Lejeunecysta* spp.  
*Lingulodinium machaerophorum* (Deflandre & Cookson 1955) Wall 1967  
*Melitasphaeridium choanophorum* (Deflandre & Cookson 1955) Harland & Hill 1979  
*Melitasphaeridium?* *pseudorecurvatum* (Morgenroth 1966) Bujak et al. 1980  
*Nematosphaeropsis* sp.  
*Operculodinium centrocarpum* (Deflandre & Cookson 1955) Wall 1967  
*Operculodinium* spp.  
*Palynodinium grallator*\* Gocht 1970  
*Pentadinium laticinctum* Gerlach 1961  
*Pentadinium* sp.  
*Pyxidinospis psilata* Wall & Dale 1973  
*Pyxidinospis?* sp.  
*Reticulosphaera actinocoronata* (Benedek 1972) Bujak & Matsuoka 1986  
*Rottnestia borussica*\* (Eisenack 1954) Cookson & Eisenack 1961  
*Spiniferites pseudofurcatus* (Klumpp 1953) Sarjeant 1970  
*Spiniferites ramosus* (Ehrenberg 1838) Mantell 1854  
*Spiniferites* spp.  
*Surculosphaeridium* sp.\*  
*Systematophora placacantha* (Deflandre & Cookson 1955) Davey et al. 1969  
*Tanyosphaeridium* sp.\*  
*Wetzeliella* sp.\*  
 Gen. et spec. Indet.

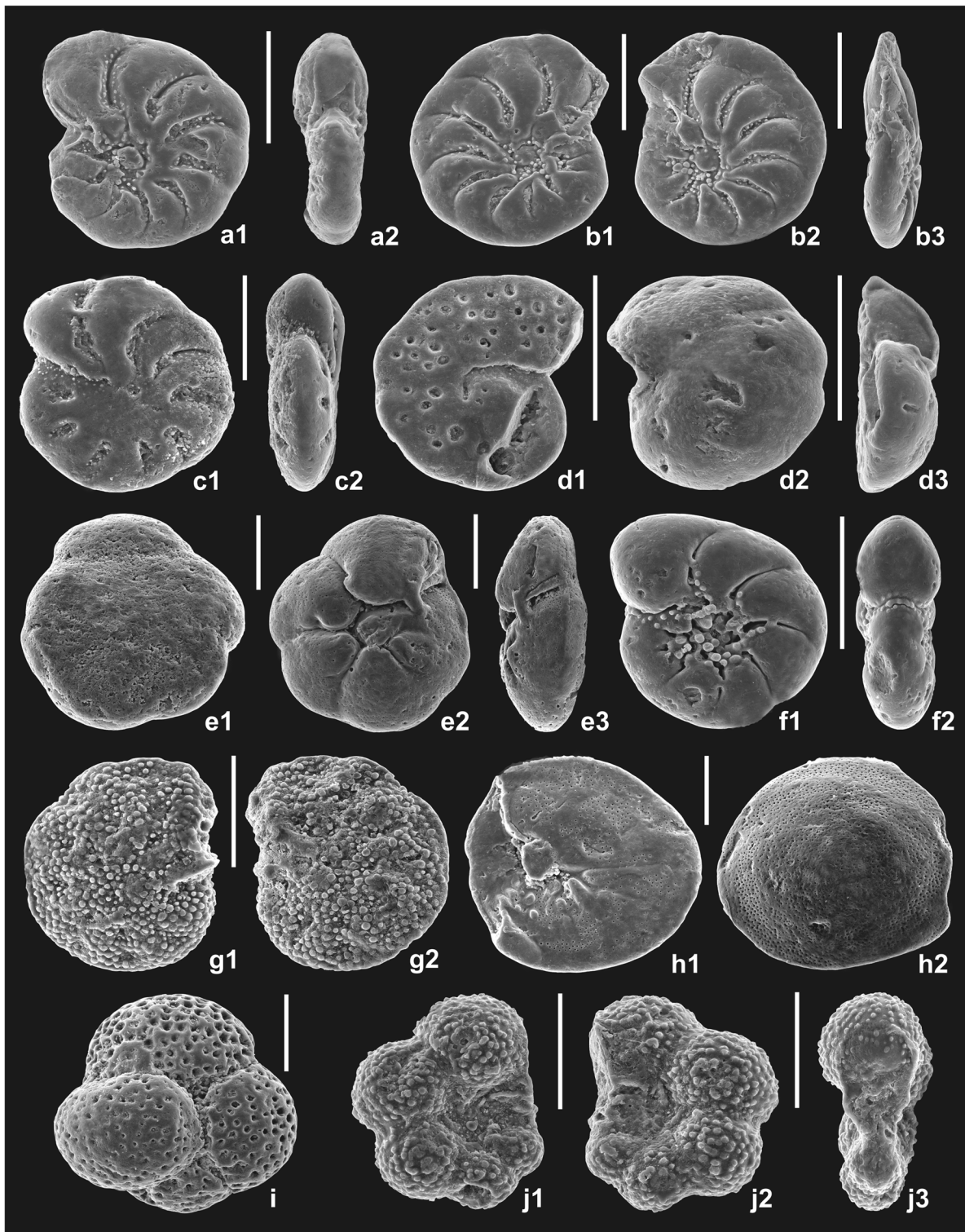
**ACRITARCHS**

*Svenkodium* sp. (acritarch)  
*Veryhachium* sp. (acritarch)

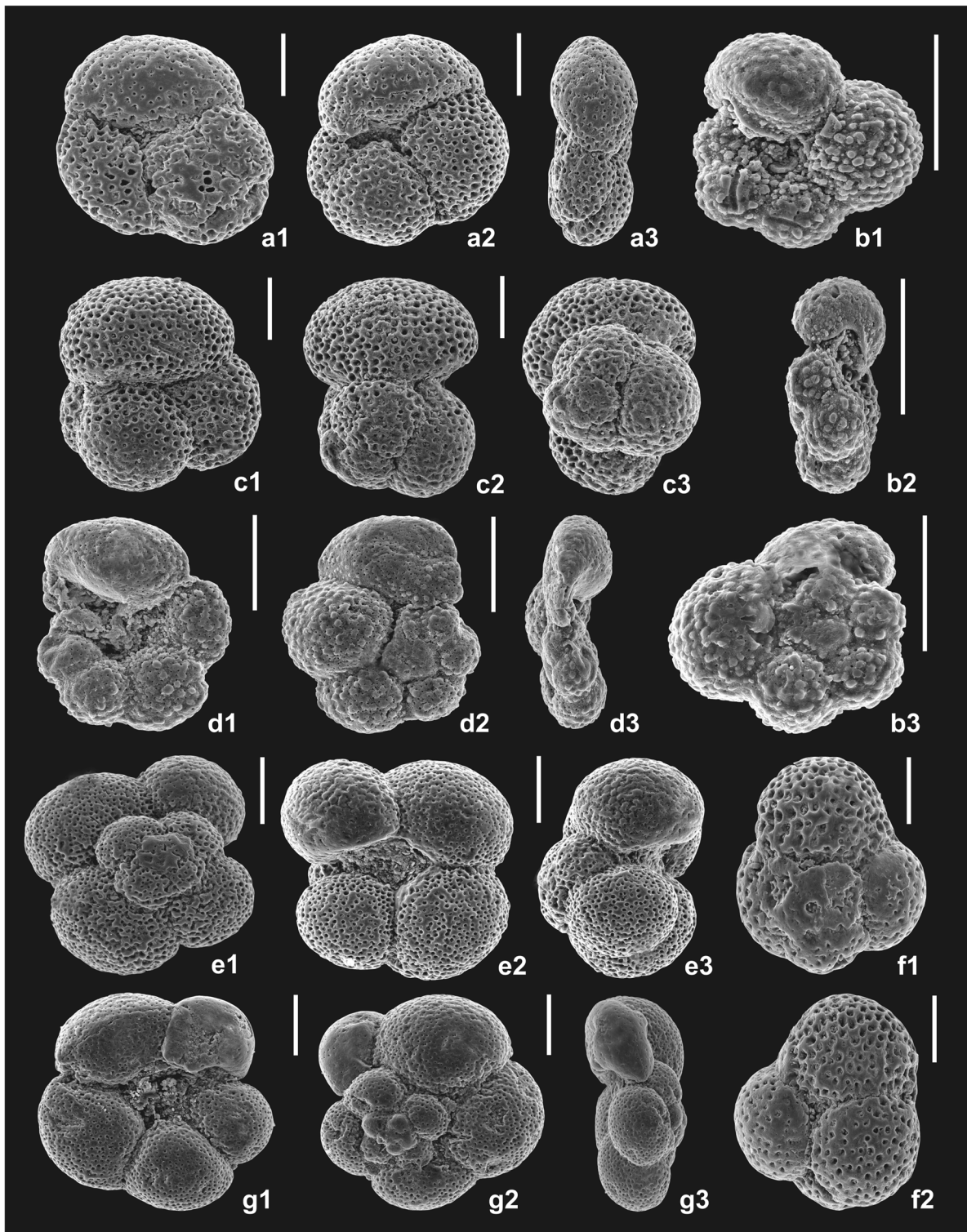


**Fig. 3** Benthic foraminifera from the Babczyn 2 borehole. **a, b** *Nonion parvus*; **c** *Quinqueloculina* sp.; **d, e** *Haynesina depressula*; **f** *Pseudotriloculina consobrina*; **g** *Elphidium* cf. *joukovi*; **h** *Elphidium aculeatum*; **i** *Bolivina plicatella*; **j** *Elphidium* sp. (sample 2/4); **k** *Haynesina* sp.; **l** *Bolivina* sp.; **m** *Rosalina obtusa*; **n** *Favulina hexagona*; **o** *Bolivina pokorny*. Scale bar = 100  $\mu$ m; **a–e, g–h, m**: Sample 1; **f**: Sample 6; **i, k–l**: Sample 3; **j, n–o**: Sample 4



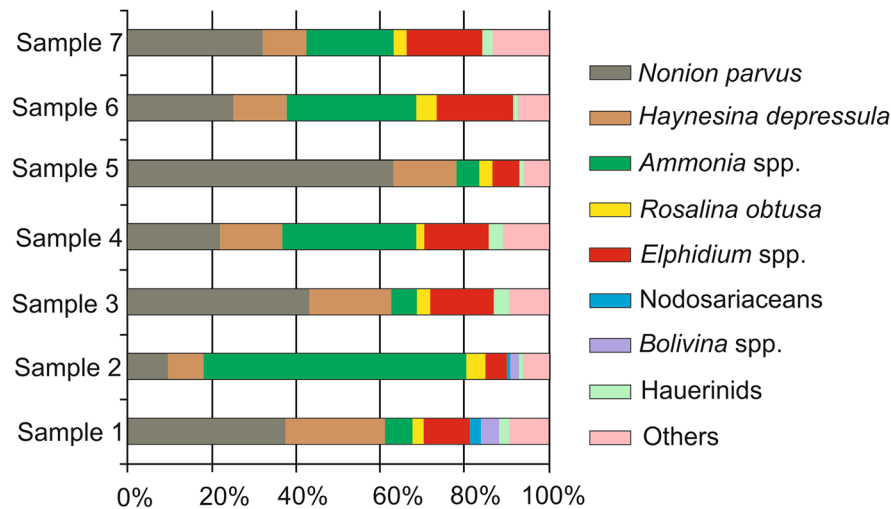
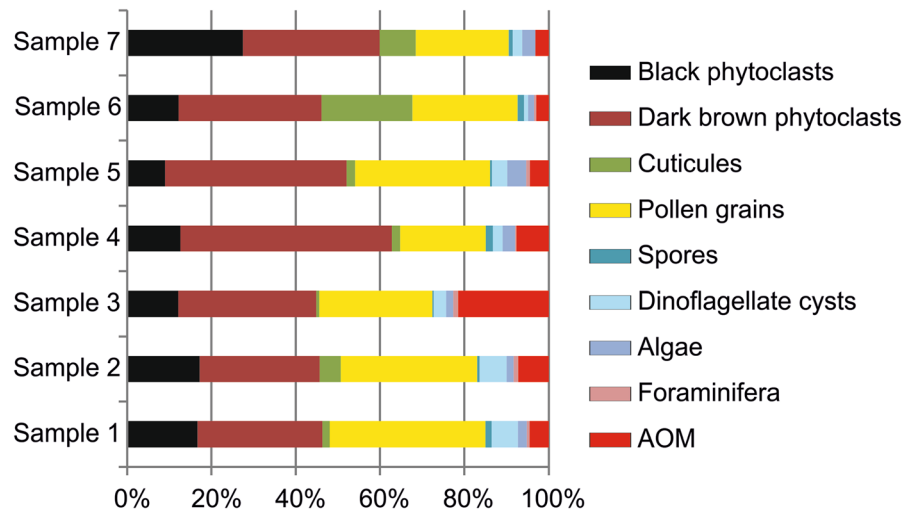


**Fig. 4** Benthic and planktonic foraminifera from the Babczyn 2 borehole. **a, b** *Haynesina depressula*; **c** *Haynesina* sp.; **d** *Lobatula lobatula*; **e** *Ammonia* sp. (transitional from parkinsoniana to tepida); **f** *Nonion parvus*; **g** *Elphidium* sp.; **h** *Asterigerinata planorbis*; **i** *Globoturborotalita* cf. *druryi*; **j** *Globigerinelloides* sp. (Cretaceous form). Scale bar = 100  $\mu$ m; **a, d, f, g, j**: Sample 5; **b, e, h, i**: Sample 6; **c**: Sample 7



**Fig. 5** Planktonic foraminifera from the Babczyn 2 borehole. **a** *Trilobatus* sp.; **b** *Tenuitellinata?* sp. A; **c** *Trilobatus altospiralis*; **d** *Tenuitellinata?* sp. B; **e** *Globigerina bulloides*; **f** *Globoturborotalita* cf. *druryi*; **g** *Globigerina tarchanensis*. Scale bar = 100 μm; **a, e–g**: Sample 6; **b, d**: Sample 1; **c**: Sample 3



**FORAMINIFERS****PALYNOFACIES**

**Fig. 6** Relative abundances of dominant and common foraminifer species or groups of foraminifer species in the Babczyn 2 borehole interval studied (above) and corresponding palynofacies changes (below). AOM = Amorphous organic matter

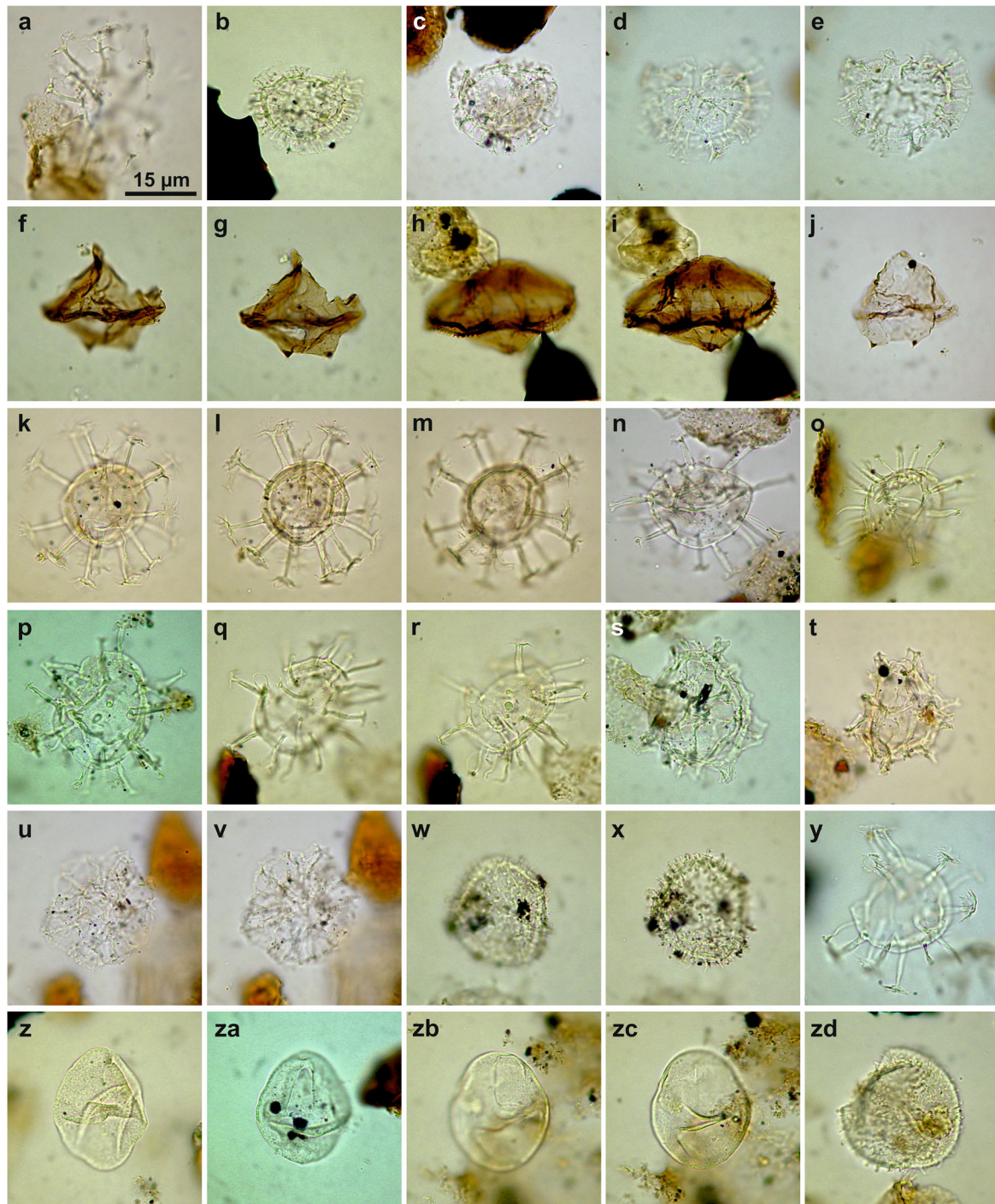
## 5 Interpretation

The presence of marine palynomorphs (dinoflagellate cysts) and foraminifera suggests a marine environment during deposition of the interval in question. Interestingly, the material contains very rare *Leiosphaeridia*, a prasinophycean genus (see e.g. Guy-Ohlson 1996) that commonly occurs in the Miocene of the Carpathian Foredeep, accumulated in stress environments associated with increased salinity (e.g. Gedl 2016). Moreover, the dinoflagellate cyst assemblages lack *Polysphaeridium*, another indicator of increased (e.g. Bradford and Wall 1984) or decreased salinity (Edwards and Andrieu 1992).

Frequent occurrence of this genus was reported from strata that followed the middle Miocene Badenian Salinity Crisis (e.g. Gedl and Peryt 2011; Peryt et al. 2014; Gedl 2016; Gedl et al. 2016). Preceding strata, in contrast, yielded no *Polysphaeridium* or rare specimens of this genus (e.g. Peryt and Gedl 2010).

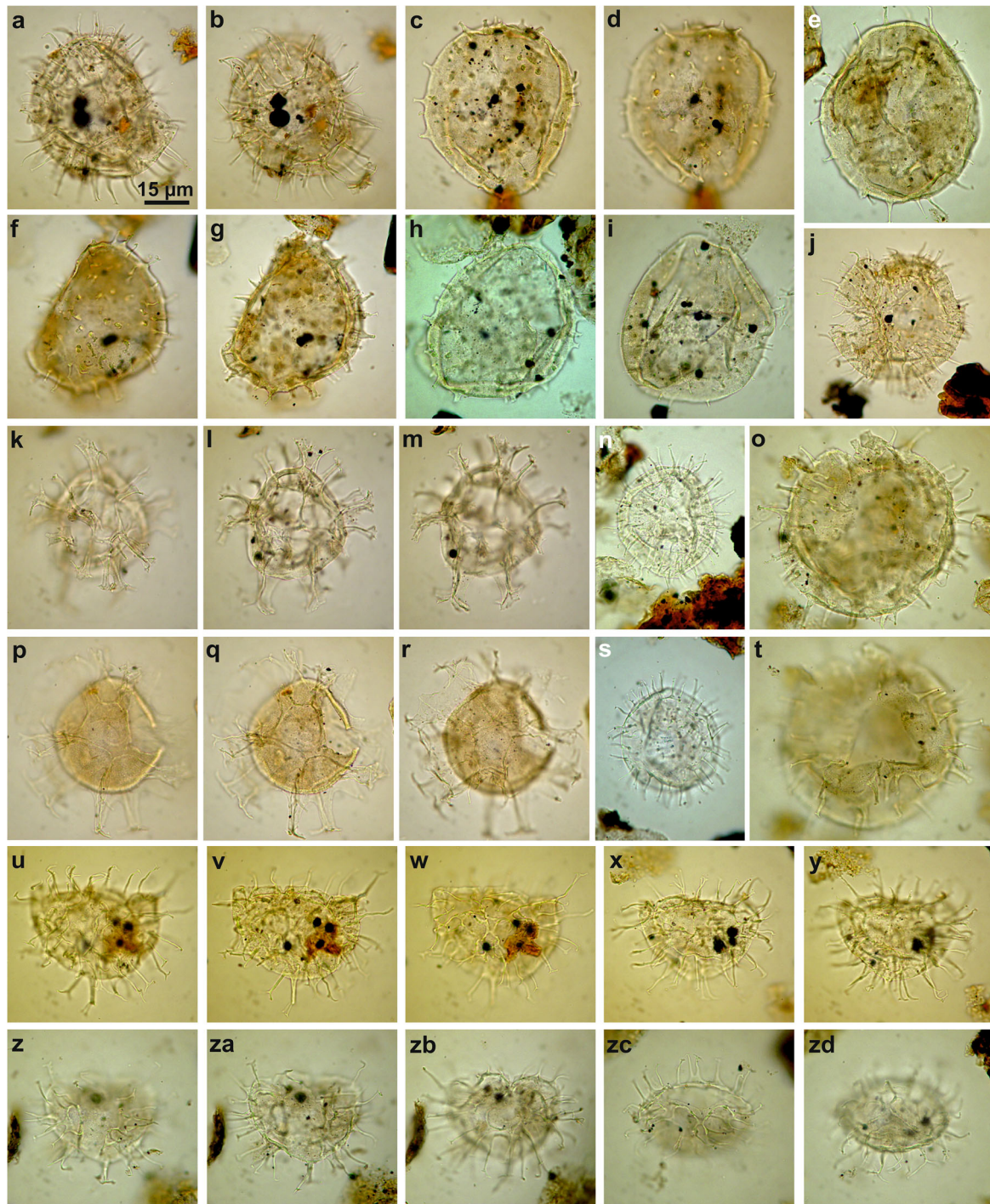
Dominant taxa in the benthic foraminiferal assemblages of the interval, i.e. *Nonion parvus*, *Haynesina depressula* and *Ammonia* spp., represent shallow infaunally living species, preferring muddy or clayey substrate for thriving, tolerant of suboxic environments, brackish to normal marine salinity, and inner shelf depths





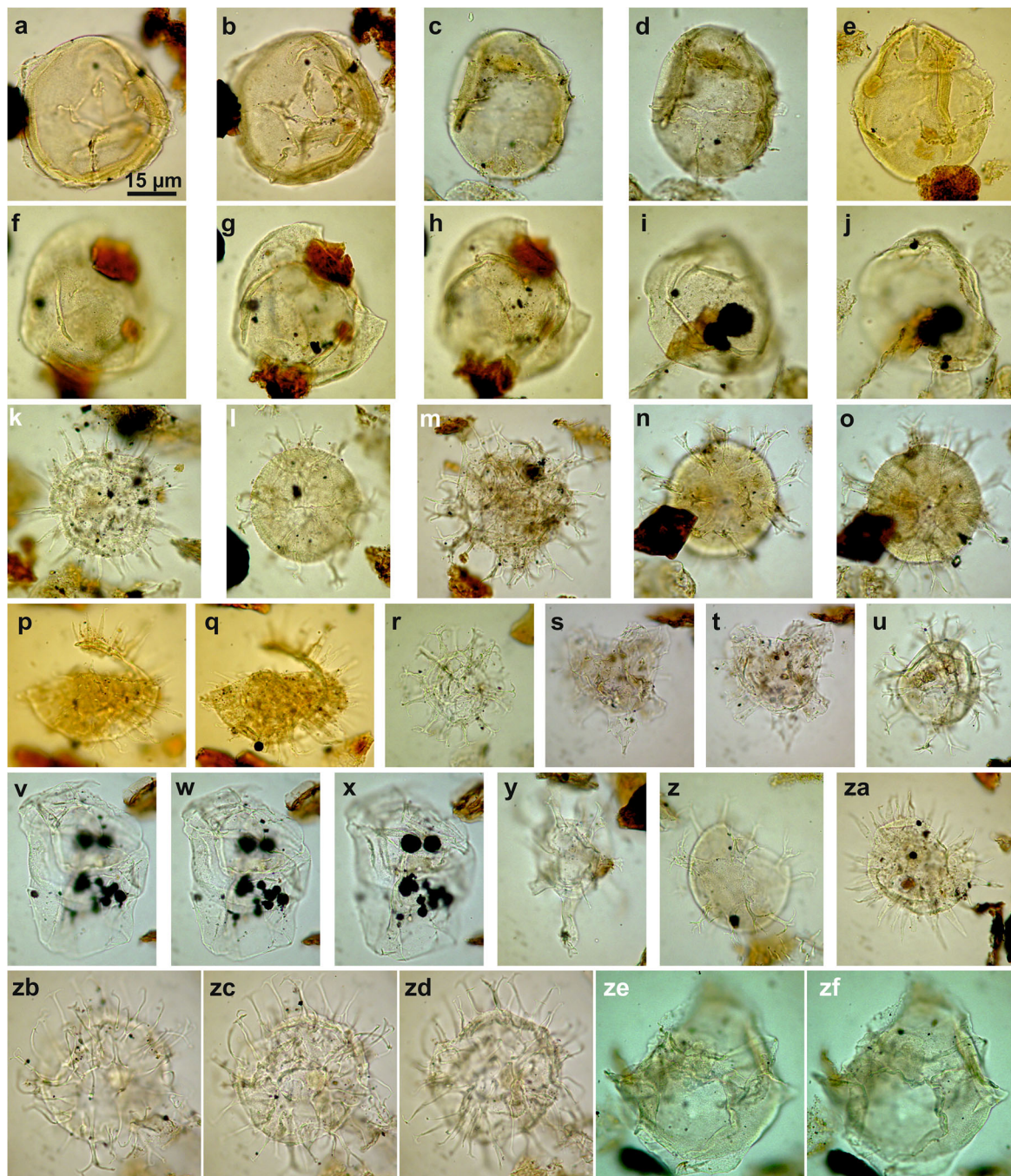
**Fig. 7** Dinoflagellate cysts from the Babczyn 2 borehole (scale bar in **a** refers to all other photomicrographs; photo by P. Gedl). **a** *Reticulatosphaera actinocoronata*; **b** *Labyrinthodinium truncatum*; **c** *Labyrinthodinium truncatum*; **d, e** *Labyrinthodinium truncatum* (same specimen, various foci); **f, g** *Lejeunecysta* sp. (same specimen, various foci); **h, i** *Lejeunecysta* sp. (same specimen, various foci); **j** *Lejeunecysta* sp.; **k–m** *Melitasphaeridium choanophorum* (same specimen, various foci); **n** *Melitasphaeridium?pseudorecurvatum*; **o** *Melitasphaeridium?pseudorecurvatum*; **p** *Melitasphaeridium?pseudorecurvatum*; **q, r** *Melitasphaeridium?pseudorecurvatum* (same specimen, various foci); **s** *Impagidinium?aculeatum*; **t** *Impagidinium?aculeatum*; **u, v** *Nematosphaeropsis* sp. (same specimen, various foci); **w, x** *Operculodinium?* sp. (same specimen, various foci); **y** *Melitasphaeridium choanophorum*; **z** *Pyxidinoopsis psilata*; **za** *Pyxidinoopsis psilata*; **zb, zc** *Pyxidinoopsis psilata* (same specimen, various foci); **zd** Gen. et spec. Indet. **a**: Sample 7; **b, d, e, s, y**: Sample 1; **c, j**: Sample 4; **f, g**: Sample 5; **h, i, n, o, u, v, z, zb–zd**: Sample 3; **k–m, t**: Sample 6; **p–r, w, x, za**: Sample 2





**Fig. 8** Dinoflagellate cysts from the Babczyn 2 borehole (scale bar in **a** refers to all other photomicrographs; photo by P. Gedl). **a, b** *Operculodinium centrocarpum* (same specimen, various foci); **c, d** *Operculodinium* sp. A, intermediate form to *O.* sp. B (same specimen, various foci); **e** *Operculodinium centrocarpum*, large morphotype with relatively short and sparse processes; **f, g** *Operculodinium* sp. A (same specimen, various foci); **h** *Operculodinium* sp. B; **i** *Operculodinium* sp. B; **j** *Operculodinium centrocarpum*; **k–m** *Spiniferites pseudofurcatus* (same specimen, various foci); **n** *Operculodinium centrocarpum*; **o, t** *Operculodinium centrocarpum*, large morphotype with relatively short and sparse processes (same specimen, various foci); **p–r** *Spiniferites* sp., morphotype with high parasutural ridges (same specimen, various foci); **s** *Operculodinium centrocarpum*, small morphotype with smooth cyst wall; **u–w** *Systematophora placacantha* (same specimen, various foci); **x, y** *Systematophora placacantha*, morphotype with reduced proximal ridges, similar to *S. ancyrea* (same specimen, various foci); **z–zb** *Systematophora placacantha* (same specimen, various foci); **zc, zd** *Systematophora placacantha* (same specimen, various foci). **a, b, k–m, p–r**: Sample 7; **c–e, j**: Sample 6; **f, g, x, y**: Sample 4; **h, i, n**: Sample 2; **o, t, z–zd**: Sample 3; **s**: Sample 1; **u–w**: Sample 5





**Fig. 9** Dinoflagellate cysts from the Babczyn 2 borehole (scale bar in **a** refers to all other photomicrographs; photo by P. Gedl). **a, b** *Pentadinium* sp., species with reduced periphagmal ridges (same specimen, various foci); **c, d** *Pentadinium* sp. (same specimen, various foci); **e** *Pentadinium* sp.; **f–h** *Pyxidinospis?* sp., large species devoid of any parasutural features except for 1P archaeopyle (same specimen, various foci); **i, j** *Pyxidinospis?* sp. (same specimen, various foci); **k** *Lingulodinium machaerophorum*; **l** *Spiniferites* sp., species with thick, spongy cyst wall; **m** *Spiniferites* sp.; **n, o** *Spiniferites* sp., species with thick, spongy cyst wall (same specimen, various foci); **p, q** *Lingulodinium machaerophorum*, specimen with 5P archaeopyle (same specimen, various foci); **r** *Spiniferites ramosus*; **s, t** *Hystrichokolpoma* sp. (same specimen, various foci); **u** *Spiniferites ramosus*; **v–x** *Hystrichosphaeropsis obscura*, specimen with granular endophragm, and periphragm bearing small, irregularly distributed spines on hypocyst (same specimen, various foci); **y** *Hystrichokolpoma* sp.; **z** *Achomosphaera* sp.; **za** *Lingulodinium machaerophorum*; **zb–zd** *Systematophora placacantha*, complete specimen with operculum, disruption suture visible in **zd** (same specimen, various foci); **ze, zf** *Pentadinium laticinctum* (same specimen, various foci). **a–d, z**: Sample 6; **e**: Sample 5; **f–l**: Sample 3; **m–q, s–u, za**: Sample 4; **r, v–y**: Sample 1; **zb–zf**: Sample 2

**Table 2** Distribution of dinoflagellate cysts and acritarchs (asterisked are reworked species). x – Appearance of a taxon beyond the count. Total count includes taxa presumed to be in situ only

[illegible]

(Richter 1964; Zaninetti 1982; Murray 1991, 2006; Alve and Murray 1999). *Elphidium* spp., *Rosalina obtusa* and hauerinids, common in the material, are epifaunally living species preferring well-oxygenated environments (Langer 1993; Hayward et al. 1997; Alve and Murray 1999). Deep infaunally living foraminifers, indicators of dysoxic environments, are not recorded in the material.

Taxonomically impoverished foraminiferal assemblages, dominated by a few species with very small sizes, indicate adverse environmental conditions (e.g. Bernard 1986; Murray 1991, 2006; Sen Gupta and Machain-Castillo 1993; Hayward et al. 1997).

Nonionids, represented in the material by *Nonion parvus* and *Haynesina depressula*, are infaunal organisms, widespread in marginal marine environments, common in sediments with highly variable mud and total organic carbon (TOC) contents (Murray 1968, 2006; Alve and Murray 1999; Vaniček et al. 2000). *Haynesina* tolerates lower salinity (0–30‰), while *Nonion* prefers normal marine salinity (Murray 1991). *Ammonia*, an opportunistic genus widespread in marginal marine environments worldwide (Walton and Sloan 1990; Murray 1991, 2006; Buzas-Stephens et al. 2003), is common in sediments with highly variable mud and TOC contents and able to tolerate low oxygen for several days (Moodley and Hess 1992; Murray 2006). The genus is represented, in the material, by *A. parkinsoniana* and *A. tepida* with common transitional forms. Their environmental requirements are quite well-recognized, which enables to interpret environmental changes. The two species – common to abundant in the foraminiferal assemblages – are well adapted to salinity-stressed conditions (Fiorini 2004).

Assemblages dominated by the two species are characteristic of environments strongly influenced by fluvial

waters. *A. tepida* is a typical species of river-dominated shelves, benefited from a noticeable input of riverine phytodetritus to the sediment and the most tolerant for high organic matter supply (Debeney et al. 2009). The significant changes in relative abundance in the *Ammonia* spp. group throughout the interval may indicate changes in salinity and oxygenation of bottom waters.

The benthic foraminiferal assemblages in the interval are dominated by a few infaunal species preferring muddy or clayey substrate for living, brackish to normal marine salinity, and inner shelf depths. Planktonic foraminifera recorded in the material are indicators of shallow and cool water (Bicchi et al. 2003). However, their scarcity in the material studied may indicate that they did not live there but they were transported by waves from deeper part of the sea. Shallow, cool water with slightly lowered oxygenation at the bottom and a slightly hyposaline to normal salinity marine environment is thus concluded for the foraminiferal assemblage from the marly intercalation in the Badenian gypsum.

No indications of salinity fluctuations have been recorded throughout the interval. Although the predominance of terrestrial elements in the composition of dinoflagellate cysts points to an intense influx from neighbouring land, pollen grains could be airborne. Higher proportions of cuticles (samples from the upper part of succession), especially large-sized, can be associated with source proximity and/or increased intensity of terrestrial input. However, freshwater algae occur in none of these samples. Lack of peridinioids commonly associated with nutrient-rich estuarine or upwelling environments additionally excludes freshwater input and points rather at oligotrophic conditions in the water column (photic zone).



## 6 Discussion

As the Badenian evaporite basin was located in a depression in which the brine top level occurred below the contemporaneous sea level, it could be subject to rapid flooding when the sea level rose or when the physical barrier blocking this basin from the Tethys/Paratethys reservoir was temporarily removed (Peryt 2006). The connection of the Carpathian Foredeep Basin with the marine reservoir was short-lived. After such environmental change, benthic foraminifers started to colonize a new, previously defaunated niche, and the pattern of benthic foraminiferal colonization is similar in each case to that related to the reflooding terminating the Badenian Salinity Crisis (cf. Szczechura 2000; Peryt and Peryt 2009; Gedl and Peryt 2011). This refers in particular to the poorly diversified, small and strongly abraded foraminifera occurring just above the gypsum in the Jamnica S-119 borehole section (located some 100 km WNW of the Babczyn 2 borehole) and described by Szczechura (2000). She concluded that a dominance of infaunal elements in the assemblage, as well as the state of preservation of the tests and their low diversity, indicates oxygen-deficient conditions and/or insufficient  $\text{CaCO}_3$  saturation. Peryt et al. (2004) recorded an impoverished foraminiferal assemblage dominated by *Nonion* and *Haynesina* from siliciclastic deposits, overlying gypsum deposits, of the Ptashkino section (East Crimea, Ukraine). They interpreted this assemblage as typical for a shallow water marsh or lagoon environment with a decreased salinity. Thus, it seems that the foraminiferal assemblage of the Babczyn 2 borehole represents a typical late Badenian pioneer, colonizing assemblage. Palynofacies and dinocysts from Jamnica S-119 borehole (Gedl 1999) and Babczyn 2 borehole also show similarities. In Jamnica S-119 borehole, continental elements dominate the assemblages coming from the lower part, and marine elements (dinocysts) start to be more common above it. The dinocysts assemblages are also similar in both sections – they are characterized by lack of *Polysphaeridium*. *Leiosphaeridia* appears in Jamnica S-119 borehole in the sample from the depth interval of 257–258 m, but its more common occurrence was noted in the sample from the depth of 255–256 m (Gedl 1999), which is a counterpart of samples from the upper part of the Babczyn 2 borehole clay intercalation in gypsum.

The marly clay intercalation of the Babczyn 2 borehole intercalation, containing crushed mollusc (*Modiolus*?) shell fragments, was previously interpreted by Śliwiński et al. (2012) as karst cavity infilling. The middle Miocene karstification of Badenian gypsum deposits of the Carpathian Foredeep occurred in two phases: soon after gypsum deposition and then after deposition of the lower series of the Pecten clays with *Neobulimina longa* (see Osmólski 1976, with references therein). However, there

is no proof that the marly clays in the uppermost part of the gypsum sequence of the Babczyn 2 borehole represent karst cavity infilling. The composition of the micro-palaeontological assemblages differs both from those recorded in the strata overlying gypsum deposits at Shchyrets (Peryt et al. 2014) and from the assemblages of the Pecten beds in the Babczyn 2 borehole.

It remains enigmatic, however, why no such intercalations of marine clays have been reported from elsewhere. One possible explanation is that the upper parts of the gypsum sequence have been eroded prior to the onset of deposition of the Late Badenian Ratyn Limestone and/or marine clays. In the final stages of the Badenian Salinity Crisis, gypsum beds that previously accumulated along the basin margins became then exposed, leading to reworking of clastic gypsum into the deeper basin (Kasprzyk 1993; Peryt 1996, 2000; de Leeuw et al. 2018). As the result, the marine facies of the Ratyn Limestone in western Ukraine overlies various gypsum units (even the equivalent of unit 'e' in southern Poland – see Peryt 1996: Fig. 4). Consequently, it is probable that the intercalations of marine clays escaped from the erosion in few cases only (e.g., clays deposited in local depressions). In addition, the Pecten Beds bear intercalations of clastic gypsum and this indicates a partial erosion of the marginal gypsum before and during deposition of these strata (Śliwiński et al. 2012).

## 7 Implications

The marine salina model is successfully applied for the Fore-Carpathian Basin (Peryt 2001, 2006, 2013b; Bąbel 2004, 2007; Cendón et al. 2004). It assumes that the Badenian evaporite basin was located in a depression in which the brine top level occurred below the contemporaneous sea level, and it was supplied with seawater seeping through a barrier that separated the basin from the sea or overflowing it occasionally in the form of short-lived marine transgressions. Consequently, it was in fact a saline lake supplied with marine water (Bąbel 2007) as far as the Polish and Ukrainian parts of the basin are concerned. Sedimentary history of the Badenian gypsum suggests two major salinity rises (and hence two saline cyclothems were recognized in the Carpathian Foredeep Basin – see Bąbel 1999b, with references therein) and several marine influxes causing partial reworking and/or dissolution of pre-existing gypsum (Kasprzyk 1999, with discussion therein).

As discussed by de Leeuw et al. (2018), global sea-level generally remained low during the Badenian Salinity Crisis although some of the modelled short-term global highstands may have temporarily increased the connectivity of the Central Paratethys with the global ocean, leading to a decrease in its salinity as indicated



by the short-lived return of normal marine foraminifera in the Borków section (Peryt 2013a). Accordingly, during eustatic sea-level rise or tectonically triggered modification of the barrier between the open sea and the Carpathian Foredeep Basin, new marine water could enter this depression and bring with it a temporary pulse of marine fauna (Peryt 2001). However, this not necessarily led to the origin of microfauna-bearing strata, as described by Peryt (2013a) and in this paper, or to thin discontinuous lenticular limestone characterized by Peryt (2001), which is equivalent to unit 'h' in southern Poland (Kasprzyk 1993) and the marker bed 2 in western Ukraine (Peryt 2001). The unit clearly indicates considerable brine dilution and is mostly developed as clastic, laminated and redeposited gypsum forming an intercalation within a sabre gypsum unit. In western Ukraine the intercalation is passing shoreward into thin lenticular marine limestone indicating that this brine-dilution was not triggered by a climatically controlled influx of meteoric waters which have earlier caused the basinwide changes in salinity in most of the Carpathian Foredeep Basin, making possible the successful application of the event-stratigraphy methods (Bąbel 1999a, 1999b, 2005; Bąbel and Bogucki 2007; Peryt 2001, 2006). On the other hand, given the size of the Carpathian Foredeep Basin that is the largest European foredeep basin (see Oszczypko et al. 2006), no wonder that there are differences in the development of the gypsum facies between the western and eastern parts of the foredeep (Peryt et al. 1997; Peryt 2013b; Wysocka et al. 2016). In the westernmost part of the Badenian evaporite basin, in Moravia, clay intercalations and large pore structures between the selenite crystals occur (Peryt et al. 1997). The majority of the Moravian gypsum sequence is interpreted as originated in deeper, density-stratified waters, with a seawater layer present, as evidenced by the occurrence of an assemblage of Serravalian planktonic foraminifers in many parts of the gypsum sequence (Peryt et al. 1997: Fig. 7). The water circulation pattern in the Badenian evaporite basin of the Central Paratethys was quite complex: antiestuarine brine circulation is assumed for the Early and mid-Badenian (Báldi 2006), including the time interval of evaporite deposition (Bąbel and Becker 2006). In the Late Badenian, a reversal of circulation to estuarine type occurred (Báldi 2006). Relatively common microfossils found in clay intercalations within gypsum along the northern Carpathian Foredeep, in particular in Moravia, strongly suggest that there existed, as compared to the current reconstruction, an additional inflow channel. This channel was supplying the Polish Carpathian Basin from the south during

the evaporite deposition and probably in the 300 kyr following, during the generally low global sea-level (de Leeuw et al. 2018).

## 8 Conclusions

- 1) Short-lived temporary connections between the Central Paratethys and the Mediterranean existed during the middle Miocene Badenian Salinity Crisis.
- 2) This was facilitated by the palaeogeographical context, in particular by the location of the Badenian evaporite basin below the contemporaneous sea-level, and by the geotectonical context.
- 3) One of such connections left behind marine microfossils in a marly clay intercalation in the uppermost part of the gypsum sequence in SE Poland.
- 4) Both foraminiferal and dinoflagellate assemblages indicate brackish to normal marine salinity at inner shelf depths; however, dinoflagellate cyst assemblages that tolerate increased salinity are missing.
- 5) Marine palynomorphs (dinoflagellate cysts) and foraminiferal assemblages indicate a marine depositional environment of marly clay intercalation within gypsum sequence.
- 6) At the same time they strongly suggest that there existed additional, compared to the assumed so far, channels for marine organisms migration.

## Abbreviations

AOM: Amorphous organic matter; TOC: Total organic carbon

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## Authors' contributions

DP and TMP measured the section studied and collected the samples. DP identified and analyzed the foraminiferal assemblages and PG identified and analyzed the palynofacies and dinoflagellate cysts. The figures were prepared by DP (Figs. 3, 4 and 5 and a part of Fig. 6), PG (Figs. 7, 8 and 9 and a part of Fig. 6) and TMP (Figs. 1 and 2). The tables were done by DP (a part of Table 1) and PG (a part of Table 1, and Table 2). DP, PG and TMP drafted the manuscript. TMP did the final version of the manuscript that was then read and approved by DP and PG.

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## Availability of data and materials

The datasets and material analyzed in this study are available from the first two authors upon reasonable request.

## Competing interests

The authors declare that they have no competing interests. All authors have approved this manuscript and no author has financial or other contractual agreements that might cause conflicts of interest.

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