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Palynology of Lower Oligocene brown coal and lowermost Middle Miocene sand deposits from the Łukowa-4 borehole (Carpathian Foredeep, SE Poland) – implications for palaeogeographical reconstructions

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Brown coal and overlying sand strata from the Łukowa-4 borehole, located in the northeastern sector of the Carpathian Foredeep in Poland, were studied for palynology. These strata are underlain by Upper Eocene sands, and covered by Middle Miocene rocks. Coal beds yielded infrequent sporomorphs and freshwater algae *Botryococcus*. The presence of the latter indicates that these deposits accumulated in a freshwater environment whereas sporomorph assemblages point to the presence of mixed forests with a significant portion of thermophilous taxa. Age of the coal beds has been established based both on the presence of species that appear for the last time in the Early Oligocene, and on the similarity with sporomorph spectra from the Lower Oligocene of the Polish Lowlands. Overlying sands yielded marine dinoflagellate cysts, which point to a marine sedimentary setting, and frequent sporomorphs. The latter indicate the presence of mixed mesophytic forests, bush swamps, swamp forests, and riparian forests in the vicinity of lacustrine environments. Stratigraphic analysis of dinoflagellate cyst and sporomorph assemblages suggests that the sands accumulated in early stages of Miocene transgression in the Carpathian Foredeep in the latest Early–early Middle Miocene. Our climatic interpretation of the sporomorph spectra suggests that the climate during deposition of the strata was relatively warm, although less frequent thermophilous taxa recorded in the Miocene sands suggest a slightly cooler climate than that deducted from the spectra yielded by the underlying Lower Oligocene coal beds. Correlation of Lower Oligocene coal beds with neighbouring coeval marine sands suggests diverse morphological conditions in the Carpathian foreland at that time, partly covered by a sea, and partly emerged. A similar, morphologically diverse basement in the Carpathian foreland favoured accumulation of Lower Miocene phytogenic deposits. A similar stratigraphic position of both Lower Oligocene and Lower Miocene coal beds in the Carpathian Foredeep may result in a false correlation of these strata devoid of fossils, which are commonly regarded as Miocene.

Key words: sporomorphs, dinoflagellate cysts, palynostratigraphy, palaeoenvironment, Oligocene–Miocene, Carpathian Foredeep.

INTRODUCTION

Brown-coal deposits are widespread at the base of the Miocene succession in the Carpathian Foredeep Basin (e.g., Kasiński and Piwocki, 1994). They occur in two main areas along its northern margin of the Polish sector (Fig. 1): in Silesia (Kędzierzyn-Koźle–Gliwice area) where they have been distinguished as the Kłodnica Formation (see e.g., Alexandrowicz, 1963, 1970; Alexandrowicz et al., 1982) and in northern part (between Chomentów and Trzydnik) known as the Trzydnik Formation (e.g., Czarnocki, 1932, 1933; Konior, 1948; Bielecka, 1957; Kowalewski, 1958; Radwański, 1969, 1973; Szymanko and Wójcik, 1982; Pawłowski et al., 1985). Most of these phytogenic deposits were accumulated in a system of lagoonal--lacustrine settings that stretched along the northern margin of the Carpathian Foredeep before marine transgression that started in the Middle Miocene (Kasiński and Piwocki, 1994; for correlation of overlying marine strata see e.g., Olszewska, 1999). Continental settings of their accumulation is evidenced by the infrequent, but occasional mass occurrence of terrestrial (gastropods *Helix* and *Succinea*), freshwater (gastropods, e.g., *Lymnaea* and *Planorbis*, and bivalvia *Congeria*), and/or brackish to hypersaline (gastropods *Hydrobia* and *Potamides*, bivalve *Modiola*, and foraminifera *Ammonia beccarii*) fossils (Kasiński and Piwocki, 1994). Although their oldest occurrences are known mostly from the Paleogene–Neogene, but some show longer stratigraphic ranges (e.g., *A. beccarii* is known since the Late Cretaceous; Brooks, 1967); this makes that ac-

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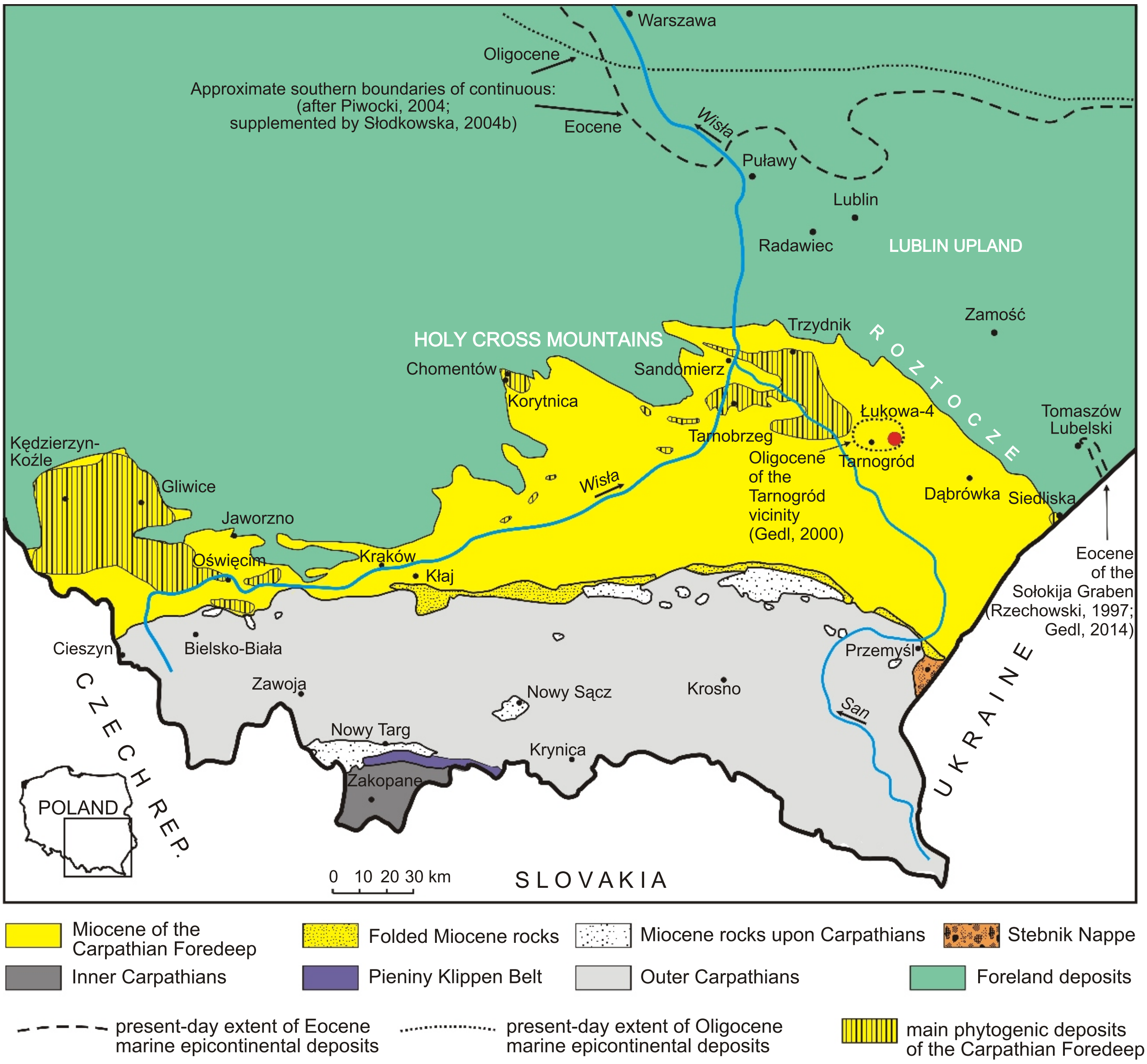

Fig. 1. Location of the Łukowa-4 borehole and a geological sketch-map of SE Poland showing positions of main geological structures and localities mentioned in the text (based on Żytko et al., 1989, from Oszczypko, 1996; hatched areas of the coal deposit occurrences after Kasiński and Piwocki, 1994)

curate ages of the host strata have never been established – they are most commonly referred to the Lower Miocene, mainly on the basis of the age of the overlying younger marine strata, which are Middle Miocene in age (Garecka et al., 1996; Garecka and Jugowiec, 1999; Olszewska, 1999).

Some of these sites were studied for palynology; sporomorph assemblages allowed their dating as Lower Miocene–lower Middle Miocene (Karpatian; Worobiec in Krąpiec et al., 2011). Accurate dating of these brown-coal deposits is essential not only for palaeogeographic reconstructions but also for interpretation of tectonic processes in the Miocene in this part of Poland, which led to significant changes due to folding and overthrusting of the Carpathian orogen. The occurrence of Miocene brown coal was used as a tool for correlation of Carpathian Foredeep strata that occur in various tectonic positions, like the elevated Roztocze and the lowered central Carpathian Foredeep area (e.g., Krąpiec et al., 2011). In the last two decades, however, some of the brown coals of the Carpathian Foredeep yielded sporomorph assemblages that might indicate an older, Paleogene age of these phytogenic deposits (Słodkowska in Myśliwiec and Śmist, 2006). These discoveries appeared at the same time when the first well-dated records of Paleogene marine strata underlying the Miocene succession in the eastern sector of the Carpathian Foredeep have been reported (e.g., Gedl, 2000; Myśliwiec and Śmist, 2006). Therefore, we undertook detailed palynological studies of the available cores of brown coals and overlying strata from the Łukowa-4 borehole (Fig. 2) located in the northeastern sector of the Carpathian Foredeep (Fig. 1). In this borehole, phytogenic deposits occur at a depth of 804–807 m (Fig. 2); they rest on the Upper Eocene marine sandy deposits, and are covered by cream-coloured sands of uncertain age (Gedl, 2015); followed by Middle Miocene (Badenian) marly deposits (Myśliwiec and Śmist, 2006).

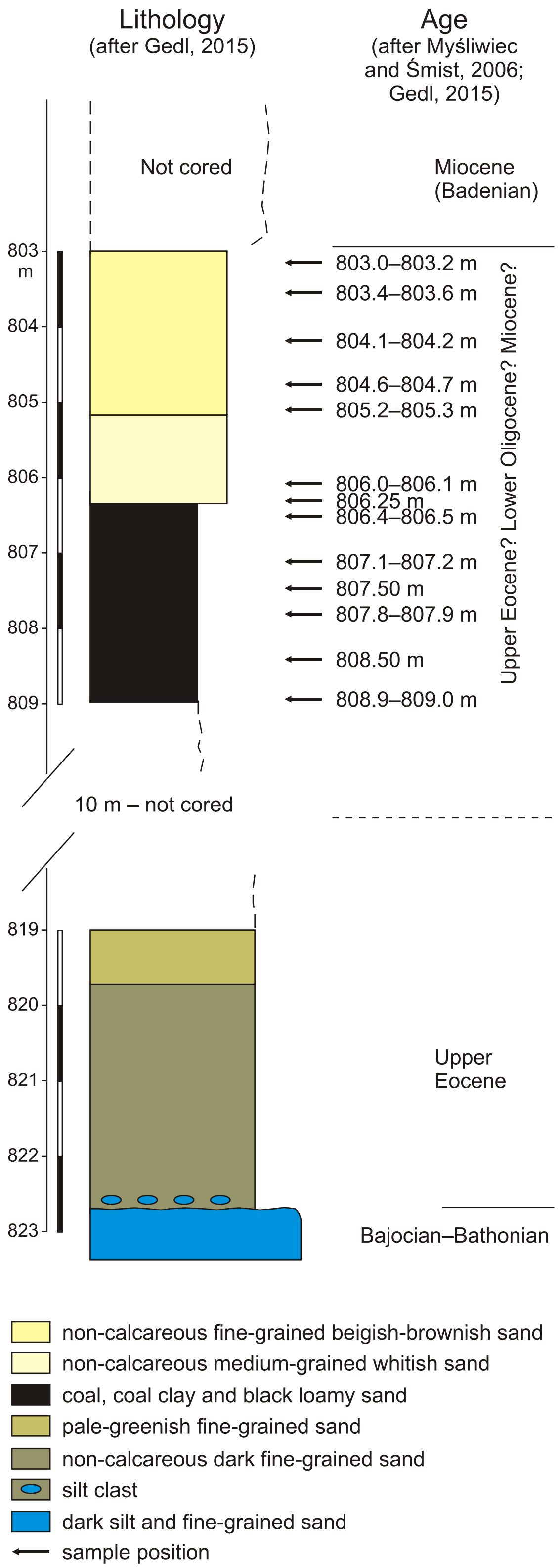

Fig. 2. Lithology and sample position in the 803–823 m interval in the Łukowa-4 borehole

GEOLOGICAL SETTING

The Carpathian Foredeep Basin was a basin system developed at the front of northward-migrating Carpathian nappes. They formed, due to overload of the overthrusting nappes and deflection of pre-Miocene basement, a basin system that stretched arcuately over the distance of 1300 km from Austria, through the Czech Republic, Poland and Ukraine to Romania (e.g., Ney et al., 1974; Kotlarczyk, 1985; Oszczypko et al., 2006). Marine strata that filled the foredeep basin reached a variable thickness, even up to 5 km in the Ukrainian part. Their accumulation started during the Badenian (Langhian) correlated with the NN5 Calcareous Nannoplankton Zone (NN4 in the westernmost part of the Polish sector) and the M5 Planktonic Foraminifera Zone (Garecka et al., 1996; Garecka and Jugowiec, 1999; Olszewska, 1999; for zonal correlation see Berggren et al., 1995).

The Badenian marine transgression covered a geologically diverse basement, which caused that the basal intervals of the Miocene succession rest upon rocks of various ages in different areas of the Carpathian Foredeep – from Precambrian to Upper Cretaceous (see e.g., Karnkowski and Ozimkowski, 2001: figs. 2, 3; Oszczypko et al., 2006: fig. 2). In the eastern part of the Carpathian Foredeep, isolated sites with marine and continental Paleogene deposits occur at the base of the Miocene; they represent remnants of an Eocene and Oligocene cover eroded prior and/or during early stages of the Badenian transgression (e.g., Moryc, 1995; Gedl, 2000, 2012, 2015; Myśliwiec and Śmist, 2006). The pre-Miocene basement had been generally exposed to subaerial conditions at least since the latest Cretaceous; later, it underwent long-lasting erosional processes that led to a highly diverse relief, with over 1 km deep palaeovalleys (e.g., Karnkowski and Ozimkowski, 2001: figs. 1, 2). As a consequence, the earliest deposits of the Badenian transgression, as well as preceding continental deposits show high variability as they were deposited in a morphologically diverse area (see e.g., Bogacz, 1967; Radwański, 1968; Oszczypko and Tomaś, 1976, Kasiński and Piwocki, 1994; Moryc, 1995). The morphologically diverse basement included uplifted areas covered with vegetation and depressions occupied by lakes and/or bogs. Particularly suitable morphology convenient for phytogenic deposit accumulation appeared along the northern margin of the Carpathian Foredeep, where a gently inclined valley system occurred (e.g., Kasiński and Piwocki, 1994). Main outlines of this morphological system existed presumably already during the short-lasting Middle–Late Eocene and Early Oligocene transgressions that covered at least the eastern part of the Carpathian Foredeep in Poland (e.g., Buraczyński and Krzowski, 1994; Gedl, 2000, 2012, 2014, 2015). Hence, frequent facies changes can be expected in the Paleogene strata of this area, including interfingering of marine and continental facies.

MATERIAL AND METHODS

The Łukowa-4 borehole was drilled in the northeastern part of the Polish sector of the Carpathian Foredeep, near Tarnogród (Fig. 1). It penetrated the whole Miocene succession that is 803 m thick in this area (see Myśliwiec and Śmist, 2006). Below, the 803–809 m depth core interval (Fig. 2) consists of two different lithologies. Medium- to coarse-grained sands, non-cal-

Fig. 3. Lithology of the upper part of the coal beds and overlying sands in the Łukowa-4 borehole (from Gedl, 2015)

careous and pale in colour (whitish to beigish-brown), occur at the top of this interval (803.0–806.4 m). Six samples from these sands were studied (depths 803.0–803.2 m, 803.4–803.6 m, 804.1–804.2 m, 804.6–804.7 m, 805.2–805.3 m, 806.0–806.1 m). Below, brown coal and coaly clay and sand occur (806.4–809.0 m); four samples from these phytogenic deposits were studied (depths 806.4–806.5 m, 807.1–807.2 m, 807.8–807.9 m, and 808.9–809.0 m). The boundary between coal and pale sand is sharp (Fig. 3). Below, Upper Eocene glauconitic sands are underlain by Middle Jurassic sandy deposits (Gedl, 2015; Fig. 2).

These samples were processed in the micropalaeontological laboratory of the Institute of Geological Sciences, Polish Academy of Sciences, Kraków. The procedure applied included 38% hydrochloric-acid (HCl) treatment, 40% hydrofluoric-acid (HF) treatment, heavy-liquid ($ZnCl_2$ + HCl; density 2.0 g·cm^{-3}) separation, ultrasound for 10–15 s and sieving at 10 μm on a nylon mesh. The quantities of rock for analysis were variable, depending on the lithology: 120–200 g for sand samples and 10 g for phytogenic samples. The same set of samples was used by Gedl (2015). Additional slides were made and analysed for the present study. Palynological slides were made using glycerine jelly as a mounting medium. These rock samples, their palynological residues and slides are stored in the collection of the Institute of Geological Sciences, Polish Academy of Sciences, Kraków.

Three additional samples taken from brown coal (depths 806.25 m, 807.50 m and 808.50 m) were processed at the Polish Geological Institute – National Research Institute, Warszawa, using heavy-liquid (CdJ_2 + KJ; density 2.21 g·cm^{-3}) separation. Then, the organic content was processed according to the modified Erdtman's acetolysis method (Moore et al., 1991). Palynological slides were made from each sample, using glycerine jelly as a mounting medium.

Taxonomy of dinoflagellate cysts follows Fensome et al. (2008). The sporomorph taxa identified were classified to an appropriate palaeofloristical element, mainly on the basis of the Atlas of Pollen and Spores of the Polish Neogene (Stuchlik et al., 2001, 2002, 2009, 2014). The following palaeofloristical elements were distinguished (Appendix 1*): palaeotropical (P), including: tropical (P1) and subtropical (P2), as well as arctotertiary (A), including: warm-temperate (A1) and temperate (A2).

Dinoflagellate cysts and other aquatic palynomorphs were photographed (Figs. 4–7) using a *Carl Zeiss Axiolab* microscope with a *Sony DSC-S75* camera and *Carl Zeiss Achroplan x100* oil lens. Microphotographs of selected sporomorphs (Fig. 8) were taken using a *Nikon Eclipse* microscope fitted with a *Canon* digital camera.

RESULTS OF THE PALYNOLOGICAL STUDY

Samples from the 803–809 m interval were studied for palynofacies and dinoflagellate cysts by Gedl (2015). This paper presents results of palynological study of the same set of samples studied for sporomorphs (EW), results of sporomorph studies from three additional samples from coal beds (BS), and new results of dinoflagellate cyst studies from additional slides from the sandy interval (PG).

DINOFLAGELLATE CYSTS AND OTHER AQUATIC PALYNOMORPHS

Coal beds (806.4–809 m). Phytogenic strata yielded no marine dinoflagellate cysts; frequent forms of uncertain origin, possibly freshwater algae (dinoflagellate cysts?) were found in a sample from 807.1–807.2 m depth (Gedl, 2015: fig. 9H–K).

Sandy interval (803.0–806.4 m). Dinoflagellate cysts occur in all five samples from this interval; their distribution is shown in

* Supplementary data associated with this article can be found, in the online version, at doi: 10.7306/gq.1305

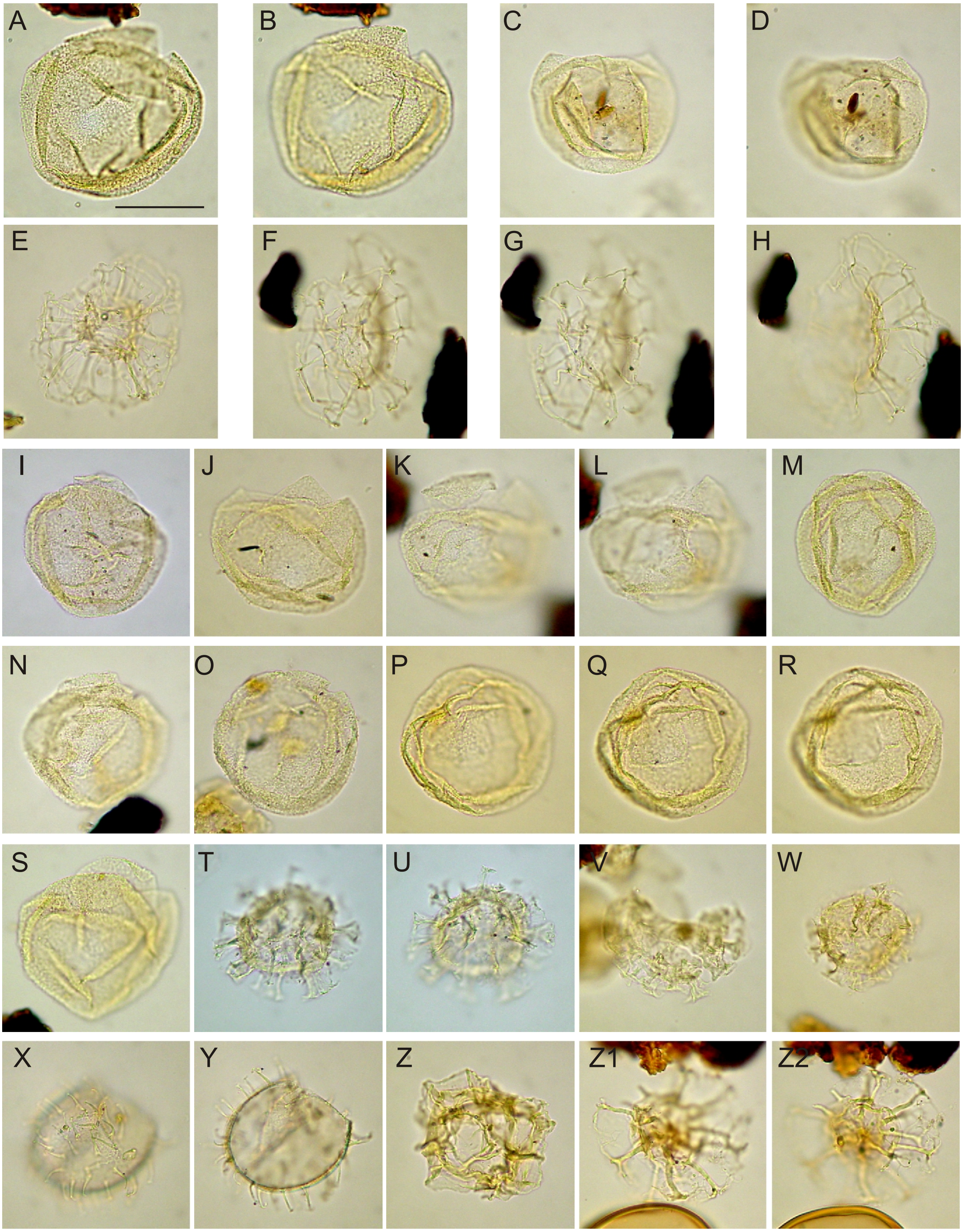

Fig. 4. Dinoflagellate cysts from the sands at the 803.0–806.4 m depth in the Łukowa-4 borehole

A, B – large, over 50 μm in diameter, specimen of *Batiacasphaera micropapillata*; **C, D, I–S** – *Batiacasphaera micropapillata*; **E–H** – *Nematosphaeropsis labyrinthus*; **T, U** – *Labyrinthodinium truncatum truncatum*; **V, W** – *Labyrinthodinium truncatum modicum*; **X, Y** – *Operculodinium* sp.; **Z** – *Impagidinium*? sp.; **Z1, Z2** – *Reticulatosphaera actinocoronata*; A–I, Z1, Z2: 803.0–803.2 m, J, X–Z: 803.4–803.6 m; K, L, N–R: 804.1–804.2 m; M, S–W: 805.2–805.3 m

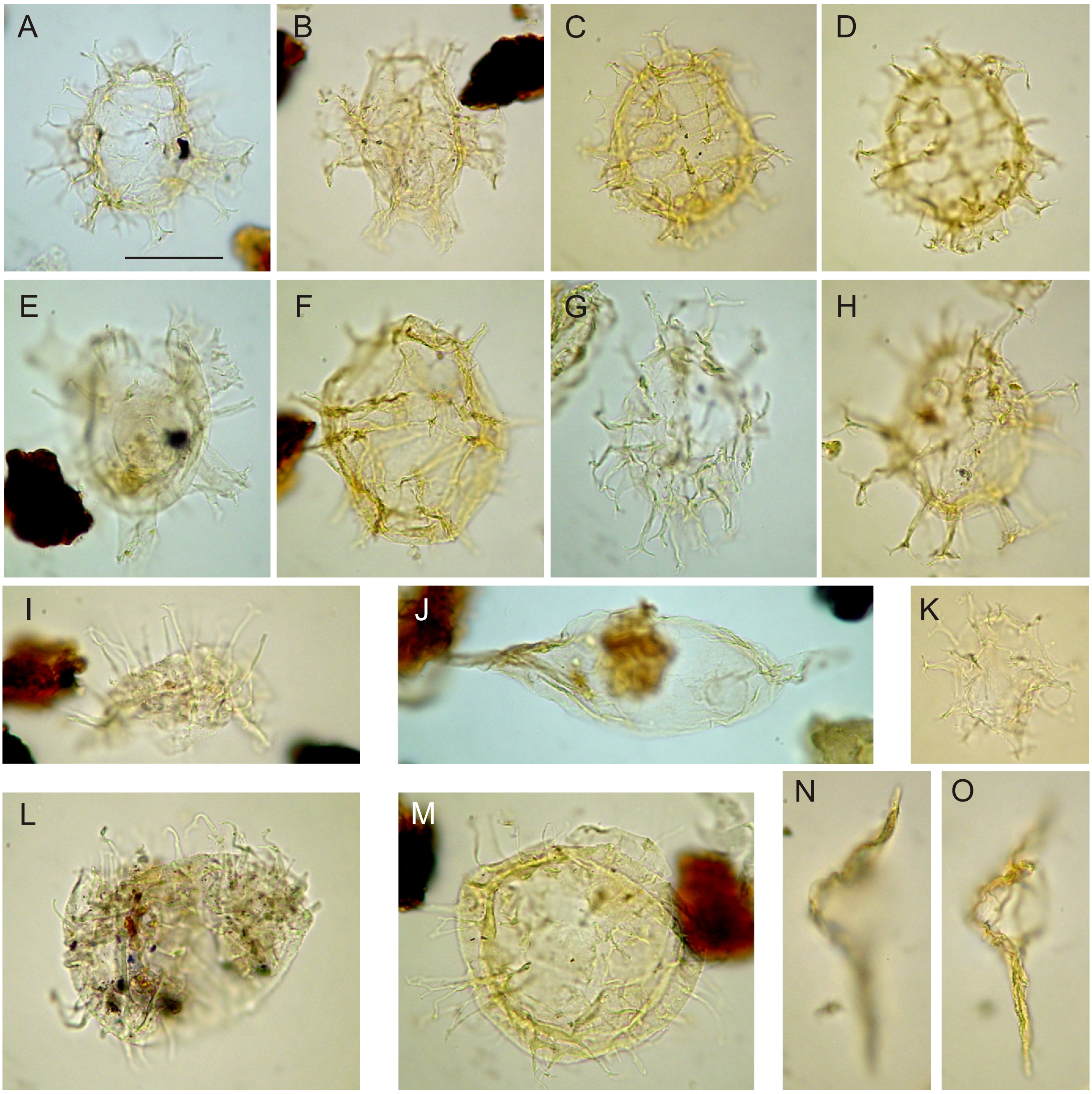

Fig. 5. Dinoflagellate cysts from the sands at the 803.0–806.4 m depth in the Łukowa-4 borehole

A–D – *Spiniferites* spp.; **E** – *Hystrichokolpoma rigaudiae*; **F–H** – *Spiniferites* spp.; **I** – isolated operculum of *Cleistosphaeridium placacanthum*; **J** – *Palaeocystodinium golzowense*; **K** – *Spiniferites* sp.; **L** – *Cleistosphaeridium placacanthum*; **M** – *Cleistosphaeridium* ?*ancyreum;* **N, O** – "*Palaeocystodinium striatogranulosum*"; scale bar in A is 25 µm and refers to all photographs; A, C–I, L, M: 805.2–805.3 m; B, J, N, O: 803.0–803.2 m; K: 806.0–806.1 m

Appendix 1 and the specimens are presented in Figures 4, 5 and 7. Dinoflagellate cysts are rare to very rare, being highly dispersed by terrestrial elements. The latter are main elements of palynofacies: all samples yielded a generally uniform palynofacies consisting of dark brown and black equidimensional phytoclasts and sporomorphs (mainly bisaccate pollen grains; see below). Their proportion may vary from sample to sample; the highest proportions of black opaque phytoclasts and bisaccate pollen grains are in samples from 803.3–803.4 m and 806.0–806.1 m depths.

Dinoflagellate cyst assemblages are the mixtures of variously preserved forms. Generally, they include very well-preserved, pale-coloured specimens, and darker, much worse-preserved, commonly indeterminable forms. Unfortunately, this division cannot be simply correlated with various ages, as it could be suspected according to the following scheme: darker, poorly preserved forms are reworked, whereas the pale-coloured ones are *in situ* (see chapter Age interpretation).

Well-preserved forms include both specimens considered to be *in situ* (i.e., species with known stratigraphic ranges not

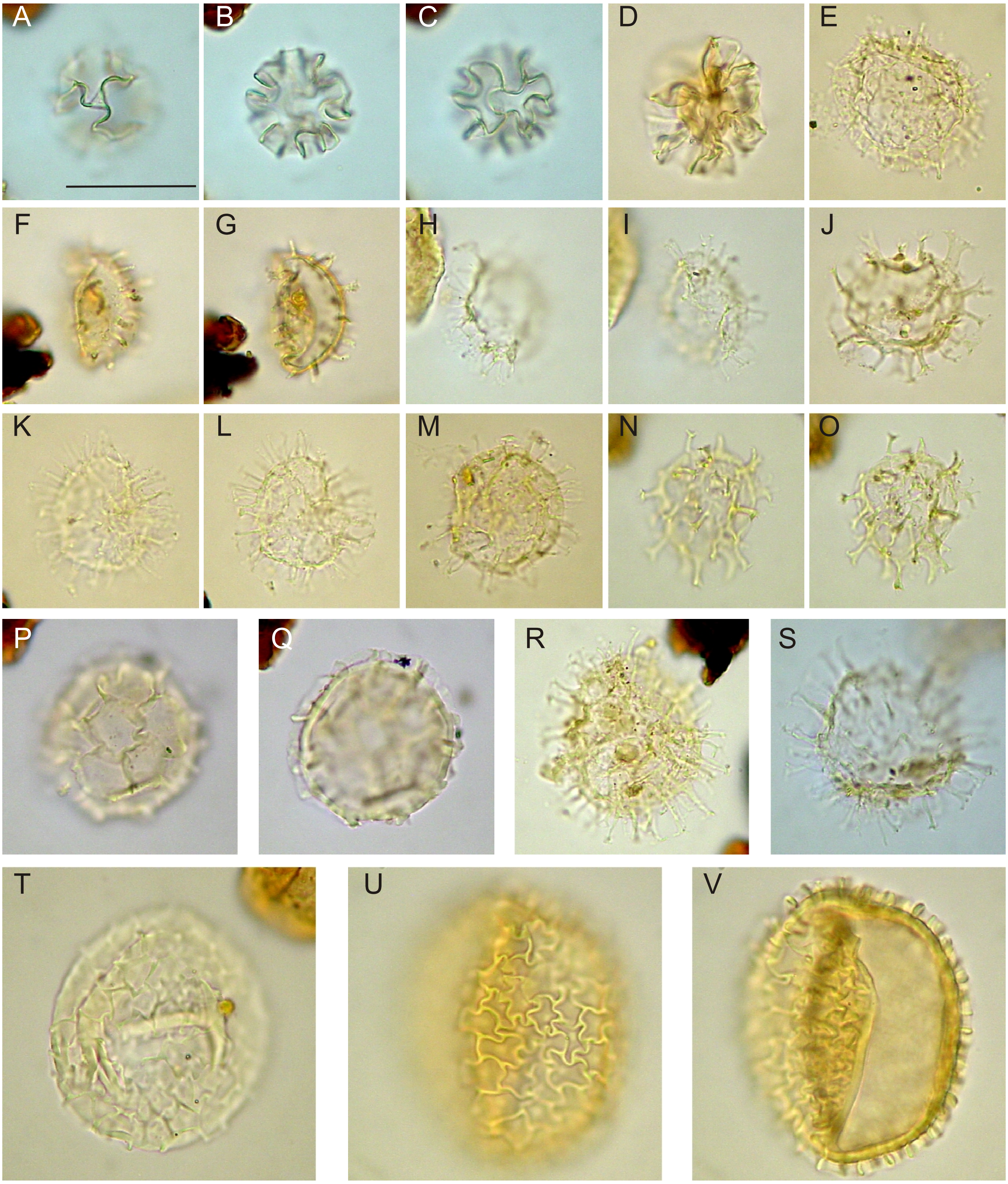

Fig. 6. Acritarchs and prasinophyceans from the sands at the 803.0–806.4 m depth in the Łukowa-4 borehole

A–D – *Cymatiosphaera* sp. 1; **E–G** – *Nannobarbophora gedlii*; **H–O** – relatively small chorate acritarchs, ?*Micrhystridium*; **P, Q** – *Cymatiosphaera* sp. 2; **R, S** – relatively large chorate acritarch, ?*Micrhystridium*; **T–V** – *Cymatiosphaera* sp. 3; A–D, F, G, P–R: 803.0–803.2 m; E: 806.0–806.1 m; H–O, S–V: 805.2–805.3 m; scale bar in A is 25 μm and refers to all photographs

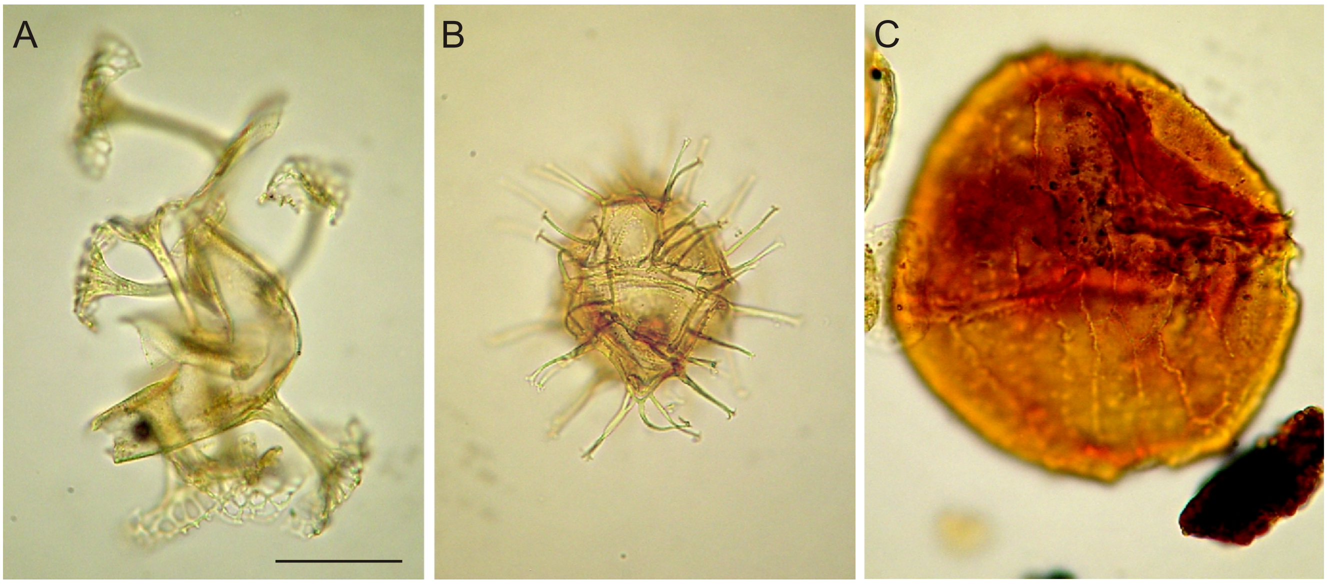

Fig. 7. Reworked dinoflagellate cysts from the sands at the 803.0–806.4 m depth in the Łukowa-4 borehole

A – *Areosphaeridium diktyoplokum*; **B** – *Phthanoperidinium comatum*; **C** – *Cribroperidinium* sp.; A, B: 803.4–803.6 m, C: 803.0–803.2 m; scale bar in A is 25 µm and refers to all photographs

older than Early–Middle Miocene), and specimens reworked from older strata (i.e., species known to have appeared for the last time before the Miocene). Representatives of the first group are Eocene species (e.g., *Areosphaeridium diktyoplokum*, *Phthanoperidinium comatum*; Fig. 7A, B) that most likely come from underlying Eocene sands (Gedl, 2015; see also Gedl, 2012). Cretaceous species are also well-preserved but infrequent and slightly darker than the Eocene ones (e.g., *Cribroperidinum* sp., *Surculosphaeridium*? *longifurcatum*; Fig. 7C). Species *in situ* are *Labyrinthodinium truncatum truncatum, L. truncatum modicum*, and "*Palaeocystodinium striatogranulosum*" – all appeared for the first time during the Early Miocene (e.g., Williams et al., 2004).

Their distinction is based solely on comparison of their ranges, as the preservation state is the same. This bears a problem in assigning the correct age to well-preserved species with Paleogene–Neogene age-range such as *Batiacasphaera micropapillata*, *Cleistosphaeridium* ?*ancyreum*, *C. placacanthum*, *Hystrichokolpoma rigaudiae*, *Impagidinium* sp., *Lingulodinium machaerophorum*, *Nematosphaeropsis labyrinthus*, *Operculodinium* sp., *Palaeocystodinium golzowense*, *Reticulatosphaera actinocoronata*, and *Spiniferites* spp. They are treated arbitrarily as *in situ* here. Some of these species found in the present material have bimodal state of preservation (*Li. machaerophorum, R. actinocoronata, Spiniferites* spp.) which suggests that they may represent both reworked (Paleogene) and *in situ* forms (Miocene).

Poorly preserved forms, commonly incomplete and showing a higher degree of maturity, are evidently reworked; *Wetzeliella* sp. and *Deflandrea* sp. come from Paleogene strata; several others, indeterminable, may be also of Mesozoic age.

Dinoflagellate cysts are associated by well-preserved acritarchs and *Cymatiosphaera* (*Prasinophycean* algae; Fig. 6). Acritarchs are represented by subspherical chorate species, some attributable to *Nannobarbophora gedlii* found in samples from 803.0–803.2 and 806.0–806.1 m depths (Fig. 6F, G). The other chorate forms are questionably attributed to *Micrhystridium*, among which a simple division is made between smaller (up to 25 µm diameter; Fig. 6H–O) and larger forms (Fig. 6R, S).

Cymatiosphaera is represented by three species that differ by size and height of their crests. *Cymatiosphaera* sp. 1 is a small form with high crests; its diameter does not exceed 25 µm (Fig. 6A–D). *Cymatiosphaera* sp. 2 is slightly larger with very short crests that form relatively large polygonal fields (Fig. 6P, Q). The largest is *Cymatiosphaera* sp. 3, which is over 30 m in diameter; low crests form a dense pattern of smooth polygonal fields (Fig. 6T–V); this species resembles *Cymatiosphaera* sp. B from the Miocene of the Ukrainian Carpathian Foredeep Basin, which differ by positive relief on polygonal fields (Gedl et al., 2016). It should be noted that *Cymatiosphaera* sp. 1 and *Nannobarbophora gedlii* occur in the Kortynica Clays (the latter as *Svenkodinium versteeghii*; Gedl, 1996).

SPOROMORPHS

Sporomorph assemblages suitable for detailed studies have been found in five samples (803.0–803.2 m, 803.4–803.6 m, 804.1–804.2 m, 804.6–804.7 m, and 805.2–805.3 m depths). Pollen grains and spores are very frequent in most of them, but their preservation varies from excellently preserved specimens to completely corroded ones (especially bisaccate pollen grains) with highly damaged structure. Samples from the 806.0–806.1 and 807.10 m depths were barren. Samples from the 806.4–806.5 m, 807.1–807.2 m, 807.8–807.9 m depths contain no sporomorphs, however, colonies of *Botryococcus* algae were encountered in these samples. Although the samples taken from brown coal (806.25 m, 807.50 m and 808.50 m depths) yielded only sparse pollen grains and spores, but they included several stratigraphically important species.

A total of 72 fossil species (including 16 species of plant spores, 13 species of gymnosperm pollen, and 43 species of angiosperm pollen) were identified (Fig. 8 and Appendix 1). In all samples, pollen grains of conifers clearly prevail (Appen-

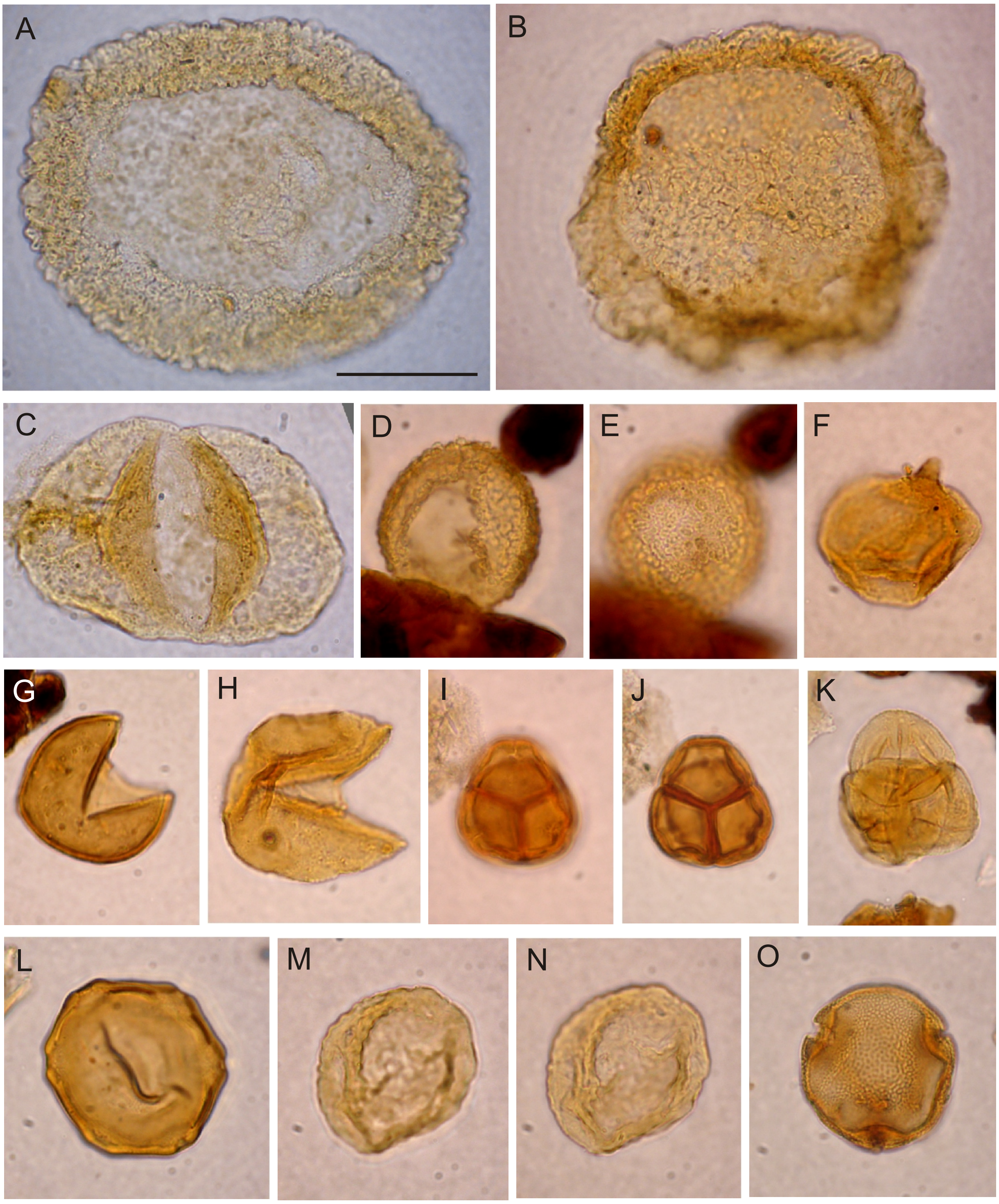

Fig. 8. Pollen grains from the sands at the 803.0–806.4 m depth in the Łukowa-4 borehole

A, B – *Zonalapollenites* sp.; **C** – *Cathayapollis* sp.; **D, E** – *Sciadopityspollenites serratus*; **F** – *Sequoiapollenites* sp.; **G** – *Inaperturopollenites* sp.; **H** – *Inaperturopollenites concedipites*; **I, J** – *Ericipites callidus*; **K** – *Ericipites* sp.; **L** – *Polyatriopollenites stellatus*; **M, N** – *Ulmipollenites undulosus*; **O** – *Intratriporopollenites* sp.; scale bar in A is 25 μm and refers to all photographs; A, C, H, L, O: 805.2–805.3 m; B, F, G, I–K, M, N: 803.0–803.2 m; D, E: 804.6–804.7 m; H: 805.2–805.3 m

dix 1). Some bisaccate pollen grains are included into "small bisaccates" group, which includes corroded, difficult to determine specimens, probably, at least partly, recycled.

Coal beds (806.4–809 m). Samples taken from brown coal were prepared using two different methods, including heavy-liquid separation with two different liquids: $ZnCl_2$ + HCl (density 2.0 g·cm^{-3}) and CdJ_2 + KJ (density 2.21 g·cm^{-3}). Only samples prepared with the later mixture (depth 808.50–806.25 m) yielded sparse sporomorphs. In these samples, Cupressaceae, *Sciadopitys* and bisaccate pollen grains of Pinaceae are relatively common. Angiosperms are represented by pollen grains of fossil species *Cupuliferoipollenites pusillus*, *Fususpollenites fusus*, *Momipites quietus*, *Myricipites* sp., *Platanipollis ipelensis, Platycaryapollenites* sp., *Symplocoipollenites* sp., *Tricolporopollenites fallax*, *T. pseudocingulum*, Ericaceae and *Betula*. Among spores, i.a., *Cicatricosisporites dorogensis*, *Ci. paradorogensis*, and *Neogenisporis neogenicus* are recorded. These samples contain colonies of *Botryococcus* and some algae of uncertain taxonomy in a sample from 807.1–807.2 m depth, interpreted by Gedl (2015) as possibly freshwater dinoflagellate cysts.

Many fossil species recorded in the brown coal (spores of *Cicatricosisporites dorogensis*, *Ci. paradorogensis* and *Neogenisporis neogenicus* as well as pollen grains of *Cupuliferoipollenites pusillus*, *Fususpollenites fusus*, *Momipites quietus*, *Myricipites* sp., *Platanipollis ipelensis*, *Platycaryapollenites* sp., *Symplocoipollenites* sp., *Tricolporopollenites fallax* and *T. pseudocingulum*) represent palaeotropical (including tropical and subtropical) and palaeotropical/warm-temperate palaeofloristical elements (Appendix 1).

Sandy interval (803.0–806.4 m). Most samples taken from the deposits above the brown coal (depth 803.0–805.2 m) are rich in pollen grains and spores, but the preservation of the sporomorphs varies from excellently preserved specimens to completely corroded ones. In all samples from the uppermost part of the Łukowa-4 borehole, bisaccate pollen grains clearly prevail. Among them, *Pinus* and *Cathaya* (fossil species *Pinuspollenites labdacus, P*. sp., *Cathayapollis* sp.) as well as *Picea* are most frequent. In addition, single specimens of *Abies* pollen were encountered. Non-bisaccate pollen grains of conifers are also frequent in all these samples. Among them, pollen of *Taxodium*/*Glyptostrobus* (fossil genus *Inaperturopollenites*), *Sciadopitys*, *Tsuga* as well as *Sequoia* and other members of the Cupressaceae family are most important.

Among angiosperms, trees and shrubs strongly dominate, whereas only a few pollen grains of herbs are present. Pollen grains of Ericaceae, *Ulmus, Alnus, Tricolporopollenites pseudocingulum, Quercus* (fossil species *Quercoidites henrici* and *Quercopollenites* sp.), *Fagus, Myrica, Nyssa, Carya, Pterocarya, Betula, Castanea*/*Castanopsis* (mainly fossil species *Cupuliferoipollenites pusillus*), *Carpinus, Acer,* Mastixiaceae (fossil species *Cornaceaepollis satzveyensis*), *Eucommia, Trigonobalanus* (fossil species *Fususpollenites fusus*), Malvaceae (fossil genus *Intratriporopollenites*), and *Engelhardia* (fossil species *Momipites punctatus*) are most frequent. In addition, single specimens of Fabaceae (fossil species *Tricolporopollenites liblarensis* and *T. fallax*), Cyrillaceae/Clethraceae (fossil species *Cyrillaceaepollenites exactus*), *Fraxinus, Juglans, Liquidambar, Ilex,* Sapotaceae, *Zelkova*, and cf. *Edmundipollis* sp. were recorded.

Cryptogams are represented mainly by spores of ferns (mainly fossil species *Leiotriletes* sp., *Laevigatosporites* sp., *Neogenisporis neogenicus*, *Neogenisporis* sp., *Toroisporis* sp., *Baculatisporites* sp.), *Sphagnum* and members of the family Lycopodiaceae (fossil species *Retitriletes* sp., *Camarozonosporites* sp., and *Selagosporis* sp.).

In these samples, dinoflagellate cysts and acritarchs are present associated by rare Prasinophyceae (*Cymatiosphaera*), whereas other algae are almost absent (only one colony of *Botryococcus* encountered). Fungal spores are also very rare.

In addition, in all samples from the uppermost part of the Łukowa-4 borehole, some corroded bisaccate pollen grains included into “small bisaccates” group, at least partly recycled, are present. Moreover, in these samples other recycled pollen grains and spores are encountered. These spores are usually dark-coloured and have thick walls.

In all samples from the uppermost part of the Łukowa-4 section, palaeotropical (including tropical and subtropical) and palaeotropical/warm-temperate palaeofloristical elements are present (Appendix 1). The palaeotropical and palaeotropical/warm-temperate elements are represented by spores of, i.a., *Camarozonosporites* sp., *Leiotriletes* sp., *Neogenisporis neogenicus*, *N*. sp., and *Toroisporis* sp. as well as pollen grains of *Inaperturopollenites concedipites*, *I. dubius*, *Cornaceaepollis satzveyensis, Cupuliferoipollenites oviformis*, *Cu. pusillus, Cyrillaceaepollenites exactus*, *Fususpollenites fusus*, *Ilexpollenites margaritatus*, *Intratriporopollenites* sp., *Momipites punctatus*, *Myricipites* sp., *Nyssapollenites* sp., *Oleoidearumpollenites* sp., *Quercoidites henrici*, *Platycaryapollenites* sp., *Sapotaceoidaepollenites* sp., *Tricolporopollenites pseudocingulum*, and *T. staresedloensis*.

RECONSTRUCTION OF PLANT COMMUNITIES AND PALAEOENVIRONMENT

Coal beds (806.4–809 m). The strata from this interval accumulated in a terrestrial environment (Fig. 9). The presence of colonies of *Botryococcus* points to a freshwater environment, probably shallow lakes or bogs with periodic blooms of *Botryococcus* (Gedl, 2015). Relatively numerous palaeotropical elements suggest warm climate during sedimentation of these lignite deposits.

Although the coal samples from the 808.25–806.50 m depth interval yielded only sparse pollen grains and spores, results of palynological analysis of these samples indicate the presence of mixed forests with a significant portion of thermophilous taxa. In the vicinity there were also, i.a., members of the family Fagaceae (probably from the genera *Trigonobalanus*, *Castanea* and others), *Engelhardia, Platanus, Platycarya, Symplocos, Betula,* members of the families Myricaceae, Fabaceae, Ericaceae and others. Conifers were important elements of vegetation. Members of the families Pinaceae, Cupressaceae, and *Sciadopitys* were also present. Cryptogams were represented by thermophilous ferns from the families Schizaeaceae, Lygodiaceae and probably Gleicheniaceae.

Sandy interval (803.0–806.4 m). The presence of marine dinoflagellate cysts in sands above the coal beds indicates a marine sedimentary setting (Fig. 9). High proportion of sporomorphs, including relatively frequent spores (that are not as buoyant as the pollen grains) may indicate a nearshore marine setting along a coast covered by vegetation. The dinoflagellate cyst assemblages themselves have a limited value for precise environmental reconstruction as their true taxonomic composition is uncertain (they consist in part of reworked species; see chapter Dinoflagellate cysts and other aquatic palynomorphs). However, if the presented interpretation is acceptable, then a dominance of *Batiacasphaera micropapillata* is outstanding. Although palaeoenvironmental preferences of this species are unknown, but similar *Batiacasphaera*-dominated assemblages were described from an approximately coeval nearshore facies of the Middle Miocene strata of the Carpathian Foredeep. Common occurrence of *B. micropapillata* (associated with frequent *B. sphaerica*) was reported from the nearshore Korytnica Clays (Gedl, 1996). Gedl (1995) compared this nearshore assemblage with coeval assemblages from offshore facies that are devoid of this species (they include frequent *Impagidinium*, *Unipontidinium aquaeductum* and “*Palaeocystodinium striatogranulosum*”). Frequent *Batiacasphaera* was reported from basal strata of the Miocene succession in the westernmost part of the Carpathian Foredeep in Poland (Gedl, 1997).

The results of pollen analysis of samples taken above the coal (803.0–805.2 m depth) indicate the presence of mixed mesophytic forests, bush swamps, swamp forests, and riparian forests (Fig. 9). The swamp forests grew in the neighbouring area with a higher groundwater level and were composed of *Taxodium*, *Nyssa*, and probably also *Glyptostrobus* and *Alnus*. Wet places in the vicinity were probably overgrown by riparian forests composed of *Ulmus, Alnus, Carya, Pterocarya, Acer, Fraxinus*, *Liquidambar*, and others.

The drier places were overgrown by mesophytic forests rich in thermophilous taxa. These mesophytic forests were composed, i.a., of trees and shrubs from the family Fagaceae (probably from the genera *Quercus, Castanea, Trigonobalanus, Fagus,* and others), *Betula, Carpinus, Engelhardia, Eucommia, Acer*, and *Zelkova*, and members of the families Mastixiaceae, Malvaceae, Fabaceae, and Sapotaceae, as well as conifers, ferns, and many others. Some bisaccate pollen grains from the Pinaceae family (e.g., *Pinus*) possibly also come from plant communities growing on elevated terrains, at a distance from the locality. Nevertheless, *Cathaya, Pinus, Sciadopitys, Tsuga* and *Sequoia* were most probably important trees in the mixed forests, or they formed their own plant communities in the vicinity.

Members of the families Ericaceae, Cyrillaceae, Clethraceae and Myricaceae were probably components of bush swamps.

Composition of the palynological assemblage from the uppermost part of the Łukowa-4 section indicates that the climate during deposition of the sediment was relatively warm, although less frequent thermophilous taxa recorded in this interval suggest a little cooler conditions than deduced from the underlying spectra (Fig. 9).

AGE INTERPRETATION

Coal beds (806.4–809 m). Composition of the spore-pollen assemblage from the coal, including such fossil species as *Cupuliferoipollenites pusillus*, *Fususpollenites fusus*, *Momipites quietus*, *Platanipollis ipelensis*, *Symplocoipollenites* sp., *Tricolporopollenites fallax*, *T. pseudocingulum* and *Neogenisporis neogenicus*, generally points to Oligocene or Lower Miocene age of the material. In addition, two fossil species *Cicatricosisporites dorogensis* and *Ci. paradorogensis* were recorded among the spores. These two species have their upper stratigraphic limit in the Early Oligocene (Grabowska, 1996b) and their presence, together with the whole composition of the assemblage, indicates that the age of the lignite is most probably Lower Oligocene (Fig. 9).

Sandy interval (803.0–806.4 m). Among dinoflagellate cyst species considered to be *in situ* (see chapter Dinoflagellate cysts and other aquatic palynomorphs) two species have relatively short stratigraphic ranges that allow dating of the sands above the coal beds. These are *Labyrinthodinium truncatum truncatum*, *L. truncatum modicum*, and “*Palaeocystodinium striatogranulosum*”. “*P. striatogranulosum*”, an informally described species by Zevenboom and Santarelli (in Zevenboom, 1995) from the Miocene of Italy, is believed to have a stratigraphical range limited to the Late Aquitanian–Early Tortonian (NN2–8 zones; Zevenboom, 1995; see also Williams et al., 2004). In the material studied, only a single specimen of this species is noted (sample from 803.0–803.2 m depth); its scarcity may be associated with possibly offshore preferences of this species as suggested by Gedl (1995). *Labyrinthodinium truncatum*, as a species, is given various ages of its first appearances depending on latitudes (Williams et al., 2004): Late Aquitanian in high latitudes of the Northern Hemisphere, Burdigalian/Langhian interval in mid-latitudes of the Northern Hemisphere, and mid-Langhian in equatorial areas (the two latter applicable to the position of the material studied). The Langhian first appearance of this species was suggested by, i.a., Piasecki (1980), Zevenboom (1995), Munsterman and Brinkhuis (2004); see also De Verteuil and Norris (1996) for discussion. The latter authors suggested a slightly lower the lowest occurrence of the subspecies *L. truncatum modicum* in the NN4 Zone (i.e., possibly in the Upper Burdigalian; for correlation see Berggren et al., 1995). The presence of both species, but particularly *Labyrinthodinium truncatum*, shows that the sands that overlie coal beds in the Łukowa-4 borehole are likely not older than Middle Miocene (Fig. 9).

Composition of the spore-pollen spectra from the sands is generally similar to those from the Oligocene to Middle Miocene palynofloras from Poland (see Discussion). The assemblage studied is rich in pollen grains of the Ulmaceae (fossil genus *Ulmipollenites*) and Ericaceae families. In addition, there are abundant pollen of such conifers as *Pinus, Sciadopitys*, and *Tsuga*. The whole assemblage is relatively poor in species and dominated by arctoteriary elements. These features of the spore-pollen spectra are most similar to the Early to Middle Miocene assemblages from its cooler climatic phases (see Piwocki and Ziembińska-Tworzydło, 1997; Ziembińska-Tworzydło, 1998), particularly to palynofloras from climatic phase IV – *Ulmipollenites* spore-pollen zone, Late Burdigalian in age. On the other hand, relatively significant presence of palaeotropical and palaeotropical/warm-temperate elements is recorded (including fossil species *Camarozonosporites* sp., *Leiotriletes* sp., *Neogenisporis neogenicus, Neogenisporis* sp., *Toroisporis* sp., *Cornaceaepollis satzveyensis, Cupuliferoipollenites oviformis*, *Cu. pusillus*, *Cyrillaceaepollenites exactus*, *Fususpollenites fusus*, *Momipites punctatus*, *Quercoidites henrici*, *Platycaryapollenites* sp., *Sapotaceoidaepollenites* sp., *Tricolporopollenites pseudocingulum*, and *T. staresedloensis*). In this case, we can suspect that the more resistant pollen grains (Ericaceae, *Ulmus, Pinus*) could be over-represented and therefore the spore-pollen assemblage from the sandy interval has only a limited stratigraphic significance.

DISCUSSION

The dating of the coal beds from the Łukowa-4 borehole suggests that they accumulated during the Early Oligocene. Finding of Lower Oligocene coal beds in the Carpathian Foredeep adds important data to palaeogeographic reconstructions of the Carpathian foreland during the Paleogene. It shows that there were some emerged areas in the Rupelian, although most of the area was covered by the sea. The coal beds from the Łukowa-4 borehole can be correlated with marine sands described from neighbouring boreholes near Tarnogród (Gedl, 2000); they yielded dinoflagellate cysts such as *Areoligera*? *semicirculata, Chiropteridium galea, Ch. lobospinosum, Pentadinium laticinctum, Reticulatosphaera actinocoronata, Rhombodinium draco, Wetzeliella gochtii*, and *W. symmetrica incisa*. Age of their assemblages, as compared with stratigraphic ranges given by Williams et al. (2004), is Late Rupelian–earliest Chattian. A similar age can be suggested by comparison with Oligocene dinoflagellate cyst assemblages from epicontinental strata of central and northern Poland, described by Grabowska (1974, 1987, 1996a), Grabowska and Ważyńska (1997), and Słodkowska (2004a, b). These assemblages included frequent

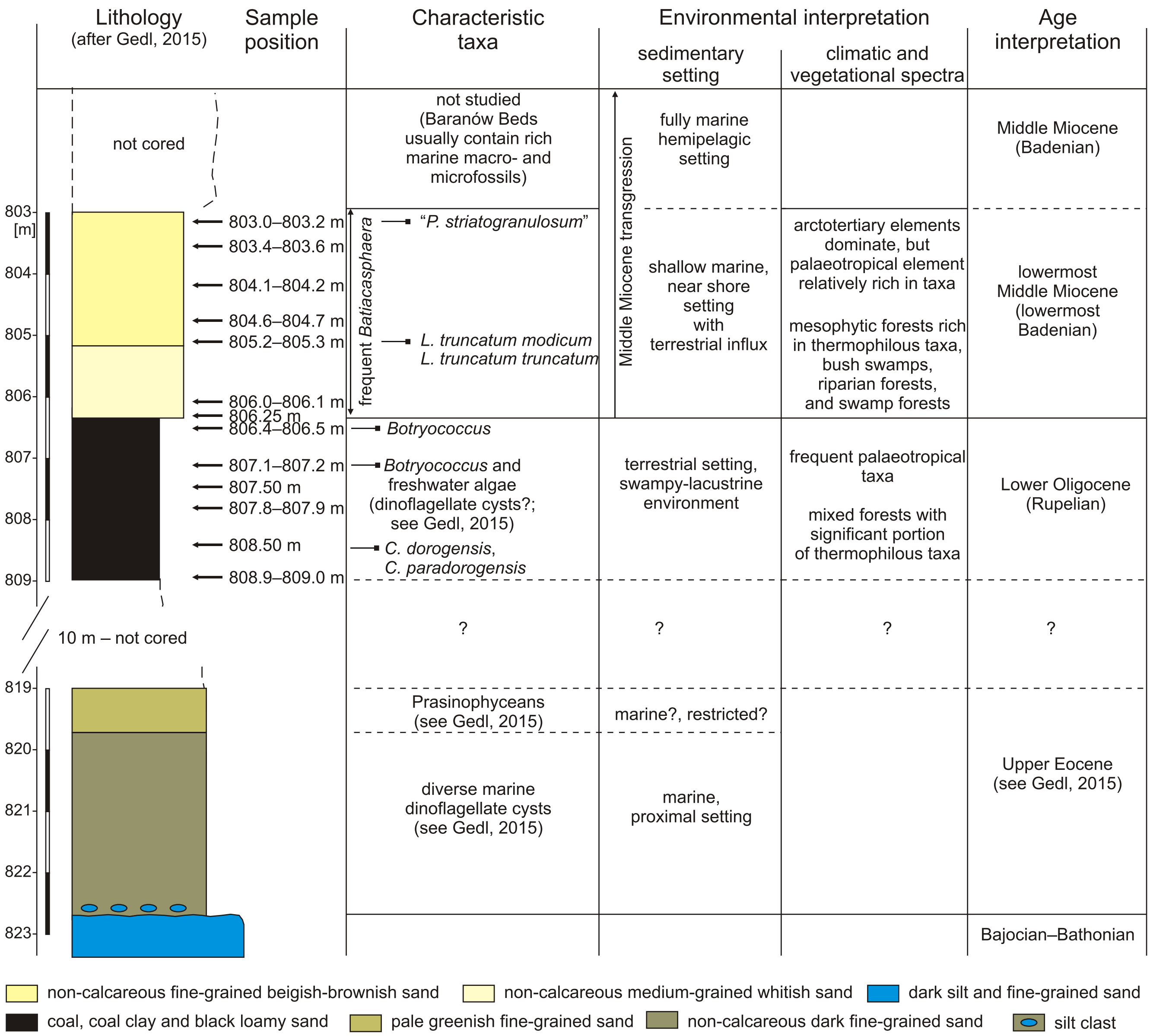

Fig. 9. Synthetic compilation of the Paleogene and basal Miocene interval from the 803–823 m depth in the Łukowa-4 borehole

Chiropteridium lobospinosum, associated with, i.a., *Wetzeliella symmetrica* and *Rhombodinium draco*.

This correlation is further supported by comparison of sporomorphs from the upper part of the Lower Oligocene section in the Polish Lowlands, which is represented by the marine Rupel Formation (an equivalent of the Septarian Clays and Boom Clays from NW Europe; see Piwocki, 2004) and the Upper Mosina Formation, as well as the continental/brackish Czempin Formation (formerly the Toruń Clays; see Piwocki, 2004). The spore-pollen spectra from these strata include, i.a., *Cicatricosisporites dorogensis, Camarozonosporites heskemansis, Boehlensipollis hohli, Cupanieidites eucalyptoides, Fususpollenites fusus, Cupuliferoipollenites pusillus, Cu. oviformis, Edmundipollis edmundi, Tricolporopollenites liblarensis, T. fallax, T. staresedloensis, Quercoidites microhenrici, Momipites quietus, Platycaryapollenites, Platanipollis ipelensis* (e.g., Grabowska, 1965, 1983, 1987; Grabowska and Piwocki, 1975; Słodkowska, 2009). Accordingly, the composition of the sporomorph assemblage from the brown coal in the Łukowa-4 borehole (806.4–809 m depth), particularly the presence of *Cicatricosiporites dorogensis, Ci. paradorogensis, Platanipollis ipelensis*, *Fususpollenites fusus* and small tricolporate pollen grains, points to similarity of the above-mentioned assemblage to the Lower Oligocene palynofloras from the Polish Lowlands.

Our discovery of Lower Oligocene phytogenic deposits in the Carpathian Foredeep, and their correlation with coeval marine strata in the neighbourhood, suggest that the basement of the Carpathian foreland during the Early Oligocene was morphologically diverse. The Rupelian marine transgression inundated down-dropped areas, whereas on elevated areas, phytogenic terrestrial accumulation took place in continental, freshwater conditions, most likely in a lacustrine environment, as indicated by the presence of *Botryococcus*. However, data scarcity (the Łukowa-4 borehole material is the only so-far discovered trace of Early Oligocene terrestrial accumulation in the Carpathian Foredeep) does not justify a further-reaching palaeogeographic reconstruction. Moryc (1995) described continental deposits below the Miocene succession in the eastern part of the Carpathian Foredeep in the Rzeszów region, but the precision of the earlier dating of those deposits does not allow correlation with the Łukowa-4 phytogenic series.

A similar morphology was postulated for early stages of the subsequent Miocene marine transgression that covered the morphologically highly diverse basement (e.g., Czarnocki, 1958; Radwański, 1968; Oszczypko and Tomaś, 1976, Kasiński and Piwocki, 1994; Moryc, 1995; Karnkowski and Ozimkowski, 2001). At that time, similar continental to brackish sedimentary settings occupied the northern margin of the foredeep, where phytogenic accumulation took place (e.g., Kasiński and Piwocki, 1994). These coal beds are commonly underlain by sandy deposits of uncertain, presumably Paleogene age (see example of the coal beds from Trzydnik; Kasiński and Piwocki, 1994: figs. 3, 5a). The Lower Oligocene coal beds from the Łukowa-4 borehole occupy a similar stratigraphic position (they are underlain by the Upper Eocene in this borehole). These similarities may indicate that some of the phytogenic deposits of the Carpathian Foredeep, which are commonly devoid of fossils (or contain long-ranging freshwater/brackish forms), are in fact Oligocene in age.

Another problem in palaeogeographic reconstructions of Early Oligocene palaeoenvironments of the Carpathian foreland results from the lack of cored material below the coal beds in the Łukowa-4 borehole (806.4–809 m depth), which does not allow tracing the relation between the coal beds and underlying strata. The coal beds in the Łukowa-4 borehole are separated from the Upper Eocene sands by an almost 10 m thick gap (Gedl, 2015). Lack of core material from this interval makes that it is not possible to find out whether the coal beds rest upon the Oligocene marine sand (like that known from the nearby boreholes at Tarnogród; Gedl, 2000; Myśliwiec and Śmist, 2006; Fig. 1) and represent a record of a shallowing marine basin that gradually became brackish and freshwater, and the lacustrine phytogenic deposition is a result of a final phase in a regressive cycle, or the coal beds overlie older Eocene strata and they represent a facies laterally interfingering with marine sands.

Our age interpretation of the coal beds in the Łukowa-4 borehole is also important for tectonic studies of the Carpathian Foredeep, as these strata have been used as a correlative level with some Miocene phytogenic deposits, e.g., at Siedliska and Dąbrówka from the Roztocze area (e.g., Krąpiec et al., 2011; Fig. 1). However, the palynoflora in the lignite from the Łukowa-4 section shows some similarities to the Miocene assemblages from Siedliska and Dąbrówka. Brown coals from the two latter localities were dated palynologically to Early or Middle Miocene (most probably Karpatian; Worobiec in Krąpiec et al., 2011). The spore-pollen assemblage from the Łukowa coal, like both palynofloras from Roztocze, is rich in palaeotropical taxa. Nevertheless, different taxa dominate in particular assemblages. In both palynofloras from Siedliska and Dąbrówka, numerous pollen grains of *Edmundipollis* sp., *Cupuliferoipollenites oviformis*, *Ilexpollenites margaritatus, I. propinquus, I. iliacus, Quercoidites henrici*, *Cyrillaceaepollenites exactus*, *Tricolporopollenites liblarensis*, *T. quisqualis, Cornaceaepollis satzveyensis*, *Platycaryapollenites* sp., and *Arecipites* sp. were recorded. In contrast, pollen of those species is absent in the palynoflora from the Łukowa coal, but such species as *Platanipollis ipelensis*, *Cicatricosisporites dorogensis* and *Ci. paradorogensis* are recorded. These differences also suggest that the Łukowa coal is most probably older than the brown coal from Siedliska and Dąbrówka.

Other sites with phytogenic deposits in SE Poland are also younger than the coal beds from the Łukowa-4 borehole. Lignite-bearing deposits in the Trzydnik area (northern margin of the Carpathian Foredeep; Fig. 1) accumulated during the latest Karpatian and Early Badenian (Moravian) on the basement composed of Upper Cretaceous and Oligocene marine deposits (Kasiński and Piwocki, 1994: fig. 5a). More northwards, in the lowland area, an approximately 10 m thick section of brown coal at the village of Radawiec (about 20 km west of Lublin; Fig. 1) was dated as the Middle Miocene (Słodkowska in Henkel and Danel, 2015).

Our interpretation of the age of the sands that overlie coal beds in the Łukowa-4 borehole, based on dinoflagellate cysts and sporomorphs, shows that they were accumulated most likely during the latest Early and earliest Middle Miocene (Late Karpatian–Early Badenian, i.e., Late Burdigalian–Early Langhian). The sands have yielded no *Unipontidinium aquaeductum*, the species characteristic of Badenian strata underlying the Badenian evaporites in the Carpathian Foredeep in Poland (e.g., Gedl, 1996, 1997, 1999, 2005; Peryt and Gedl, 2010). This species is known to have its first appearance in the Middle or Late Langhian (Williams et al., 2004). The presence of *Labyrinthodinium truncatum truncatum* and *L. truncatum* modicum suggests Langhian age (see De Verteuil and Norris, 1996), although latest Burdigalian age cannot be excluded as *L. truncatum* shows diachronic first appearances depending on the latitude (Williams et al., 2004). Therefore, the lack of *U. aquaeductum* (if not caused by palaeoenvironmental factors) and the presence of *L. truncatum* in Łukowa-4 material may indicate that the sands accumulated during early stages of the Langhian (Badenian) or slightly earlier, during the latest Burdigalian (Karpatian). The latter possibility seems more reliable when sporomorph dating is compared, but dinoflagellate cyst data point rather at the lower Middle Miocene age of the sands. A similar assemblage with frequent *Batiacasphaera micropapillata* was described from the Middle Miocene strata of the Polish Lowlands in Legnica (Gedl and Worobiec, 2005).

Comparison of the spore-pollen spectra from the sand that overlies the coal with those examined previously in Paleogene and Neogene deposits of Poland (e.g., spore-pollen zones in Piwocki and Ziembińska-Tworzydło, 1997) shows that the assemblage from the uppermost part of the Łukowa-4 section is generally similar to the Oligocene and Early to Middle Miocene palynofloras. Unfortunately, spore-pollen assemblages from the Upper Oligocene–Lower Miocene deposits have no strongly distinctive features (Grabowska, 1996b). The spore-pollen assemblages are significantly poorer in taxa than the older palynofloras, which is most probably caused by a climate change. Those assemblages are usually dominated by pollen grains of conifers from the fossil genera *Pinuspollenites*, *Inaperturopollenites, Sequoiapollenites* and, in some cases, *Zonalapollenites* (= *Tsugaepollenites*). Among angiosperms, *Cupuliferoipollenites pusillus* (= *Castaneoideaepollis pusillus*), *Tricolporopollenites liblarensis, Quercoidites microhenrici*, *Myricipites* spp. and *Cyrillaceaepollenites megaexactus* (= *Tricolporopollenites megaexactus*) are present in the Late Oligocene–Early Miocene assemblages. Those fossil taxa have relatively long stratigraphic ranges and thus show a limited stratigraphic significance.

Composition of the spore-pollen spectra from the sands is similar to that of the Early Miocene assemblages from its cooler climatic phases (Piwocki and Ziembińska-Tworzydło, 1997; Ziembińska-Tworzydło, 1998), particularly to palynofloras from climatic phase IV – *Ulmipollenites* spore-pollen zone. The assemblages of the *Ulmipollenites* spore-pollen zone are known from few localities in the Fore-Sudetic Monocline and in the Polish Lowlands (Ziembińska-Tworzydło, 1998). Pollen grains of the Ulmaceae family (fossil genus *Ulmipollenites*) and the numerous accompanying Ericaceae are the indicative pollen taxa for this phase. The whole assemblage of the phase is poor in species and dominated by arctotertiary elements, whereas palaeotropical elements are scarce and represented mainly by subtropical taxa. In contrast, the spore-pollen spectra from the uppermost part of the Łukowa-4 section contain relatively numerous palaeotropical and palaeotropical/warm-temperate elements.

Taking into consideration the whole composition of the spectra from the sands, an early Middle Miocene age of the sands is most probable.

CONCLUSIONS

A 10 m thick cored interval from the Łukowa-4 borehole, formerly improperly dated as Paleogene (respectively Upper Eocene?, Oligocene?, Lower Miocene?; Gedl, 2015), yielded sporomorphs and dinoflagellate cysts that allow its more accurate dating.

We can assume that the age of the Łukowa brown coal, based on sporomorph spectra, is most probably Lower Oligocene, whereas the overlying sands are Miocene in age. Although the absence of sporomorphs that would unambiguously define the age of the sands and the presence of some reworked specimens do not allow for certain conclusions about their age, but the presence of dinoflagellate cysts allow their dating as the earliest Middle Miocene. Thus, the sands represent the initial stage of the Badenian (Middle Miocene) transgression, which pass upward into marly strata of the Baranów Beds.

Our discovery of the Lower Oligocene coal beds in the Łukowa-4 borehole may indicate that some other phytogenic deposits of the Carpathian Foredeep might be of similar age. This refers to the phytogenic beds that occur in a similar stratigraphic position and contain no age-diagnostic fossil evidence, and their Miocene age is based on the age of the overlying fossiliferous Miocene deposits.

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