

DINOFLAGELLATE CYSTS FROM THE PALAEOGENE OF THE ŁUKOWA-4 BOREHOLE (CARPATHIAN FOREDEEP, SE POLAND): BIOSTRATIGRAPHY AND PALAEOENVIRONMENT

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Abstract: This paper documents the presence of Eocene marine strata in the Carpathian Foredeep area in Poland. Assemblages of marine dinoflagellate cysts have been found in sands penetrated by the Łukowa-4 borehole below the Miocene succession of the foredeep. Their age is interpreted as Late Eocene. The presence of marine strata of this age in this area sheds new light on the palaeogeography of the Carpathian foreland during the Late Eocene. The dinoflagellate cysts described are compared with coeval Carpathian and epicontinental assemblages; possible connections between these two basins are discussed. Phylogenetic deposits that occur above the marine sands of the Łukowa-4 borehole contain freshwater palynomorphs, indicating their swamp and lacustrine origins. The overlying sand contains impoverished dinoflagellate cyst assemblages; their age is discussed.

Key words: Dinoflagellate cysts, Eocene, Palaeogene, biostratigraphy, palaeoenvironment, Carpathian Foredeep.

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INTRODUCTION

The Carpathian Foredeep Basin (Fig. 1) was formed at the front of north-migrating Carpathian nappes during the Early–Middle Miocene orogenic phase; it is filled with mainly Middle Miocene fine clastic deposits, 200–300 m thick in the western part of the Polish sector, and over 2 km thick in its eastern part. The Miocene succession of the foredeep lies on a diverse substratum, e.g., Carboniferous, Jurassic, Upper Cretaceous, and locally Precambrian rocks. Earlier, during the Palaeogene, the area of the Carpathian foreland was believed to have been a land mass (e.g., Moryc, 1995), commonly known as the Meta-Carpathian Swell, that separated the Carpathian marine basin from the epicontinental sea of the Polish Lowlands. The beginning of its formation is dated by means of its youngest marine deposits, represented by the Upper Cretaceous (mainly Maastrichtian) strata. However, a precise reconstruction of Carpathian foreland history during the Palaeogene is difficult, owing to the scarcity of well dated deposits known from boreholes only. Some authors suggested the presence of marine Eocene and/or Oligocene deposits below the Miocene succession (e.g., Kowalewski, 1957; Kasiński and Piwocki, 1994), but these assumptions were based on lithological criteria only. The only palaeontologically documented marine deposits are the Oligocene sands in the Tarnogród area (Gedl, 2000; Myśliwiec and Śmist, 2006; Fig. 1). Palaeogene dinoflagellate cyst assemblages from glauconitic

sands of the Łukowa-4 borehole (Fig. 1) described in this paper, show that this part of the present-day Carpathian Foredeep was also flooded by the sea during the Late Eocene. The closest marine Eocene deposits of the epicontinental basin are evidenced at Roztocze (e.g., Buraczyński and Krzowski, 1994; Gaździcka, 1994; Gedl, 2014; Fig. 1). Palaeoenvironmental analysis of the phylogenetic deposits that overlie the marine sand shows that they accumulated in a freshwater environment; the dating of them, presented in this paper, aims at correlation with known coal-bearing strata at the base of the Carpathian Foredeep succession.

MATERIAL

The Palaeogene in the Łukowa-4 borehole was penetrated at a depth of 822.75–803.0 m (Fig. 2). It rests on Middle Jurassic sands (Figs 2, 3A) and is covered by marls of the Middle Miocene Baranów Beds. This almost 20 m-thick succession was cored in its lowermost and upper parts (the middle interval from 811–819 m intentionally was not cored). The lower interval includes a uniform 3.5 m-thick non-calcareous, dark grey-greenish, fine-grained sand with frequent bioturbation (819.0–822.75 m; Figs 2, 3); silt clasts of Middle Jurassic substratum occur in the basal 15 cm (822.6–75 m; Fig. 2). The upper cored interval (803–809 m; Fig. 2) consists of coal and coaly clay and loamy sand in its lower part (806.4–809.0 m; Figs 2, 4A–D), and whitish to

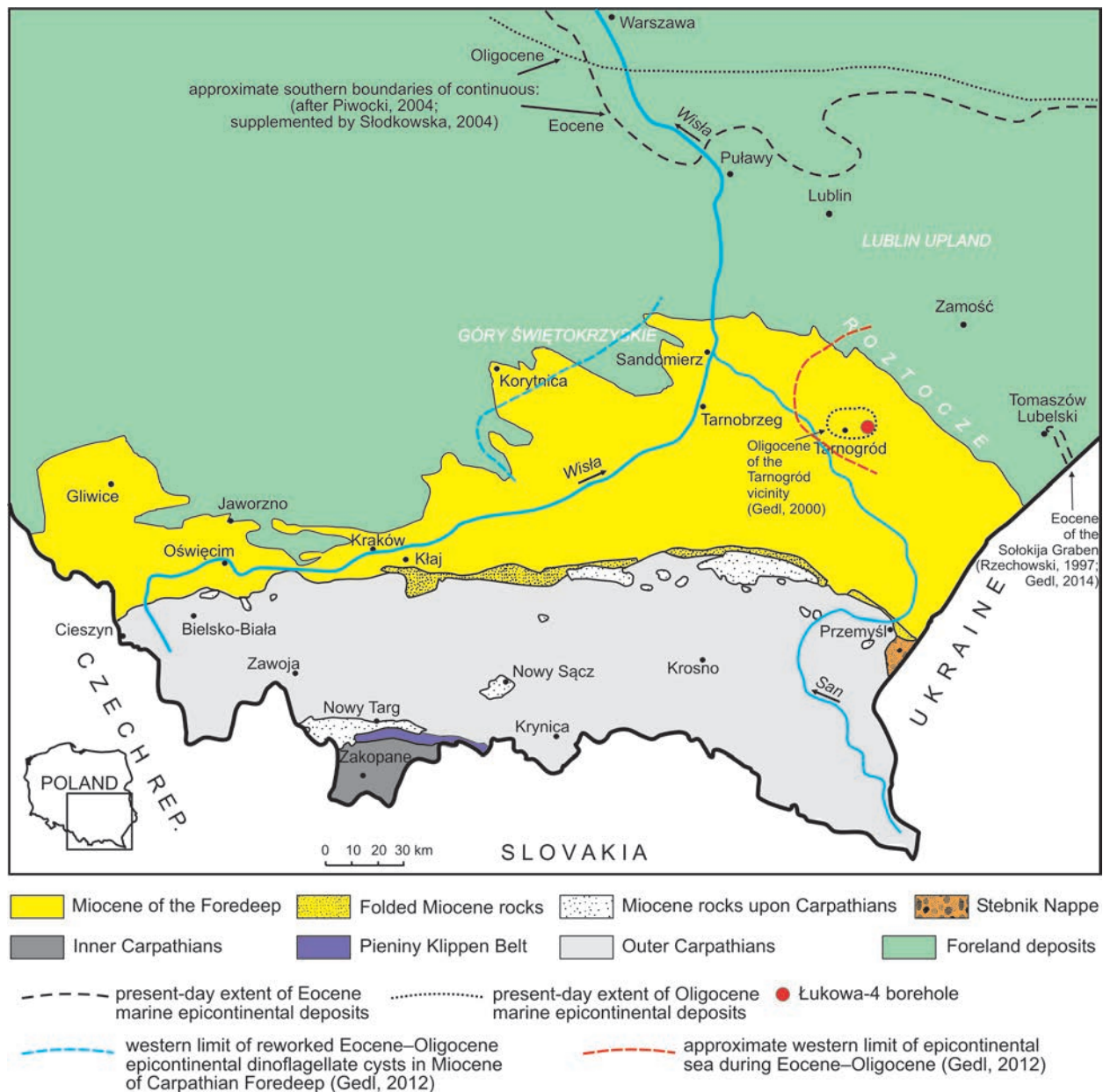


Fig. 1. Location of the Łukowa-4 borehole and simplified geological map of south-eastern Poland (from Gedl, 2012).

pale beigish-brownish, non-calcareous, fine- to medium-grained sand above it (803.0–806.4 m; Figs 2, 4D–H). The boundary between the phytogenic strata and overlying sands is sharp (Fig. 4D). There was no core recovery from the lower part of the planned 803–811 m coring interval; hence, no samples are available for the passage between the coals and the underlying sands; Myśliwiec and Śmist (2006, fig. 3) mistakenly draw this interval as cored.

METHODS

The samples were processed in the micropalaeontological laboratory of the Institute of Geological Sciences, Polish Academy of Sciences, Kraków. The palynological procedure applied included 38% hydrochloric-acid (HCl) treatment, 40% hydrofluoric-acid (HF) treatment, heavy-liquid

($\text{ZnCl}_2 + \text{HCl}$; density $2.0 \text{ g}\cdot\text{cm}^{-3}$) separation, ultrasound for 10–15 s and sieving at $10 \mu\text{m}$ on a nylon mesh. The organic residuum of organic-rich samples from the basal interval and coal was divided. A part was examined for palynofacies without any other treatment; another part was subjected to short-lasting (up to 10 s) nitric-acid (100% HNO_3 fuming) oxidation and analysed for dinoflagellate cysts.

The quantity of rock processed was variable, depending on the lithology: 120–200 g for sand samples and 10 g for phytogenic samples. Palynological slides were made from each sample, using glycerine 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.

Dinoflagellate cyst assemblages were analysed for their diversity; they were counted up to at least 300, except for samples from the topmost interval (pale-coloured sands

from the depths of 803.0–806.4 m), which contain impoverished assemblages. On this basis, the Shannon-Weaver diversity index (H') was calculated as: $H' = -\sum p_i \ln(p_i)$ where p_i is the relative abundance of each taxon; the Shannon-Weaver index was expressed as: $e^{H'}$ (Shannon and Weaver, 1949).

RESULTS

All samples yielded palynological organic matter, the quantity of which was highly variable. Samples from sand in the lower cored interval (820–822.75 m) contained larger amounts, except for the topmost sample (819.0–1 m) with distinctly less organic matter. Samples from phytogenic interval (806.4–809.0 m) were generally very rich in palynological organic matter, except for a single sample from black mud with sand-filled burrows (807.8 m), which yielded much lower amounts. The whitish sand that overlies the coaly interval (806.0–1 m) contained trace amounts of palynological organic matter; this increased slightly in the overlying darker sand (803–805.3 m).

Basal sand (819–822.75 m)

The palynofacies of the dark-coloured quartz sand is dominated by dark-brown phytoclasts, which are commonly black and opaque in their thickest central parts, being transparent at the edges (70–90% at average; Fig. 5C), and sporomorphs (10–20%); the latter are represented mainly by bisaccate pollen grains (Fig. 5E). Aquatic algae and dinoflagellate cysts occur in all samples studied; their proportions rarely exceed 1–2%. Short-lasting oxidation with concentrated nitric acid (HNO_3) led to the removal of most of the dark brown phytoclasts (Fig. 5A) leaving residues enriched in palynomorphs and cuticle remains (Fig. 5B). Their proportions are shown below.

Oxidized residues of all samples from this interval (except for the topmost sample from a depth of 819.0–1 m) are dominated by sporomorphs (40–60%) represented mainly by bisaccate pollen grains (up to 90% of the sporomorphs; Fig. 5D). Dark brown and black phytoclasts are up to 20–25%; small-sized phytoclasts of uncertain origin (palynodebris) represent a similar proportion. Aquatic elements are represented by prasinophycean algae (up to 10%) and dinoflagellate cysts (15%). The algae are diverse and consist of various species of *Leiosphaeridia*, *Cymatiosphaera*, *Tasmanites*, and others. Dinoflagellate cysts are also diverse with more than 90 identified taxa (their distribution is shown in Table 1, selected taxa are illustrated in Figures 6–8). Their assemblages are dominated by chorate gonyaulacoids represented by *Spiniferites ramosus* (and morphologically similar *Achomosphaera* sp.), *Homotryblum* (mainly *H. aculeatum*), *Operculodinium* (*O. centrocarpum*, *O. microtriainum*) and peridinioids represented by *Deflandrea* (*D. phosphoritica*, *D. heterophlycta*), *Charlesdownieag1033* (mainly *C. coleothrypta*), *Lejeunecysta serrata* and Peridinioid sp. A. The dinoflagellate cysts and algae are well-preserved; their walls are transparent and pale-coloured. However, especially the former frequently are mechanically damaged and the larger specimens are preserved as fragments only.

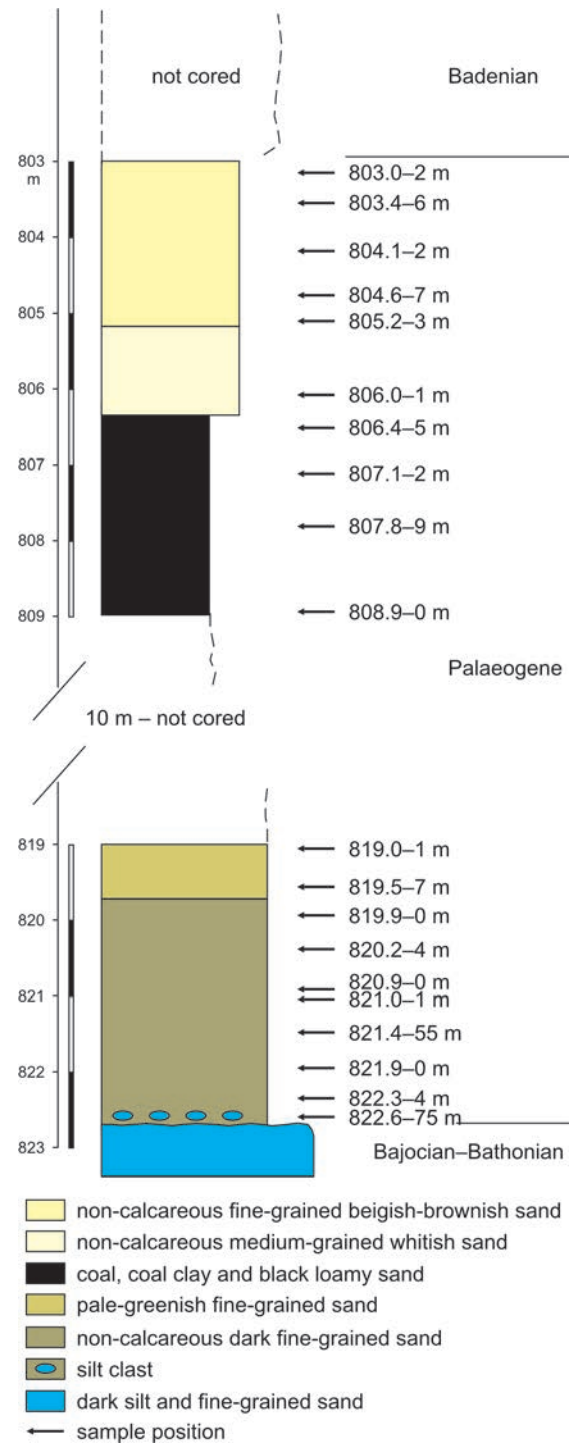


Fig. 2. Lithological log of the 803–823 m interval of the Łukowa-4 borehole and location of samples studied.

A different palynofacies was found in the non-oxidized residue from the sample from the topmost part of the cored sand interval (819.0–1 m; Fig. 5F). It consists of black opaque phytoclasts (60%; commonly with transparent edges), algae (30%) and sporomorphs (10%), represented by dark brown spores and mainly pale pollen grains. The green algae of this sample are mainly prasinophycean, and are taxonomically similar to the ones from the underlying deposits. They

Table 1 continued

Taxon	Lithology	dark quartz sands								coal		pale quartz sands										
		822.6-75	822.3-4	821.9-0	821.4-55	821.0-1	820.9-0	820.2-4	819.9-0	819.5-7	819.0-1	808.9-0	807.8-9	807.1-2	806.4-5	806.0-1	805.2-3	804.6-7	804.1-2	803.4-6	803.0-2	
53.	<i>Cribooperidinium tenuitabulatum</i>			3																		
54.	<i>Areosphaeridium michoudii</i>			1																		
55.	<i>Operculodinium?</i> sp.			1																		
56.	<i>Operculodinium divergens</i>			2	2	1		1	1	3												
57.	<i>Operculodinium tiara</i>			1	1																	
58.	<i>Hystrichosphaeridium?</i> sp.			1																		
59.	<i>Polysphaeridium zoharyi</i>			2		1		1	1	1												
60.	<i>Pentatidium lophophorum</i>			1		1																
61.	<i>Enneadocysta arcuata</i>			1	1	?	?	?														
62.	<i>Apteodinium</i> sp.			1																		
63.	<i>Cleistosphaeridium placacanthum</i>			1	1	1			1													?
64.	<i>Kallosphaeridium</i> sp.			1																		
65.	<i>Distatodinium ellipticum</i>			2		2	1			1												
66.	<i>Distatodinium virgatum</i>			1						1												
67.	<i>Elytrocysta?</i> sp.			1						1	1											
68.	<i>Cordosphaeridium</i> cf. <i>minimum</i>			1	3	1	2	2	1													
69.	<i>Batiacasphaera micropallata</i>			1		1																
70.	<i>Fibrocysta axialis</i>			1		1					2											
71.	<i>Distatodinium</i> cf. <i>craterum</i>			1																		
72.	<i>Araneosphaera araneosa</i>			1						1												
73.	<i>Spiniferites</i> cf. <i>pseudofurcatus</i>			1	1	1																
74.	<i>Hystrichokolpoma salacia</i>					1			1	1												
75.	<i>Hystrichosphaeropsis rectangularis</i>						1															
76.	<i>Operculodinium janduchenei?</i>						2			3	1											
77.	<i>Corrudinium incompositum</i>						1															
78.	<i>Achilleodinium biformoides</i>						1															
79.	<i>Operculodinium</i> sp. A sensu Gedl, 2013					2																
80.	<i>Diphyes colligerum</i>								1		1											
81.	<i>Cordosphaeridium</i> sp. A sensu Gedl, 2013								1	1												
82.	<i>Pyxidopsis</i> sp. C sensu Gedl, 2005								1													
83.	<i>Hystrichokolpoma cinctum</i>								2													
84.	<i>Rottnestia?</i> sp.								1													
85.	<i>Hystrichokolpoma unispinum</i>								1													
86.	<i>Phthanoperidinium amoenum</i>									1												
87.	<i>Hystrichostrogylon coninckii</i>									1												
88.	<i>Heterelaucacysta porosa</i>										1											
89.	<i>Thalassiphora delicata</i>										1											
90.	<i>Spiniferites pseudofurcatus</i>									1												
91.	<i>Enneadocysta pectiniformis</i>									1												
92.	freshwater dinoflagellate cysts											x										
93.	<i>Batiacasphaera?</i> spp.															27	9	18	5	12		
94.	<i>Impletosphaeridium?</i> sp.															8	3			9		
95.	<i>Homotryblium?</i> sp.															2				1		
96.	<i>Nematosphaeropsis</i> sp.															1	1					
97.	<i>Operculodinium</i> sp.															1		1		3		
98.	<i>Impletosphaeridium</i> sp.															1						
99.	<i>Surculosphaeridium longifurcatum</i>																1					
100.	<i>Circulodinium</i> sp.																1					
101.	<i>Apectodinium</i> sp.																		2			
102.	<i>Dapsilidinium</i> sp.																		1		1	
103.	<i>Selenopemphix nephroides</i>																					1
104.	<i>Vectidinium?</i> sp.																					1

? – uncertain occurrence due to fragmentarily preserved specimen; x – mass occurrence of presumably freshwater forms; not calculated, owing to taxonomical uncertainties

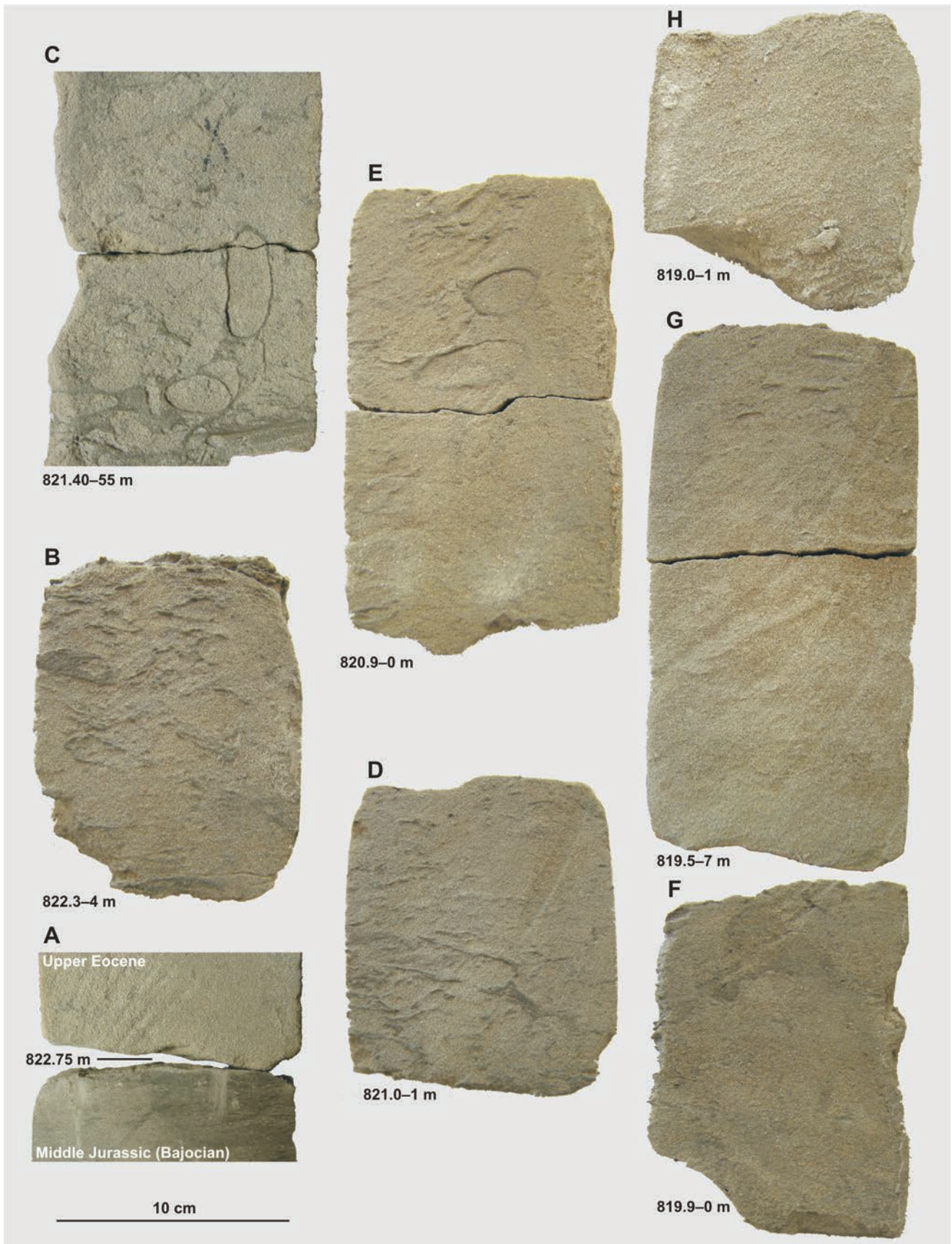


Fig. 3. Lithology of the basal sand from the lower cored interval 822–819 m. **A.** Boundary between the Middle Jurassic and Palaeogene at a depth of 822.75 m. **B–E.** Bioturbated (*Ophiomorpha?* isp.) non-calcareous dark grey-greenish sand from the basal part of the Eocene succession. **F, G.** Non-calcareous grey-greenish sand with infrequent traces of bioturbation. **H.** Pale-coloured non-calcareous fine-grained sand without traces of bioturbation.

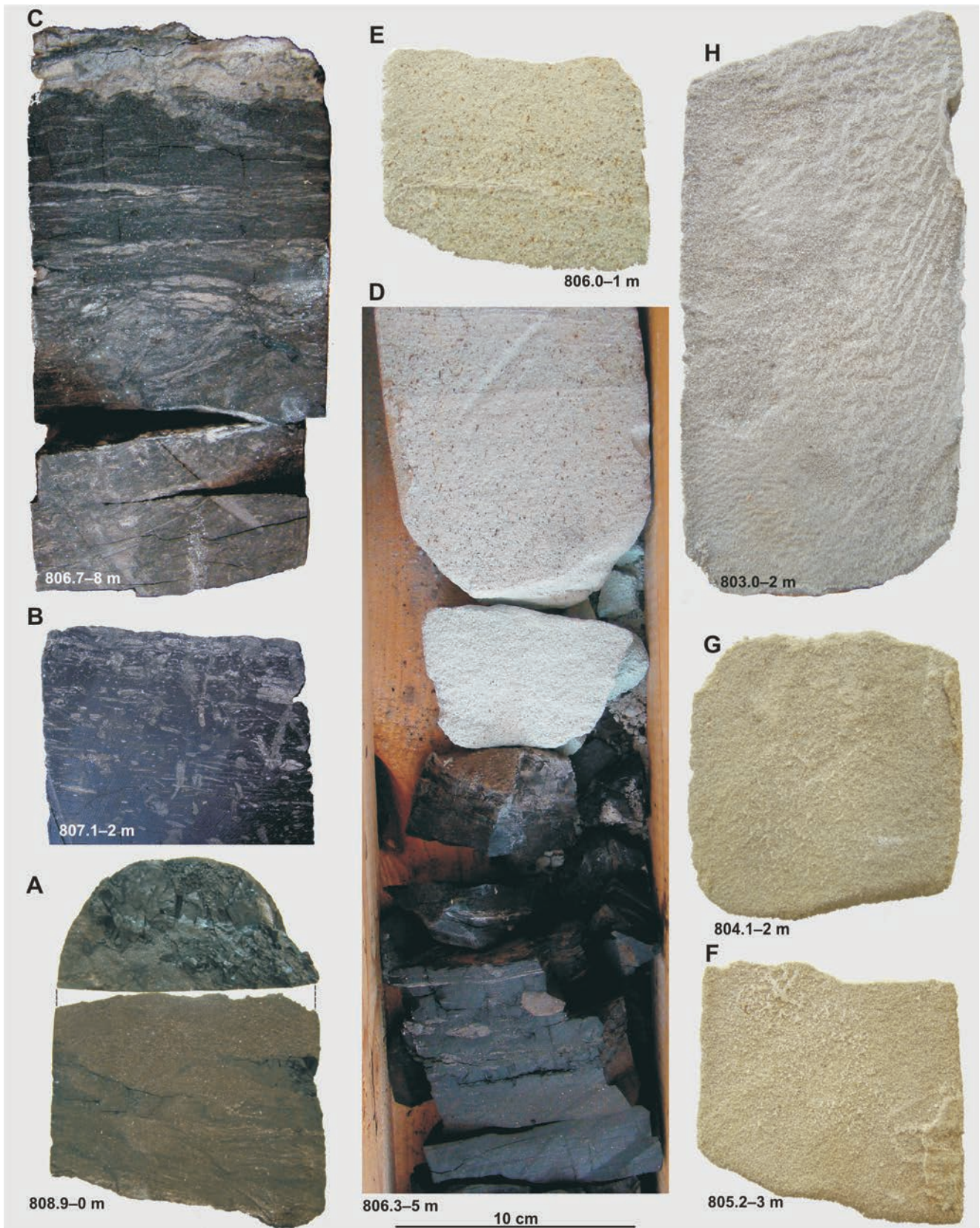


Fig. 4. Lithology of the upper cored interval 809–803 m, containing coal and overlying sand. **A.** Dark-brown silt and sand with coal lenses (lower photograph shows a cross-section, the upper one shows core surface with hyalinous coal lens). **B.** Black clay with bioturbations filled with white silt. **C.** Brown to black clay and silt with coal intercalations and layers and lenses of white silt. **D.** Sharp boundary between phytogenic strata (black clay and coal lenses in the lower part of the photograph) and overlying whitish to pale-wil-low-green medium-grained non-calcareous sand. **E–G.** Non-calcareous beigish-brownish fine-grained sand without sedimentological structures. **H.** Pale greyish, fine-grained sand.

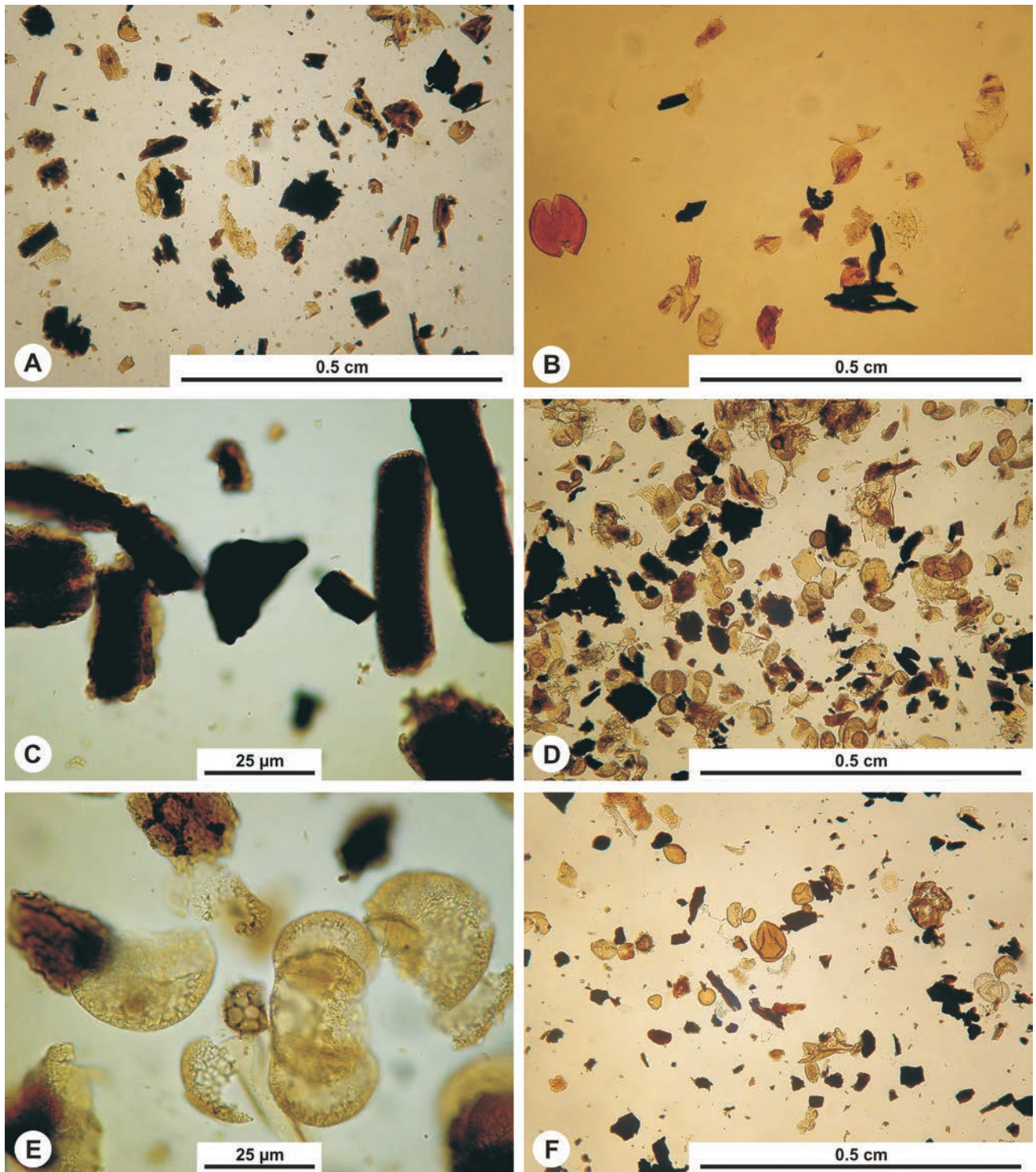


Fig. 5. Palynofacies of the lower cored interval 822–819 m. **A, B.** Comparison of palynofacies from the same sample (822.6–75 m) before (A) and after (B) HNO_3 treatment. **C.** Black opaque phytoclast (in centre) and black opaque phytoclasts with transparent edges (822.6–75 m). **D.** Palynofacies composed of black and dark brown phytoclasts, sporomorphs and dinoflagellate cysts characteristic for the bulk of basal sand succession at the depth interval of 822.75–819.5 m (sample 822.6–75 m). **E.** Bisaccate pollen grains and a prasinophycean alga *Cymatiosphaera* (in centre; sample 819.5–7 m). **F.** Palynofacies of sample from the depth 819.0–1 m composed of black opaque and dark-brown phytoclasts associated by prasinophycean algae and sporomorphs.

differ in having a slightly darker colour, due to lack of oxidation of this sample. Rare *Botryococcus* (Chlorococcales) occur. An outstanding feature is the almost complete lack of

dinoflagellate cysts – only one specimen of *Achomosphaera* sp. was found – very well preserved, pale-coloured (contamination?).

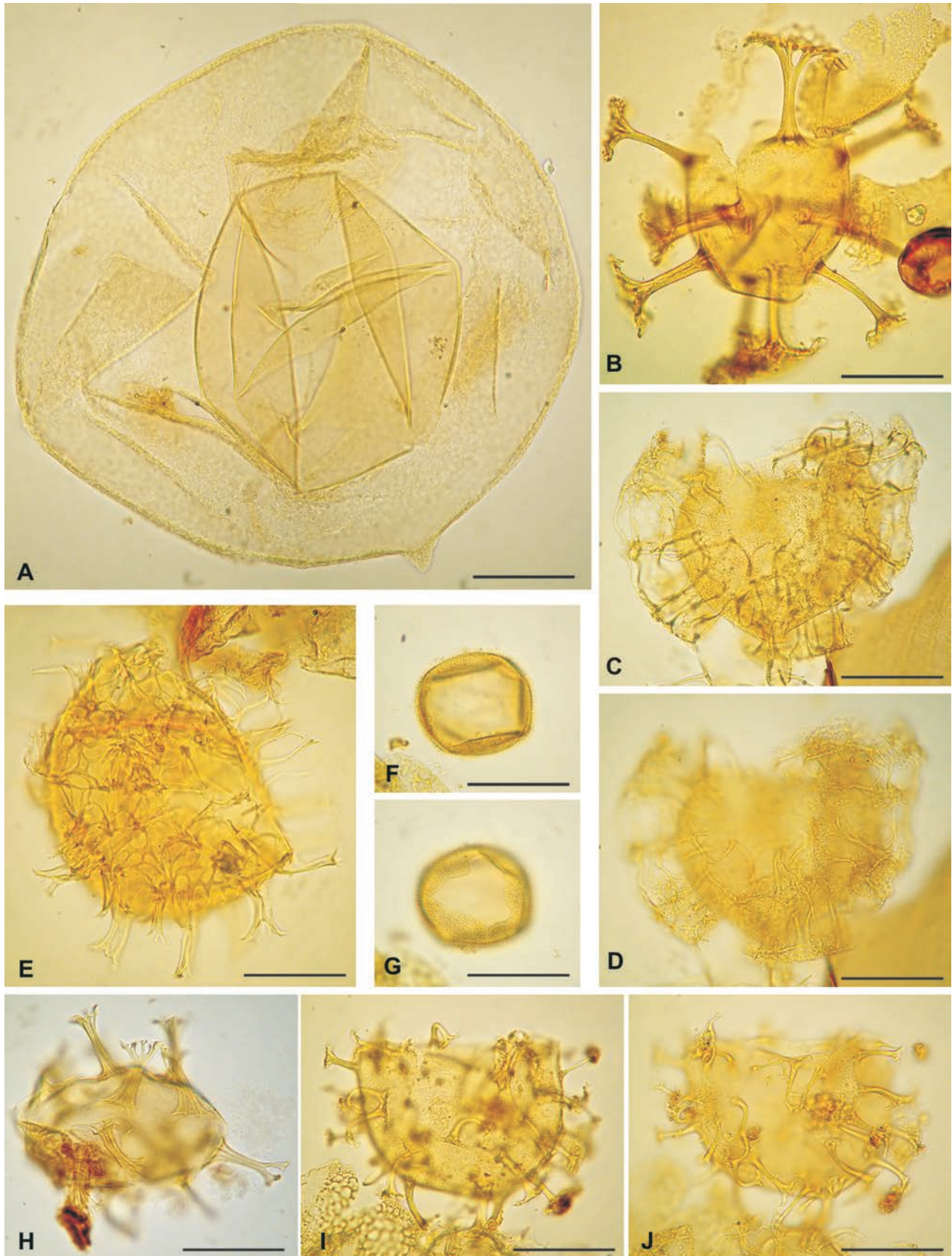


Fig. 6. Dinoflagellate cysts from the lower cored interval 822–819 m. Scale bars = 25 μ m. **A.** *Thalassiphora pelagica* (822.6–75 m). **B.** *Areosphaeridium michoudii* (821.9–0 m). **C, D.** *Glaphrocysta microfenestrata*: same specimen various foci (C – central body and process arrangement; D – distal process terminations showing their microperforations). **E.** *Operculodinium divergens* (821.4–55 m). **F, G.** *Batiacasphaera hirsuta*, same specimen, various foci (821.9–0 m). **H.** *Homotryblium floripes* (822.6–75 m). **I, J.** *Cleistosphaeridium* sp. *A sensu* Gedl, 2013, same specimen, various foci (821.4–55 m).

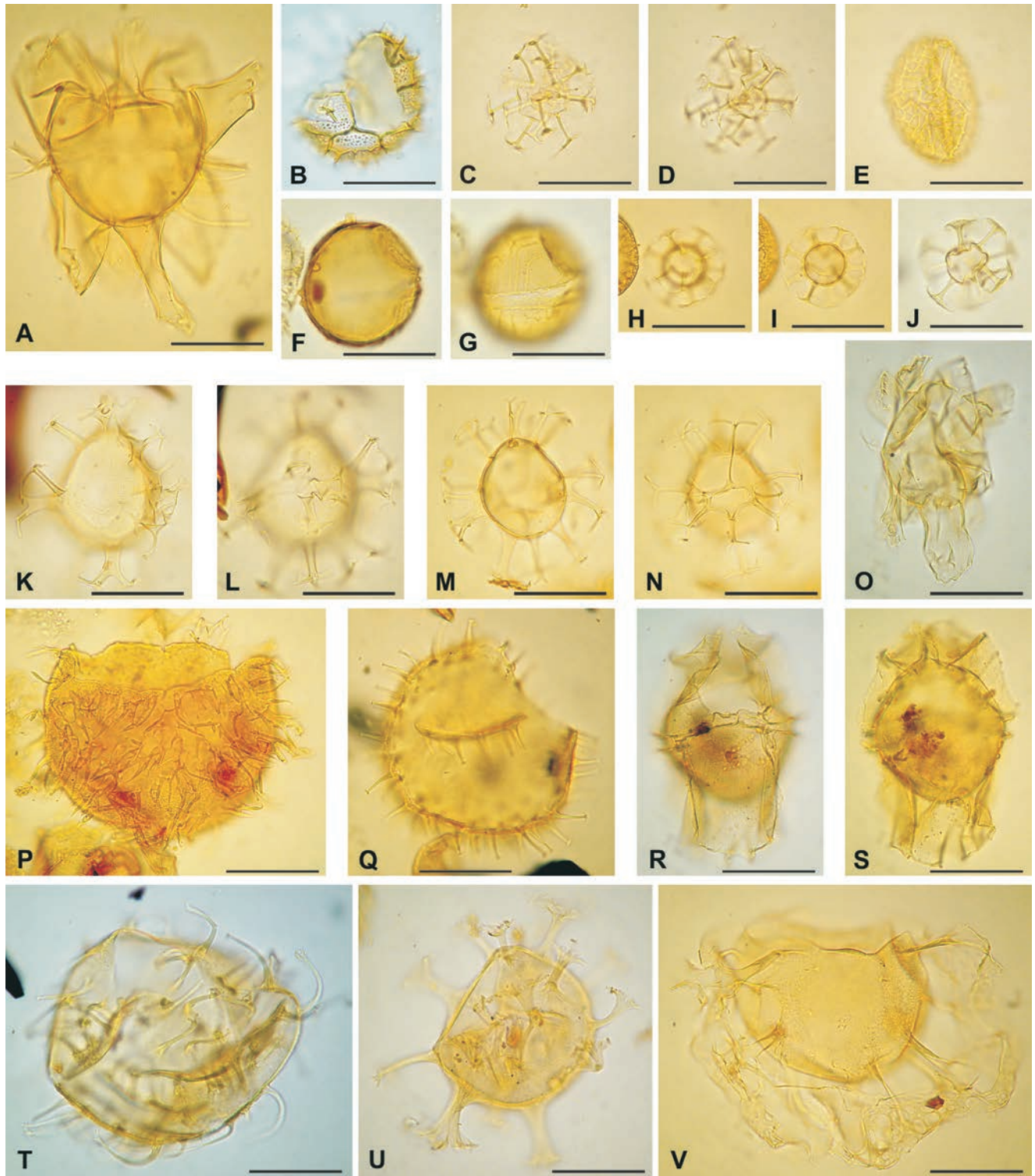


Fig. 7. Dinoflagellate cysts from the lower cored interval 822–819 m. Scale bars = 25 μ m. **A.** *Hystrichokolpoma cinctum* (820.2–4 m). **B.** *Corrudinium incompositum* (821.0–1 m). **C, D.** *Reticulosphaera actinocoronata*, same specimen, various foci (822.6–75 m). **E.** *Cerebrocysta bartonensis* (822.6–75 m). **F, G.** *Criproperidinium giuseppi*, same specimen, various foci (820.2–4 m). **H, I.** *Cordosphaeridium minimum*, same specimen, various foci (820.2–4 m). **J.** *Cordosphaeridium minimum* (820.2–4 m). **K, L.** *Achomospaera* sp., same specimen, various foci (821.4–55 m). **M, N.** *Spiniferites ramosus*, same specimen, various foci (820.2–4 m). **O.** *Hystrichokolpoma salacia* (820.2–4 m). **P.** *Heterosphaeridium* sp. A sensu Gedl, 2013 (821.9–0 m). **Q.** *Operculodinium centrocarpum* (821.4–55 m). **R, S.** *Hystrichosphaeropsis rectangularis*, same specimen, various foci (821.0–1 m). **T.** *Operculodinium microtriainum* (821.4–55 m). **U.** *Cordosphaeridium gracile* (822.6–75 m). **V.** *Glaphyrocysta semitecta* (820.2–4 m).

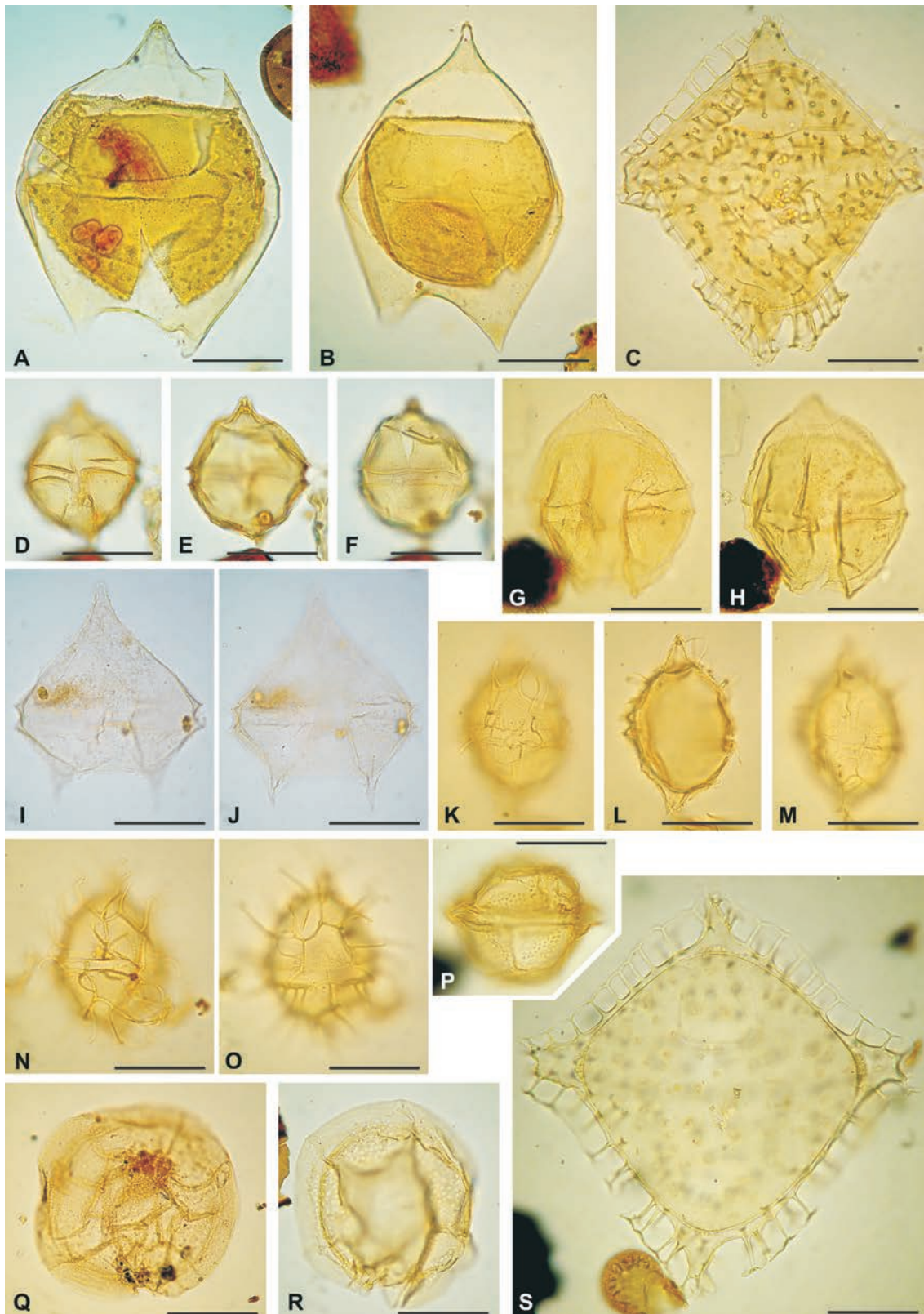


Fig. 8. Dinoflagellate cysts from the lower cored interval 822–819 m. Scale bars = 25 μ m. **A.** *Deflandrea heterophlycta* (821.0–1 m). **B.** *Deflandrea phosphoritica* (821.0–1 m). **C.** *Charlesdowniea clathrata* (822.3–4 m). **D–F.** *Phthanoperidinium?* *eocenicum*, same specimen, various foci (821.0–1 m). **G, H.** Peridinioid sp. A, same specimen, various foci: focus in G shows sculpture of periphragm covered with tubercles, whereas focus in H shows three intercalary adnate paraplates forming archaeopyle (821.9–0 m). **I, J.** *Lentinia serrata*, same specimen, various foci (821.0–1 m). **K–M.** *Phthanoperidinium comatum*, same specimen, various foci (821.4–55 m). **N, O.** *Phthanoperidinium comatum*, same specimen, various foci (821.4–55 m). **P.** *Dinopterygium cladooides*, a complete specimen in a lateral view (820.2–4 m). **Q.** *Heteraulacacysta leptalea* (820.2–4 m). **R.** *Heterelaucacysta* cf. *porosa* (820.2–4 m). **S.** *Charlesdowniea coleothrypta* (820.2–4 m).

Phytogenic deposits (806.4–809 m) and overlying sand (803–806.1 m)

Samples collected from this interval show variable palynofacies content (Fig. 9). Two basal coal samples (808.9–0 m and 807.8–9 m) yielded almost exclusively woody particles (Fig. 9A–C); these are large fragments, commonly with preserved structures (Fig. 9E), but at 807.8–9 m also frequently disintegrated to very small ones (Fig. 9D). At 808.9–0 m, equidimensional, dark-brown, massive woody particles occur, usually without clearly visible structures. A different palynofacies was noted in a higher sample from coal clay (807.1–2 m; Fig. 9G). This sample is dominated by *Botryococcus* (Fig. 9L) and thin-walled palynomorphs, presumably representing freshwater algae (Fig. 9H–K). *Botryococcus* dominates also in a higher coaly clay sample (806.4–5 m), but here it occurs as disintegrated fragments only (Fig. 9M); there are no other palynomorphs in this sample.

The overlying ca. 3 m-thick sand interval only includes small amounts of organic particles and yielded a generally uniform palynofacies. It is composed of predominant (70–80%) dark brown and black phytoclasts and 20–30% sporomorphs; the latter are mainly bisaccate pollen grains. Algae other than dinoflagellates attain 2–3% in samples from depths 803.0–2 m, 804.1–2 m, 804.6–7 m and 805.2–3 m; they are very rare in samples 803.4–6 m and 806.0–1 m. Their assemblages consist of well-preserved, diverse representatives of prasinophycean algae, such as *Tasmanites*, *Cymatospaera*, *Leiosphaeridia*, *Pterospermella*, and acritarchs, e.g., *Cystidiopsis*, *Micrhystridium* (note that a similar assemblage occurs in topmost sample of the lower sand interval; 819.0–1 m).

Dinoflagellate cysts are present exclusively in samples at 805.3–803 m from the sand interval (Fig. 10); the lowermost sample from the depth 806.0–1 m was barren. They are rare and taxonomically impoverished and show different stages of preservation. *Batiacasphaera?* spp. and *Spiniferites* are the most frequent and occur in all samples from this interval; they are pale-coloured, but commonly wrinkled or fragmented. Similarly preserved are less frequent specimens of *Operculodinium centrocarpum*, *Deflandrea ?phosphoritica*, *Impletosphaeridium?* sp., *Nematosphaeropsis* sp., *Homotryblium* sp., *Lingulodinium machaerophorum*, *Apectodinium* sp., and *Lentinia serrata*. Some specimens representing *Homotryblium* (*H. plectilum*, *H. tenuispinosum*), *Systematophora* sp., and *Dapsilidinium* sp. are evidently worse preserved, being dark-coloured. This contrasts with excellently preserved single specimens of *Charledownia coleothrypta*, *Deflandrea heterophlycta*, and *Homotryblium floripes* from sample 804.6–7 m; their mode of preservation resembles specimens from the basal sand interval (822–819 m) and may indicate either reworking of them or contamination.

INTERPRETATION

Biostratigraphy

Basal sand. Dinoflagellate cyst assemblages from the basal sand interval (822–819 m) indicate a late Priabonian–

earliest Rupelian age. This assumption is based on the co-occurrence of *Areosphaeridium diktyoplokum* and *Reticulatosphaera actinocoronata*. *A. diktyoplokum*, long believed to have disappeared at the Eocene-Oligocene boundary (e.g., Powell, 1992), is now considered to have crossed the boundary and became extinct during the earliest Rupelian (Brinkhuis, 1994; Williams *et al.*, 2004). *R. actinocoronata*, in turn, appeared for the first time during late Priabonian, both in Tethyan (Brinkhuis and Biffi, 1993; Brinkhuis, 1994) and Boreal (Heilmann-Clausen and Van Simaey, 2005; Thomsen *et al.*, 2012) realms. According to Williams *et al.* (2004), this species appeared in mid-latitudes of the Northern Hemisphere during chron C15, correlated by Berggren *et al.* (1995) with the topmost part of the *Porticulasphaera semiinvoluta* Interval Zone and lower part of the *Turborotalia cunialensis/Cribrohantkenina inflata* Concurrent-Range Zone (i.e., the middle part of the calcareous nannoplankton NP19–20 Zone).

More precise age dating is difficult and arbitrary, owing to the different age-ranging of some species in different areas. Lack of some “mid” Oligocene species, such as *Chiropteridium galea* and *Chiropteridium lobospinosum* that appeared for the first time during the late Rupelian (Biffi and Manum, 1988; Powell, 1992; Brinkhuis and Biffi, 1993; Brinkhuis, 1994; Stover *et al.*, 1996), excludes this age. The absence of some other species – *Areoligera semicirculata* and *Gerdiocysta conopeum* – could indicate an earliest Rupelian age: they appeared for the first time in the North Sea Basin in the earliest Rupelian (e.g., Van Simaey *et al.*, 2005, 2007; Śliwińska *et al.*, 2012). However, according to Williams *et al.* (2004), both species appeared for the first time in the mid-latitudes of the Northern Hemisphere in the latest Priabonian, and, thus, their absence may indicate a latest Priabonian age. *A. semicirculata* was found in Carpathians in the NP21 Zone (Gedl, 2005a). *Wetzeliiella gochtii*, another typical Early Oligocene species that is absent in the Łukowa-4 borehole, is known to occur in the uppermost Eocene of the Carpathians (Van Couvering *et al.*, 1981; Gedl, 2005a).

The absence of earliest and “mid” Rupelian species shows that basal sands of the Łukowa-4 borehole are older than the Rupelian strata described by the author from the Tarnogród area, which contain *Areoligera semicirculata*, *Chiropteridium galea*, *Chiropteridium lobospinosum* and *Wetzeliiella gochtii* (Gedl, 2000).

Another, indirect clue in favour of the latest Priabonian age of the deposits in question is a general regressive trend that took place during the earliest Oligocene (see Haq *et al.*, 1987). These interpretations allow the correlation of sands from the depth 819–822 m with mid and upper part of the NP19–20 Zone.

Coal and overlying sand. Coal samples yielded no marine dinoflagellate cysts; the one from depth 807.10 m contains some palynomorphs of uncertain origin, possibly freshwater forms (Fig. 9H–K). The lack of marine dinoflagellate cysts indicates that the age of the coal interval is unknown. Moreover, the lack of cored material between the coal and underlying sand intervals does not allow the tracing of a relationship between these two rock series. However, Słodkowska (in Myśliwiec and Śmist, 2006) described

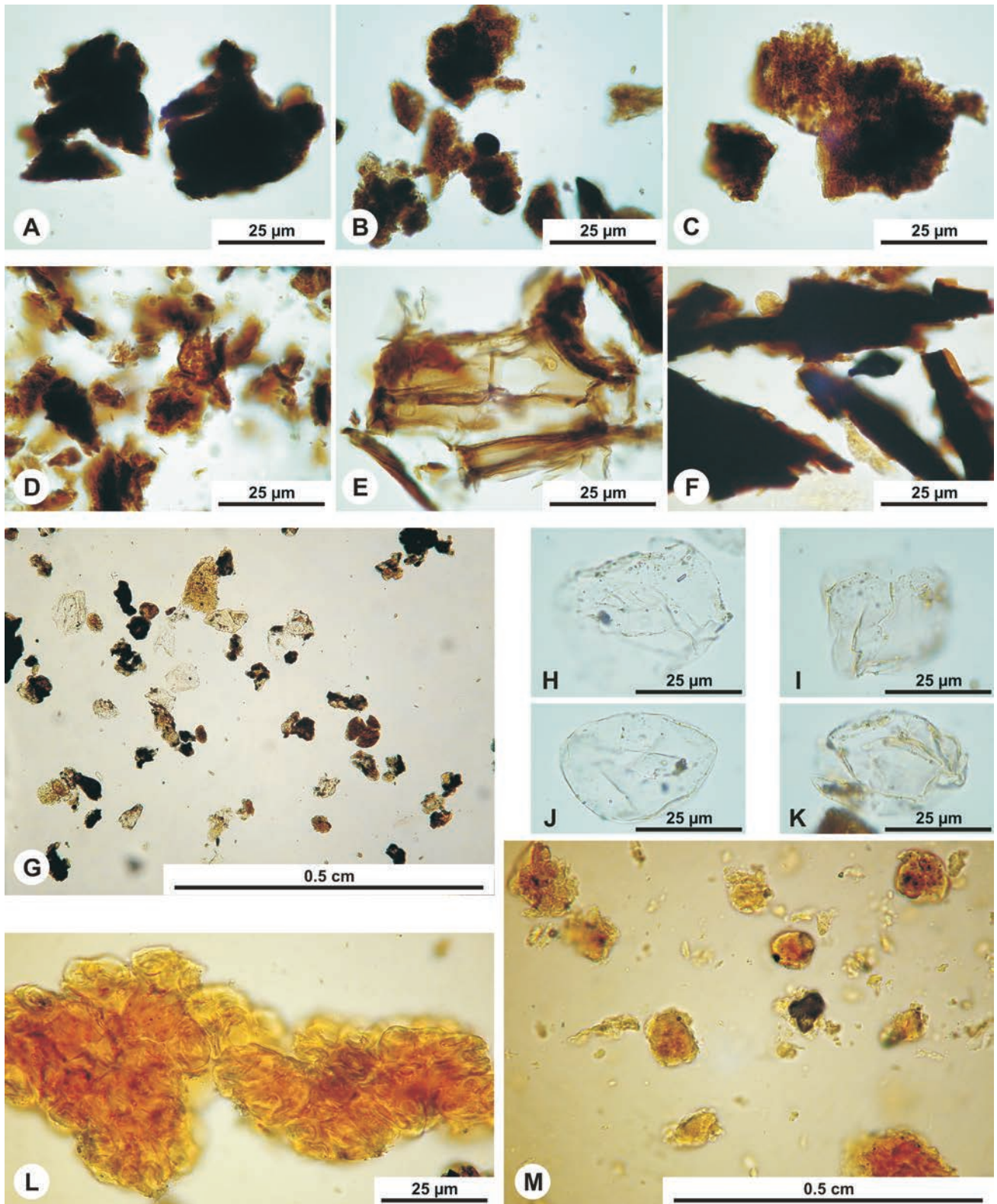


Fig. 9. Palynofacies, phytoclasts and palynomorphs of the upper cored interval 809–803 m. **A.** black massive phytoclast with transparent edges (808.9–0 m). **B, C.** Dark brown phytoclasts with poorly preserved tissue structures (808.9–0 m). **D.** Highly disintegrated woody particles (807.8–9 m). **E.** Land plant tissue fragment (807.8–9 m). **F.** Black and dark brown at the edges, elongated woody phytoclasts (807.8–9 m). **G.** Palynofacies of sample from the depth of 807.1–2 m with frequent subspherical hyalinous palynomorphs (see H–K). **H–K.** Palynomorphs of uncertain origin, presumably the freshwater dinoflagellate cysts (807.1–2 m). **L.** Freshwater colonial alga *Botryococcus* (807.1–2 m). **M.** Palynofacies of sample from the depth of 806.4–5 m, composed almost entirely of freshwater alga *Botryococcus*

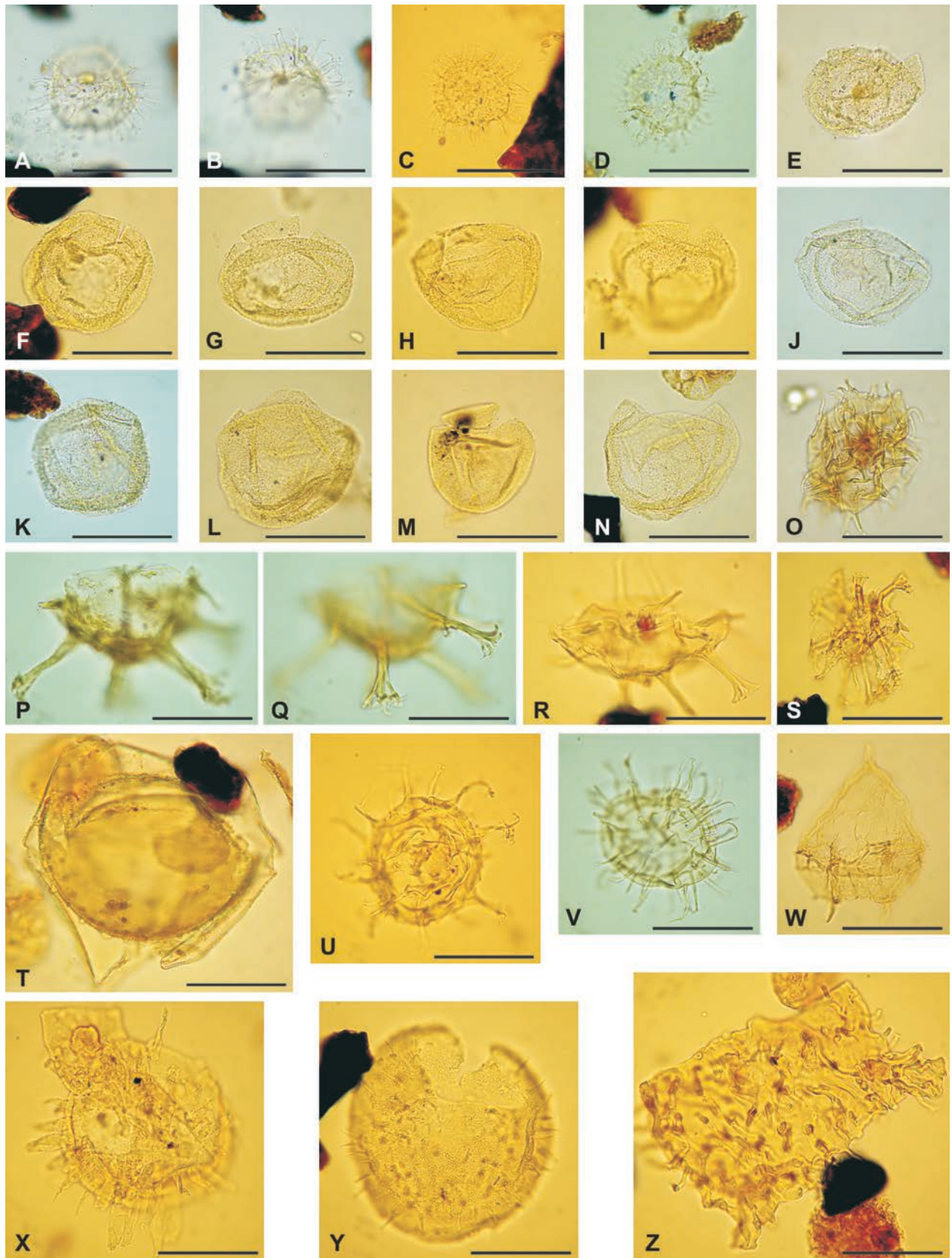


Fig. 10. Dinoflagellate cysts from the upper cored interval 809–803 m. Scale bars = 25 μ m. **A–D.** *Impletosphaeridium*? sp. (A, B – same specimen, various foci, 803.0–2 m; C – 804.6–7 m; D – 805.2–3 m). **E–N.** *Batiacasphaera*? spp. (E–K – 803.0–2 m; L – 804.1–2 m; M – 803.4–6 m; N – 805.2–3 m). **O.** *Apectodinium* sp. (804.1–2 m). **P, Q.** *Homotryblium*? sp. (805.2–3 m). **R.** *Homotryblium floripes* (804.6–7 m). **S.** *Reticulosphaera actinocoronata* – specimen with massive processes, atypical for this species (803.0–2 m). **T.** *Deflandrea heterophlycta* (804.6–7 m). **U.** *Spiniferites ramosus* (803.4–6 m). **V.** *Impletosphaeridium* sp. (805.2–3 m). **W.** *Lentinia serrata* (804.1–2 m). **X.** *Lingulodinium machaerophorum* (804.6–7 m). **Y.** *Operculodinium centrocarpum* (804.6–7 m). **Z.** *Wetzelia* sp. (804.6–7 m).

from this interval pollen grains *Fususpollenites fusus*, *Cas-taneoideaepollis pusillus*, *Engelhardtioipollenites quietus* and *Platanipollis ipelensis*, which according to her may be interpreted as indicators of an Oligocene age, although precise pointers to this age were missing among the pollen spectra.

The passage to the overlying sand series (803–806.1 m) is sharp; thus the contact is presumably erosional. The sands contain rare dinoflagellate cysts showing different degrees of preservation: poorly preserved ones are presumably recycled, whereas the excellently preserved single specimens of *Charlesdownia coleothrypta*, *Deflandrea heterophlycta* and *Homotryblum floripes* most likely are contamination, derived from Eocene sand below. Forms, which can be treated as *in situ* (*Spiniferites ramosus*, *Operculodinium centrocarpum*, *Batiacasphaera?* spp., *Impletosphaeridium* sp.), are rather non-diagnostic with regard to age.

The sand, as well as the underlying coal, could be Upper Eocene, Oligocene, or Lower Miocene. An Eocene age might be indicated by the presence of a single specimen of *Lentinia serrata* in the sample from 804.1–2 m, but on account of its scarcity it is presumably to be recycled. There is no evidence of an Oligocene age, as was seen in the neighbouring boreholes in the vicinity of Tarnogród (Gedl, 2000). There are neither typical Middle Miocene species, known from overlying Baranów beds (e.g., *Unipontidinium aquaeeductum*; Gedl, 1999a), nor Early Miocene species, such as *Tuberculodinium vancampoe*, known from the phytogenic Lower Miocene deposits of western Carpathian Foredeep (Gedl, unpubl.). Some indications of a Miocene age of the sand could be rare specimens of *Nematosphaeropsis*, a genus commonly occurring in the Middle Miocene of the Carpathian Foredeep (e.g., Gedl, 1996, 1999a, 2005b), but known also from Palaeogene strata (e.g., Gedl, 2004b).

Palaeoenvironment

Basal sand. The presence of marine dinoflagellate cysts in the basal sand interval (819–822 m) indicates a marine environment (Fig. 11). The lack of offshore species, such as *Impagidinium* and *Nematosphaeropsis* (see e.g., Brinkhuis, 1994), indicates that these sands accumulated in a relatively proximal sedimentary setting; moreover, presence of common *Homotryblum* specimens, a genus believed to have inhabited lagoonal waters with increased salinity (e.g., Köthe, 1990; Brinkhuis, 1994; Stover *et al.*, 1996; Sluijs *et al.*, 2005), confirms this interpretation. Moderate taxonomic diversity (the Shannon-Weaver value oscillates between 11 and 17, exceptional 20; Fig. 11) and the lack of any species frequency excursion points to a normal marine environment. A relatively low proportion of peridinioids, represented by *Deflandrea* (their high ratios reflect inshore, commonly brackish conditions; e.g., Köthe, 1990; Stover *et al.*, 1996; Sluijs *et al.*, 2005), shows stable salinity conditions of sea water. The highest diversity of dinoflagellate cyst assemblages is recorded at a depth of 821.9–0 m (the Shannon-Weaver value equals 20; Fig. 11). This may be interpreted as reflecting the most favourable conditions for the dinoflagellate flora, possibly related to maximal deepening of a generally shallow marine basin.

The stable marine conditions must have changed rapidly during accumulation of the topmost part of the sand interval: the sample from 819.0–1 m yielded prasinophycean algae and acritarchs only. The palaeoenvironmental factors responsible for the decline of dinoflagellate cysts are uncertain. No indications of significant shallowing are evidenced by lithological changes. The palaeoenvironmental preferences of fossil prasinophycean algae are barely known: their extant representatives are mainly marine plankton, occurring in both oceanic and coastal waters (e.g., Guy-Ohlson, 1996); they are also known from brackish and freshwater settings (Tappan, 1980). Fossil prasinophycean algae are described from similar, cosmopolitan environments (Guy-Ohlson, 1996). Prauss and Riegel (1989) suggested that their distribution was controlled by climate and salinity, in that low temperatures and reduced salinity favoured this group. A freshwater influx, which seems to be the most reliable explanation of the phytoplankton changes, may be supported by the occurrence of freshwater *Botryococcus* in the topmost sample (819.0–1 m). However, this alga is very rare; only a few specimens have been found. On the other hand, *Leiosphaeridia*, one of the recorded prasinophyceans, is also known from hypersaline palaeoenvironments (e.g., Brugman *et al.*, 1994); it was described from the evaporite deposits and overlying strata of the Carpathian Foredeep (e.g., Gedl 1997, 1999a, 2004a; Gedl in Peryt *et al.*, 1997).

The prasinophycean algae and acritarch assemblage from the topmost sample (819.0–1 m) is very similar to the assemblages from the underlying samples, where *Tasmanites*, *Cymatiosphaera*, *Leiosphaeridia*, *Pterospermella* and acritarchs co-occur with marine dinoflagellate cysts. This points to their broad palaeoenvironmental preferences, ranging from marine (samples with dinoflagellate cysts) to restricted (sample 819.0–1 m) environments.

Similar prasinophycean algae and acritarch assemblages occur in the Eocene strata of the Sołokija Graben succession at Roztocze, SE Poland (Gedl, 2014). They occur in the entire Bartonian–Lower Priabonian succession together with dinoflagellate cysts, but they are most frequent in the Lower Priabonian part, where their proportion reaches 10–30%. Dinoflagellate cysts from the same samples show an excursion of *Homotryblum* frequency (this genus is widely associated with proximal settings, commonly with increased salinity; e.g., Sluijs *et al.*, 2005) interpreted as an indication of basin shallowing (Gedl, 2014). The higher deposits of the Sołokija Graben succession, however, yielded a *Deflandrea*-dominated assemblage devoid of prasinophycean algae, which is interpreted as evidence of brackish conditions (Gedl, 2014). Such a distribution of prasinophyceans in the Sołokija succession may indicate that these algae are associated with waters of increased salinity, rather than with a brackish environment, but prasinophycean algae occur in the Eocene strata of NW Ukraine, together with low-salinity dinoflagellate cyst assemblages (Gedl and Shevchenko, 2010a, b). This indicates they had brackish palaeoenvironmental preferences. Possibly, this broad group of algae may be euryhaline and tolerant for regimes of both increased and decreased salinity, proliferating in such restricted environments.

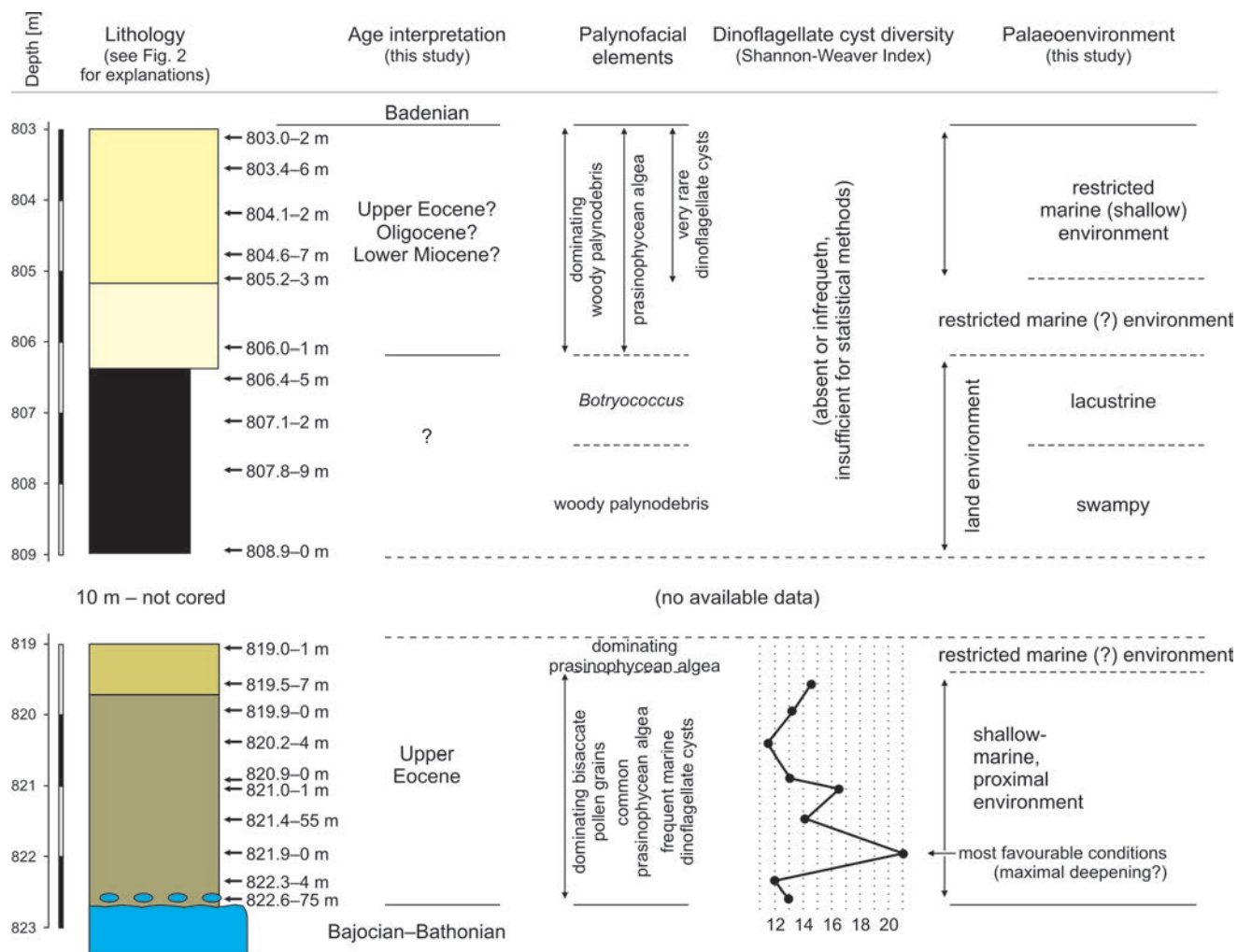


Fig. 11. Palaeoenvironmental reconstructions. Ages of overlying and underlying strata after Myśliwiec and Śmist (2006) and author's unpublished data.

Frequent prasinophycean algae and acritarchs are also known from the Oligocene epicontinental deposits of eastern Poland and western Ukraine (Gedl and Shevchenko, 2007). They are associated there with peridinioid-dominated (mainly *Wetzelielloideae*) dinoflagellate cyst assemblages, reflecting low-salinity conditions. This shows that blooms of prasinophycean algae in the Late Eocene and Rupelian of the epicontinental sea were common phenomena and they occurred at an interregional scale (see also Andreva-Grigorovich *et al.*, 2011). Interestingly, the Upper Eocene strata of the Flysch Carpathians contain no blooms of prasinophycean algae (Gedl, 1999b, 2004b, 2005a), indicating a possible separation of these two basins during the Late Eocene. The coeval strata of the Skole Nappe (the Pojepe Beds) contain only *Tasmanites* (Gedl, 2013).

Coal and overlying sand. Two coal samples (807.1–2 m and 806.4–5 m) yielded very frequent *Botryococcus* (Fig. 11). Recent representatives of these colonial chlorococcalean algae appear in temperate and tropical regions, where they are found in the fresh water of shallow bogs, ponds and small lakes (Batten and Grenfell, 1996), commonly with oligotrophic water (Wake and Hillen, 1980); *Botryococcus* colo-

nies are known also from lakes with waters of increased salinity (e.g., De Deckker, 1988). They commonly form a thick scum on the surface of the water, which after decay may become a component of torbanite (also known as bog-head coal); *Botryococcus* is also known as an important component of some organic-rich shales (Largeau *et al.*, 1984; De Deckker, 1988; Batten and Grenfell, 1996). Hence, the mass occurrence of *Botryococcus* in these two samples points to a freshwater environment of the coal interval, probably shallow lakes or bogs with periodic blooms of *Botryococcus*. Two other samples from this interval (808.9–0 m and 807.8–9 m) contain large amounts of woody debris, commonly of large size; these levels were presumably accumulated in bogs, whereas the *Botryococcus* levels were accumulated in lakes.

The sands that overlie the coals were deposited during a marine transgression that covered the bogs. Although the basal sample 806.0–1 m was deposited in a continental environment (it yielded sporomorphs and lacks marine palynomorphs), but the appearance of marine elements in higher samples reflects a marine environment. The dinoflagellate cyst assemblage is highly impoverished: it consists mainly

of *Batiacasphaera*? and *Spiniferites*; *Operculodinium centrocarpum* and *Lingulodinium machaerophorum* occur at depth 804.6–7 m (other taxa are presumably reworked or contaminated; see Biostratigraphy). The *in situ* dinoflagellate cyst assemblage may be related to restricted conditions, presumably associated with shallow water. *Batiacasphaera* (mainly *B. sphaerica*) occurs in shallow-water environments of Miocene strata of the Carpathian Foredeep (Gedl, 1996, 1997, 1999a). The deepest conditions are presumably recorded in a sample from 804.6.7 m, which, in addition to being the most diversified assemblage, yielded single, poorly preserved specimens of *Nematosphaeropsis* sp. and questionable *Impagidinium* sp. Their presence, if not reworked/contaminated, may also point to a connection with a more offshore basin, since both genera are commonly linked with offshore waters (e.g., Brinkhuis, 1994; Sluijs *et al.*, 2005).

Remarks on Late Eocene palaeogeography and post-Eocene tectonics of SE Poland

A precise palaeogeographic reconstruction of the Late Eocene epicontinental basin in SE Poland is highly limited, owing to the scarcity of well dated deposits of this age. For a long time, this area was believed to have been a landmass during the Eocene and Oligocene – the Meta-Carpathian Swell that separated Carpathian basins from the Polish epicontinental basin. The Upper Eocene strata from the Łukowa-4 borehole are so far the only evidence of a Late Eocene marine transgression in the area of the present-day Carpathian Foredeep. The closest Eocene strata are known from Roztocze, where a 40 m-thick succession of marine Bartonian–Priabonian deposits occurs in the Sołokija Graben (e.g., Buraczyński and Krzowski, 1994; Gaździcka, 1994). However, according to Gedl (2014), the youngest part of the Sołokija profile represents the lower Priabonian, i.e., it is slightly older than the succession from the Łukowa-4 borehole. The transgressive nature of the latter may indicate that it represents a following transgressive pulse, which was either not recorded at Roztocze, or the evidence for it was eroded there. Further north, Upper Eocene is known from the northern surroundings of the Lublin Upland and dated for Bartonian–lower Priabonian – NP16–NP18 (e.g., Pożaryska and Locker, 1971; Pożaryska, 1977; Uberna and Odrzywolska-Bieńkowska, 1977; Kosmowska-Ceranowicz and Pożaryska, 1984; Kosmowska-Ceranowicz *et al.*, 1990; for discussion see Gedl, 2014).

The presence of marine Upper Eocene strata in the Łukowa-4 borehole shows that at least the western part of the present-day Carpathian Foredeep was flooded by the sea during the Late Eocene. The sea extended also to the Roztocze area (Sołokija Graben), which shows that both tectonic structures were not defined by then, and that their formation took place in post-Eocene time. The Middle Miocene deposits of Roztocze and the Foredeep basin show strongly different lithological development, reflecting an uplifted position of Roztocze relative to the Foredeep (e.g., Ney *et al.*, 1974; Wysocka, 2002). The marine Lower Oligocene strata known from the present-day Carpathian Fore-

deep (Gedl, 2000) have no equivalent at Roztocze. This may indicate that some tectonic movement responsible for the uplifting of Roztocze began in the late Early Oligocene, whereas the Carpathian Foredeep remained lowered and covered by the ingression of the sea.

Moryc (1995) distinguished strata in the Rzeszów–Sędziszów Małopolski area, which according to him represent terrestrial Palaeogene deposits. They lie upon a Mesozoic, Palaeozoic and Precambrian substratum and are covered by Middle Miocene fine clastic deposits. The lower unit, the Raclawówka Conglomerate Formation, contains no fossils, so its age was determined only as older than Badenian (Middle Miocene; Moryc, 1995). Above it, the Czudec Formation (not to be confused with the Czudec Clay *sensu* Rajchel, 1990) occurs. According to Moryc (1995) this informal lithostratigraphic unit consists of loamy-sandy deposits with various ratios of mudstone and sandstone, although the former predominate. Frequent coalified plant remains and coal lenses occur there. Although no marine microfauna has been found, a single layer with tiny gastropods was reported (Moryc, 1995). These features, supported by frequent macrofloral remains (A. Kotasowa in Moryc, 1995) and sporomorph assemblages (H. Kmieciak and L. Stuchlik in Moryc, 1995) led Moryc (1995) to the conclusion that this unit represents terrestrial deposits accumulated in marshy-lacustrine environment. The age of the Czudec Formation has not been precisely determined: results of palynological and macrofloristic analysis gave a wide age-range. Kotasowa (in Moryc, 1995) gave a Late Cretaceous–Recent range for the plants determined, whereas Kmieciak and Stuchlik (in Moryc, 1995) interpreted the age of the sporomorph assemblages as “Tertiary”, but both authors highlighted some similarities with Paleocene spectra (Moryc, 1995). Moryc (1995) concluded a probable Palaeogene age of the Czudec Formation, although an Early Miocene age was not excluded. He rejected, however, the interpretation of Połtowicz (1994) who opted for an Early Badenian age of this unit. In the opinion of Połtowicz, this unit remains in sedimentological contact with overlying Middle Badenian marine strata, whereas Moryc (1995) demonstrated an angular nonconformity between the Czudec Formation and the overlying marine Badenian strata. Poorly preserved dinoflagellate cysts found in the Czudec Formation of the Nosówka-9 borehole (P. Gedl in Moryc, 1995) may, if not reworked, indicate a late Priabonian age on the basis of the co-occurrence of *Areosphaeridium diktyoplokum* and *Reticulatosphaera* sp. (presumably *R. actinocoronata*); this would allow their correlation with the Late Priabonian assemblage from the basal sand of the Łukowa-4 borehole. However, if they are reworked, this would point to a post-Eocene age, i.e., Oligocene or Early Miocene accumulation of the Czudec Formation. A similar, uncertain age is suggested for the coal and overlying sands in the Łukowa-4 borehole in this paper – according to Słodkowska (in Myśliwiec and Śmist, 2006), these coaly layers contain presumably Oligocene sporomorphs. Their lithological similarities (sandy and phytogenic deposits) and marshy-lacustrine origin indicate their correlation with the continental Czudec Formation. If this interpretation is accepted, the following scenario can be suggested.

During the late Priabonian, a marine transgression covered the western part of the present-day Carpathian Foredeep; it was probably genetically linked with the early Priabonian sea, known from Roztocze (Gedl, 2014). The marine basin of the Foredeep was presumably separated from the Skole Basin by a land barrier. In the Carpathian basins, the deposition of hemipelagic Globigerina Marls took place then.

During the late Rupelian, another transgression covered the western part of the Carpathian Foredeep (Gedl, 2000); the lack of coeval deposits at Roztocze indicates that the latter area was already uplifted relative to the Foredeep area; the magnitude of the hypothetical uplift was presumably small in scale. It cannot be excluded, however, that Rupelian deposits were completely removed from Roztocze during the subsequent uplift and extensive pre-Badenian erosion. Then, in the Carpathian basins, a period of stagnant accumulation of organic Menilite facies took place.

During Chattian–Early Miocene, a major phase of tectonic activity in the Carpathian Foredeep in Poland led to the formation of high relief, associated with the uplift of the Meta-Carpathian Swell. Increased erosion of the pre-Palaeogene substratum cut several valleys, approximately perpendicular to the margin of Carpathian basins, through which eroded material was transported from north to the south. In the vicinity of Rzeszów, the Raławówka Conglomerate Formation filled the valleys (Moryc, 1995). After the cessation of the main erosive phase, the intramontane depressions were places of accumulation of fine-grained and phytogenetic in marshy-lacustrine environments (the Czudec Formation, and the coals and overlying sands from the Łukowa-4 borehole). The Chattian–Early Miocene erosive phase correlates with an intense supply of clastic material into the Carpathian basins from their northern surroundings to give the Krosno Beds facies.

Conglomeratic deposits, occurring at the base of of Miocene succession of the Carpathian Foredeep, commonly form the fillings of erosional valleys. Such deposits are known also from the central (Połtowicz, 1994) and the western (Ślącza, 1977; Moryc, 1989; Połtowicz, 1995) sectors of the Polish part of the Carpathian Foredeep. They were described as various informal lithostratigraphic units (e.g., the Zawoja Formation, the Andrychów Formation). Their age is disputable, mainly owing to the scarcity of fossils, and ranges from Eocene–Oligocene to Lower Miocene (e.g., Moryc, 1989; Oszczytko *et al.*, 2000; Oszczytko and Oszczytko-Clowes, 2003; see also Jarosiński *et al.*, 2009 and discussion: Krzywiec, 2010 and Jarosiński *et al.*, 2010).

CONCLUSIONS

1. The Łukowa-4 borehole penetrated a succession of sand and phytogenic deposits almost 20 m thick at a depth of 822.75–803.0 m between the Middle Jurassic and almost 800 m of Miocene deposits in the Carpathian Foredeep.

2. The sand from the lower part of the 20 m-thick succession yielded rich assemblages of marine dinoflagellate cysts; the phytogenic deposits contain terrestrial plant remains and freshwater algae; the overlying sand yielded terrestrial palynomorphs and palynodebris with rare dinoflagellate cysts.

3. The age of dinoflagellate cyst assemblages from the basal sand is Late Eocene (late Priabonian). The phytogenic deposits remains undated, whereas the sand above can be either Palaeogene or Neogene.

4. The marine assemblages in the basal sand show that this part of the Carpathian foreland was flooded by a sea during the latest Eocene. Subsequently, this area emerged and was covered by swampy-lacustrine environments. The overlying sand accumulated in a proximal marine environment.

5. The marine transgressions that gave rise to the deposits studied show that at least this part of the so-called Meta-Carpathian Swell had not emerged during latest Eocene. However, more precise orographic reconstruction of this part of Carpathian foreland is not possible, owing to the scarcity of well dated deposits. The marine succession in the Łukowa-4 borehole could be part of widely distributed marine deposits, removed later by erosion, but could also be the trace of an intermontane bay, connected to a marine basin in the east and/or south-east.

SELECTED TAXONOMY

In this chapter species left in open nomenclature are briefly described; they are presented in alphabetic order.

Order GONYAULACALES Taylor, 1980

Genus *Cordosphaeridium* Eisenack, 1963

Type species: *Cordosphaeridium inodes* (Klump, 1953) Eisenack, 1963.

Cordosphaeridium cf. minimum (Morgenroth, 1966)

Benedek, 1972

Fig. 12G–I

Material: Rare specimens in samples from the interval 821.9–820.0 m (Tab. 1).

Description: Subspherical central body bears short processes, up to of the central body diameter, hollow, distally open. Processes are connected by septa of height almost equal to process height. Archaeopyle type barely discernible, most likely apical.

Remarks: This species resembles *Cordosphaeridium minimum* from the Łukowa-4 borehole (Fig. 7H–J) in the general shape of the cyst and nature of processes; it has a slightly larger central body in relation to process length. It differs in high ridges connecting processes; the latter feature makes it similar to the Neogene species *Labyrinthinium truncatum* (for its stratigraphic range see e.g., Stover *et al.*, 1996). Some specimens of *C. minimum* from the Łukowa-4 borehole also have ridges connecting processes, but these are very low, proximal ridges connecting process bases only (Fig. 7H), and not almost the whole processes, as in *C. cf. minimum*.

Cordosphaeridium? sp.

Fig. 12P–R

Material: Single specimens in samples at: 822.3–4 m, 821.9–0 m and 820.9–0 m.

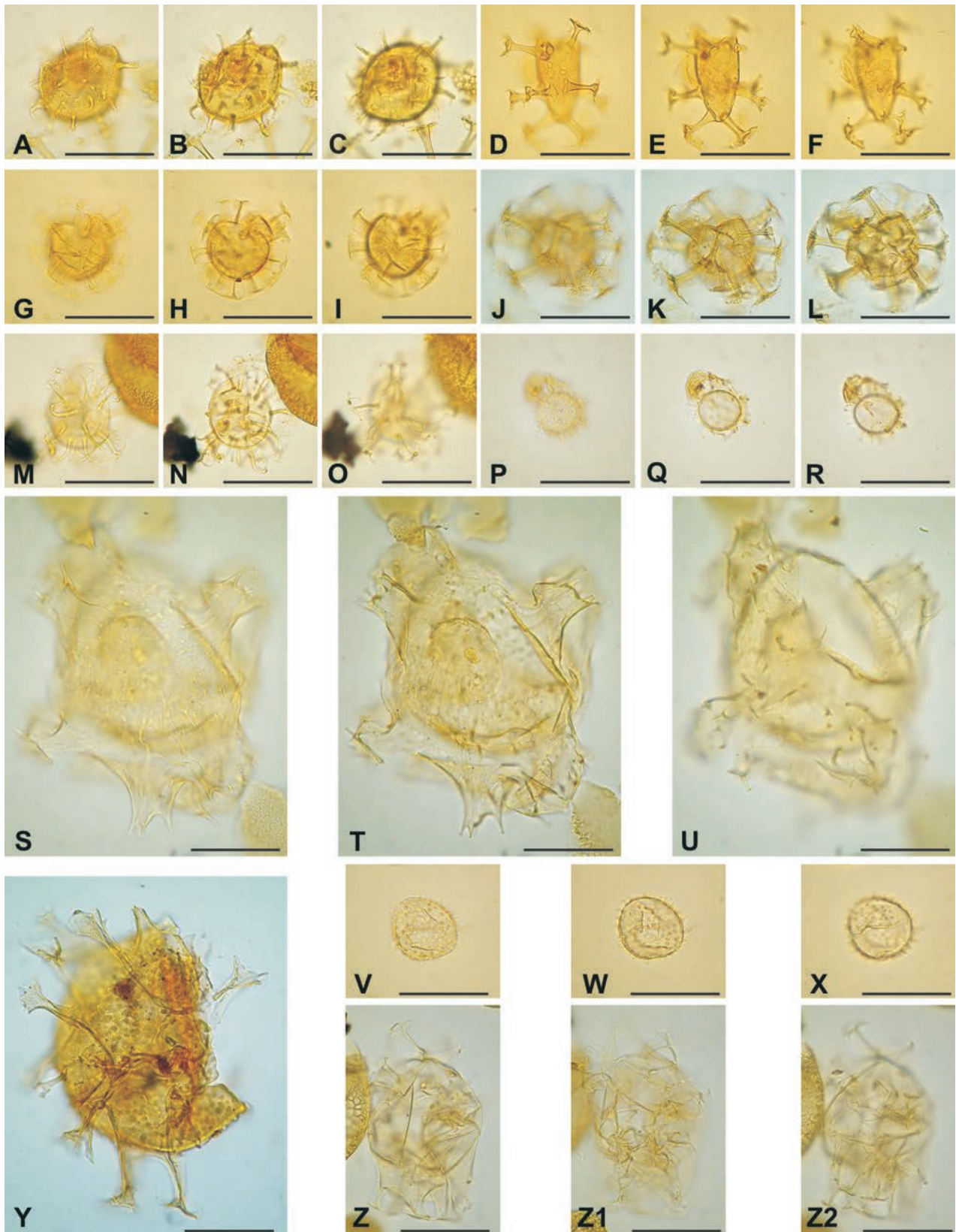


Fig. 12. Dinoflagellate cysts from the Eocene of Łukowa-4 borehole left in open nomenclature. Scale bars = 25 μ m. **A–C.** *Operculodinium?* sp. (same specimen various foci; 821.9–0 m). **D–F.** *Distatodinium* cf. *craterum* (same specimen various foci; 821.9–0 m). **G–I.** *Cordosphaeridium* cf. *minimum* (same specimen various foci; 821.9–0 m). **J–L.** *Reticulosphaera?* sp. A (same specimen various foci; 821.9–0 m). **M–O.** *Reticulosphaera?* sp. B (same specimen various foci; 820.9–0 m). **P–R.** *Cordosphaeridium?* sp. (same specimen various foci; 820.9–0 m). **S–U.** *Hystrichokolpoma?* sp. (same specimen various foci; 820.2–4 m). **V–X.** *Operculodinium janduchenei?* (same specimen various foci; 819.9–0 m). **Y.** *Spiniferites* cf. *pseudofurcatus* (821.0–1 m). **Z–Z2.** *Rottnestia?* sp. (same specimen various foci; 820.2–4 m).

Description: Very small, below 20 mm, subspherical cyst with numerous processes, which are hollow, distally open with slightly expanded margins. Archaeopyle precingular 1P. Processes seem to be proximally connected by low, delicate and poorly developed ridges.

Genus *Distatodinium* Eaton, 1976

Type species: *Distatodinium craterum* Eaton, 1976.

Distatodinium cf. *craterum* Eaton, 1976
Fig. 12D–F

Material: A single specimen in a sample from 821.9–0 m.

Description: A species of *Distatodinium* with intratabular processes in precingular and postcingular series; processes tubular, hollow, distally slightly expanded with smooth margins.

Remarks: This species closely resembles *D. craterum* and *D. paradoxum* in general cyst shape and process arrangement. It differs in the shape of processes, which in *D. craterum* are broader and terminated into long, branching spines (see Eaton, 1976). It differs from *D. paradoxum* in its lack of distal complex branching of the processes.

Genus *Heteraulacacysta* Drugg et Loeblich Jr., 1967

Type species: *Heteraulacacysta campanula* Drugg et Loeblich Jr., 1967.

Heteraulacacysta cf. *porosa* Bujak in Bujak *et al.*, 1980
Fig. 8R

Material: Rare to common in samples from the basal sand succession, except for a sample from 821.4–55 m.

Description: A species of *Heteraulacacysta* characterized by regular perforations of the central body except for paracingular crest.

Remarks: This species closely resembles *H. porosa*, from which it differs in the lack of perforations on the paracingular crest (see Bujak in Bujak *et al.*, 1980).

Genus *Homotryblium* Davey et Williams, 1966

Type species: *Homotryblium tenuispinosum* Davey et Williams, 1966.

Homotryblium? sp.
Fig. 10P, Q

Material: Two specimens in a sample from 805.2–3 m and a single specimen in a sample from 803.0–2 m.

Description: Cysts preserved as isolated hypocysts only; intratabular processes seem to be solid in proximal and middle parts, become secate in distal parts.

Remarks: This species resembles *Homotryblium plectilum* in the secate terminations of intratabular processes. In this species, however, processes are striate and hollow.

Genus *Hystrichokolpoma* Klumpp, 1953

Type species: *Hystrichokolpoma cinctum* Klumpp, 1953.

Hystrichokolpoma? sp.
Fig. 12S–U

Material: Rare specimens occur in samples from the following

depths: 822.6–75 m, 821.0–1 m, 820.9–0 m, 820.2–4 m, and 819.5–7 m.

Description: Large chorate cyst with subspherical endocyst and pericyst forming large processes with broad bases, hollow; some processes are distally closed, the smaller ones seem to be open. Periphragm with irregular perforations, covered with short solid and hollow, distally branched spines. Archaeopyle precingular 1P.

Genus *Operculodinium* Wall, 1967

Type species: *Operculodinium centrocarpum* (Deflandre et Cookson, 1955) Wall, 1967.

Operculodinium janduchenei? Head *et al.*, 1989
Fig. 12V–X

Material: Rare specimens in three samples from following depths: 821.0–1 m, 819.9–0 m, and 819.5–7 m.

Description: Small subspherical cyst with smooth wall, bearing numerous nontabular, very short, tubiform, hollow, distally open processes. Archaeopyle precingular 1P.

Remarks: This species resembles the Late Neogene species *O. janduchenei* (for stratigraphic range see Head *et al.*, 1989; McMinn, 1992). It differs slightly in the tubiform shape of the processes, which in *O. janduchenei* are more conical.

Operculodinium? sp.
Fig. 12A–C

Material: A single specimen in a sample from 821.9–0 m.

Description: Subspherical cyst with fibrous endophragm and solid, relatively short processes of two types: acuminate and branched. Archaeopyle type uncertain, presumably precingular.

Remarks: This single specimen was questionably assigned to the genus *Operculodinium*, although the bimodal shape of processes is not typical for this genus.

Genus *Reticulosphaera* Matsuoka, 1983

Type species: *Reticulosphaera stellata* Matsuoka, 1983.

Reticulosphaera? sp. A
Fig. 12J–L

Material: Rare specimens in most of the samples from the basal sand interval (see Tab. 1).

Description: Small subspherical cyst with intratabular processes of length equal to $\sim 2/3$ of the central body diameter. Processes hollow with longitudinal ribs, broad at base, narrowing upwards, distally expanded. Their distal margins with long, multiple branching spines. Archaeopyle type uncertain, most likely precingular.

Remarks: This species is similar in general shape and main ornamentation features (particularly longitudinal ribs on processes) to *Cordosphaeridium* sp. A, described by the author from the Eocene strata of the Skole Nappe, Flysch Carpathians (Gedl, 2013, p. 80, fig. 28A–E). The species from Łukowa-4 differs in longer processes, which in contrast to *Cordosphaeridium* sp. A terminate with a delicate branching system; it also lacks the net-like structure, observed on the central bodies of the Carpathian species. The branching spines at the end of processes are identical to the ones observed in *Reticulosphaera actinocoronata*. The latter feature allowed questionable assignment to the genus *Reticulosphaera*, although hollow processes with longitudinal ribs are rather atypical for this genus (see Bujak and Matsuoka, 1986).

Reticulosphaera? sp. B

Fig. 12M–O

Material: Single specimens in samples from following depths: 822.6–75 m, 822.3–4 m, 820.9–0 m, and 819.9–0 m (Tab. 1).

Description: Small subspherical cyst with smooth wall and solid, intratabular thin processes distally bifurcate with further bifurcation at tips. Archaeopyle type uncertain, most likely paracingular.

Remarks: This species was questionably assigned to the genus *Reticulosphaera*, owing to the shape of processes, which are solid and branched; however, these branches are simple compared to the anastomosing ones in *R. actinocoronata*.

Genus *Rottnestia* Cookson and Eisenack, 1961

Type species: *Rottnestia borussica* (Eisenack, 1954) Cookson et Eisenack, 1961.

Rottnestia? sp.

Fig. 12Z–Z2

Material: A single specimen in a sample from 820.2–4 m.

Description: Elongated cyst with ellipsoidal endocyst and an antapical pericoel; no apical pericoel nor horn present. Periphragm smooth. Processes presumably intergonal, hollow, thick, distally expanded with trifurcate margin. Archaeopyle not visible.

Remarks: Elongated cyst shape and process arrangement resemble the genus *Rottnestia*, but the latter possesses an apical horn that is missing in the specimen described.

Genus *Spiniferites* Mantell 1850

Type species: *Spiniferites ramosus* (Ehrenberg, 1838) Mantell, 1854.

Spiniferites cf. *pseudofurcatus* (Klumpp, 1953) Sarjeant, 1970

Fig. 12Y

Material: Single specimens in samples from the following depths: 821.9–0 m, 821.4–55 m, and 821.0–1 m.

Remarks: This species closely resembles *S. pseudofurcatus*; a characteristic feature distinguishing the specimens is a verrucate ornamentation of the endocyst. Most of other specimens from the Łukowa-4 borehole attributed to *S. pseudofurcatus* have psilate to granulate uniform ornamentation, without high relief, as in the case of *S. cf. pseudofurcatus*.

Order PERIDINIALES Haeckel, 1894

Peridinioid sp. A

Fig. 8G, H

Material: Frequent in the basal sand interval (822.75–819.5 m).

Description: A circumcavate, compressed peridinioid cyst with one apical and two antapical horns of almost equal length. Apical pericoel clearly larger than the antapical one. Paracingulum well developed as broad depression, limited by small ridges with tiny denticles; parasulcus less prominent, visible as small depression (Fig. 8G). Endophragm thin and smooth, periphragm thin and covered by densely and uniformly distributed circular granulae. Archaeopyle intercalary, three paraplates involved, all remain attached along their margins with precingular series (Fig. 8H).

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Appendix

An alphabetic listing of dinoflagellate cyst taxa found in the Łukowa-4 borehole (freshwater, undetermined forms are not included); full taxonomic citations are given in Fensome *et al.* (2008)

- Achilleodinium biformoides* (Eisenack, 1954) Eaton, 1976
Achomosphaera sp. (Fig. 7K, L)
Adnatosphaeridium multispinosum Williams et Downie, 1966
Apectodinium sp. (Fig. 10O)
Apteodinium sp.
Araneosphaera araneosa Eaton, 1976
Areosphaeridium diktyoplokum (Klumpp, 1953) Eaton, 1971
Areosphaeridium michoudii Bujak, 1994 (Fig. 6B)
Batiacasphaera hirsuta Stover, 1977 (Fig. 6F, G)
Batiacasphaera micropalillata Stover, 1977
Batiacasphaera? spp. (Fig. 10E–N)
Cerebrocysta bartonensis Bujak in Bujak *et al.*, 1980 (Fig. 7E)

- Charlesdowniea clathrata* (Eisenack, 1938) Lentin et Vozzhennikova, 1989 (Fig. 8C)
Charlesdowniea coloethrypta (Williams et Downie, 1966) Lentin et Vozzhennikova, 1989 (Fig. 8S)
Circulodinium sp.
Cleistosphaeridium placacanthum (Deflandre et Cookson, 1955) Eaton *et al.*, 2001
Cleistosphaeridium sp. A *sensu* Gedl, 2013 (Fig. 6I, J)
Cordosphaeridium cantharellus (Brosius, 1963) Gocht, 1969
Cordosphaeridium cf. *minimum* (Morgenroth, 1966) Benedek, 1972 (Fig. 11G–I)
Cordosphaeridium gracile (Eisenack, 1954) Davey et Williams, 1966 (Fig. 7U)
Cordosphaeridium inodes (Klumpp, 1953) Eisenack, 1963
Cordosphaeridium minimum (Morgenroth, 1966) Benedek, 1972 (Fig. 7H–J)
Cordosphaeridium sp. A *sensu* Gedl, 2013
Cordosphaeridium? sp. (Fig. 11P–R)
Corrudinium incompositum (Drugg, 1970) Stover et Evitt, 1978 (Fig. 7B)
Cribroperidinium giuseppi (Morgenroth, 1966) Helenes, 1984 (Fig. 7F, G)
Cribroperidinium tenuitabulatum (Gerlach, 1961) Helenes, 1984
Dapsilidinium pseudocolligerum (Stover, 1977) Bujak *et al.*, 1980
Dapsilidinium sp.
Deflandrea heterophlycta Deflandre et Cookson, 1955 (Figs 8A, 10T)
Deflandrea phosphoritica Eisenack, 1938 (Fig. 8B)
Dinopterygium cladoides Deflandre, 1935 (Fig. 8P)
Diphyes colligerum (Deflandre et Cookson, 1955) Cookson, 1965
Distatodinium ?craterum Eaton, 1976
Distatodinium cf. *craterum* Eaton, 1976 (Fig. 11D–F)
Distatodinium ellipticum (Cookson, 1965) Eaton, 1976
Distatodinium virgatum Stover, 1977
Elytrocysta? sp.
Enneadocysta arcuata (Eaton, 1971) Stover et Williams, 1995
Enneadocysta pectiniformis (Gerlach, 1961) Stover et Williams, 1995
Fibrocysta axialis (Eisenack, 1965) Stover et Evitt, 1978
Glaphyrocysta microfenestrata (Bujak, 1976) Stover et Evitt, 1978 (Fig. 6C, D)
Glaphyrocysta semitecta (Bujak in Bujak *et al.*, 1980) Lentin et Williams, 1981 (Fig. 7V)
Heteraulacacysta cf. *porosa* Bujak in Bujak *et al.*, 1980 (Fig. 8R)
Heteraulacacysta leptalea Eaton, 1976 (Fig. 8Q)
Heteraulacacysta porosa Bujak in Bujak *et al.*, 1980
Heteraulacacysta sp.
Heterosphaeridium sp. A *sensu* Gedl, 2013 (Fig. 7P)
Homotryblium aculeatum Williams, 1978
Homotryblium floripes (Deflandre et Cookson, 1955) Stover, 1975 (Figs 6H, 10R)
Homotryblium tenuispinosum Davey et Williams, 1966
Homotryblium? sp. (Fig. 10P, Q)
Hystrichokolpoma cinctum Klumpp, 1953 (Fig. 7A)
Hystrichokolpoma rigaudiae Deflandre et Cookson, 1955
Hystrichokolpoma salacia Eaton, 1976 (Fig. 7O)
Hystrichokolpoma unispinum Williams et Downie, 1966
Hystrichokolpoma? sp. (Fig. 11S–U)
Hystrichosphaeridium? sp.
Hystrichosphaeropsis rectangularis Bujak in Bujak *et al.*, 1980 (Fig. 7R, S)
Hystrichostrogylon coninckii Heilmann-Clausen in Thomsen et Heilmann-Clausen, 1985
Impagidinium sp.
Impletosphaeridium sp. (Fig. 10V)
Impletosphaeridium? sp. (Fig. 10A–D)
Kallosphaeridium sp.
Lentinia serrata Bujak in Bujak *et al.*, 1980 (Figs 8I, J, 10W)
Lingulodinium machaerophorum (Deflandre et Cookson, 1955) Wall, 1967 (Fig. 10X)
Membranophoridium aspinatum Gerlach, 1961
Microdinium spp.
Nematosphaeropsis sp.
Operculodinium centrocarpum (Deflandre et Cookson, 1955) Wall, 1967 (Figs 7Q, 10Y)
Operculodinium divergens (Eisenack, 1954) Stover et Evitt, 1978 (Fig. 6E)
Operculodinium janduchenei? Head *et al.*, 1989 (Fig. 11V–X)
Operculodinium microtriainum (Klumpp, 1953) Islam, 1983 (Fig. 7T)
Operculodinium sp.
Operculodinium sp. A *sensu* Gedl, 2013
Operculodinium tiara (Klumpp, 1953) Stover et Evitt, 1978
Operculodinium? sp. (Fig. 11A–C)
Palaeocystodinium golzowense Alberti, 1961
Pentadinium laticinctum Gerlach, 1961
Pentadinium lophophorum (Benedek, 1972) Benedek *et al.*, 1982
Peridinioid sp. A (Fig. 8G, H)
Phthanoperidinium amoenum Drugg et Loeblich Jr., 1967
Phthanoperidinium comatum (Morgenroth, 1966) Eisenack et Kjellström, 1972 (Fig. 8K–O)
Phthanoperidinium? eocenicum (Cookson et Eisenack, 1965) Lentin et Williams, 1973 (Fig. 8D–F)
Phthanoperidinium stockmansii (de Coninck, 1975) Lentin et Williams, 1977
Polysphaeridium subtile Davey et Williams, 1966
Polysphaeridium zoharyi (Rossignol, 1962) Bujak *et al.*, 1980
Pyxidiniopsis sp. C *sensu* Gedl, 2005
Reticulosphaera actinocoronata (Benedek, 1972) Bujak et Matsuoka, 1986 (Figs 7C, D, 10S)
Reticulosphaera? sp. A (Fig. 11J–L)
Reticulosphaera? sp. B (Fig. 11M–O)
Rottnestia? sp. (Fig. 11Z–Z2)
Samlandia chlamydotheca Eisenack, 1954
Selenopemphix nephroides Benedek, 1972
Spiniferites cf. *pseudofurcatus* (Klumpp, 1953) Sarjeant, 1970 (Fig. 11Y)
Spiniferites pseudofurcatus (Klumpp, 1953) Sarjeant, 1970
Spiniferites ramosus (Ehrenberg, 1838) Mantell, 1854 (Figs 7M, N, 10U)
Surculosphaeridium longifurcatum (Firtion, 1952) Davey *et al.*, 1966
Thalassiphora delicata Williams et Downie, 1966
Thalassiphora patula (Williams et Downie, 1966) Stover et Evitt, 1978
Thalassiphora pelagica (Eisenack, 1954) Eisenack et Gocht, 1960 (Fig. 6A)
Vectidinium? sp.
Wetzeliella sp. (Fig. 10Z)