PALYNOLOGY OF THE DEEP STRUCTURES OF THE CARPATHIAN FOREDEEP (3,950–5,467 M) AT THE FRONT OF CARPATHIAN OVERTHRUST, THE NS-1 BOREHOLE, SE POLAND

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Abstract: The current paper presents the results of palynological studies from deep structures at the front of the Carpathian overthrust, penetrated by the NS-1 Borehole. Both the method used and hardly accessible material from a depth of almost 5.5 km allow the presentation of new data from the Stebnik Unit, the underlying autochthonous Miocene succession, and the conglomerates that rest upon the crystalline basement. Samples collected from available cored intervals and cuttings from the lower part of the borehole provided the opportunity to study for the first time the palynological content of the strata under consideration. Samples yielded diversified material, composed of terrestrial and marine elements, commonly showing various stages of preservation. The latter indicate various origins for the material analysed, which is possibly at least partly recycled. The occurrence of this phenomenon, particularly in the Stebnik Unit and the upper part of the autochthonous Miocene sequence, confirmed also by results of earlier micropalaeontological studies, makes precise stratigraphic correlation highly debatable. The authors discuss the possibility of both Paleogene and Miocene ages for the material. Also highly debatable are the palaeoenvironmental reconstructions of this interval, although the general intense influx of terrestrial material recorded is probably responsible for the unfavourable conditions for planktonic biota. Different, optimal marine conditions can be deduced for the lower part of the autochthonous Miocene; an abundance of dinoflagellate cysts allows their precise correlation with coeval strata of the Carpathian Foredeep Basin. Palynological analysis of conglomerate matrix material gave negative results. However, this and the lithological characteristics indicate a different origin and age of these strata in comparison with other coarse-grained lithosomes, known from neighbouring areas. The generally immature state of preservation of the organic matter in the deepest part of the borehole indicates that this part of the succession was not affected by the high temperatures that would be expected at such a depth. This contrast with the much more mature palynomorphs of the overlying Stebnik Unit points to the fact that these strata were heated to a much higher degree prior to their final burial.

Key words: Dinoflagellate cysts, sporomorphs, biostratigraphy, palaeoenvironment, Stebnik Unit, autochthonous Miocene.

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INTRODUCTION

The NS-1 Borehole (the village of Sierakośce, south of the city of Przemyśl, south-eastern Poland) was planned as a research well and was intended to be one of the deepest in Poland, with a planned depth of 6 km. Its goal was to penetrate the geological structure of the Carpathian Foreland at the front of Carpathian overthrust in exploration for oil reservoirs. The NS-1 Borehole penetrated the entire succession of the Carpathian Foredeep and in the crystalline Precambrian basement reached a total depth of 5,568 m. This created a unique opportunity to study the strata occurring at these depths, i.e., the folded strata of the Stebnik Unit, the unfolded autochthonous Miocene, and its direct substratum.

The geology of this area, particularly the age of the strata within it, remains still a matter for debate. For these purpose the authors studied the rock material available from a depth interval of 5,467–3,950 m in terms of palynology, a method that is applied for the first time in the succession in this area and at this depth. The authors present the results of a taxonomical study of dinoflagellate cysts and sporomorphs, their biostratigraphical and palaeoenvironmental interpretations, including the results of palynofacies analysis, and determination of their degree of maturity.

GEOLOGY

The study area is located in south-eastern Poland, south of the city of Przemyśl, near the state boundary with Ukraine (Fig. 1). In terms of geology, it is located in the border zone of the Carpathian Foredeep, close to the Carpathian overthrust. In this area, the trend of the northern boundary (tectonic) of the Carpathians and general tectonic features (fold axis and thrust directions), predominantly latitudinal in the greater part of the Polish Carpathians, abruptly

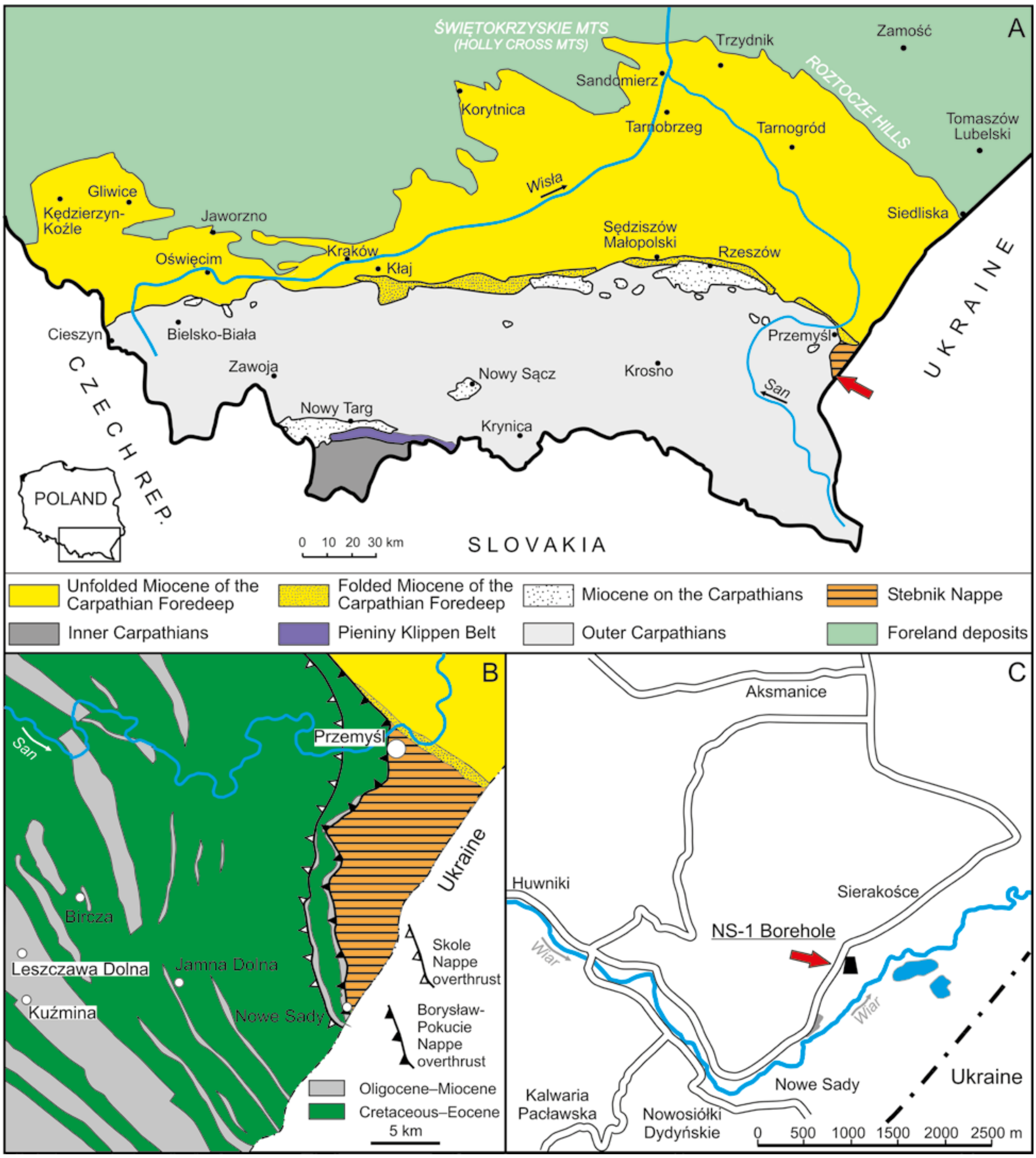

Fig. 1. Geology of the study area and location of the NS-1 Borehole. **A.** Schematic geological map of the Polish Carpathians and their foredeep and foreland (based on Żytko *et al.*, 1989, from Oszczypko, 1996) and position of the NS-1 Borehole (arrowed). **B.** Schematic geological map of the Przemyśl sigmoid area (based on Jucha, 1969; supplemented by Kotlarczyk, in Kotlarczyk *et al.*, 2006; slightly modified). **C.** Location of the NS-1 borehole (arrowed).

is replaced by a longitudinal one, forming the so-called Przemyśl sigmoid (Fig. 1A, B; see e.g., Kotlarczyk, 1988; Karnkowski, 1997). The Carpathian overthrust on to the foreland in the Przemyśl sigmoid area is a complicated structure, which has been the subject of geological studies for decades (e.g., Tołwiński, 1956; Zieliński, 1963; Ney, 1968; Książkiewicz, 1972; Garlicki, 1973; Czernicki, 1977; Kotlarczyk, 1988; Karnkowski, 1997). Despite so many studies, there are several interpretations, commonly in disagreement, related to the general structure and the affiliation of particular lithostratigraphic units to the larger structural elements and their ages.

Within the area of study, in the immediate vicinity of the NS-1 Borehole, the following tectonic and structural units (Tab. 1) can be distinguished: (1) the Carpathian nappes (the Skole and Borysław-Pokucie nappes, composed of Cretaceous–Middle Miocene flysch deposits) occur in the form of steeply dipping, imbricated folds west of the borehole; (2) the Stebnik Unit (Miocene and possibly Paleogene strata), folded and overthrust on to the (3) autochthonous Miocene of the Foredeep Basin, and (4) conglomerates of uncertain age, composed of phyllitic clasts derived from the underlying (5) the crystalline basement of Precambrian age. The NS-1 Borehole penetrated the units listed above, except for the Carpathian nappes, the easternmost limit of which occurs a few hundred metres to the west of the borehole (Fig. 1).

The complicated geological structure of the study area results from orogenic movements that took place in this area during the Early and Middle Miocene Styrian (late Burdigalian to Langhian), and Moldavian (Serravalian) orogenic phases. At that time, north and north-east overthrusting of the Carpathian nappes on to rigid, crystalline basement covered by ductile Miocene succession of the Carpathian Foredeep, led to the formation of a belt of folded Miocene, overthrust in front of migrating nappes above the autochthonous, undisturbed Miocene. This belt, of variable width, known as the Stebnik Unit, occurs at and just below the front of the Carpathian nappes, from Bochnia in the west to the Przemyśl sigmoid in the east, where it reaches the greatest width (Tołwiński, 1956; Ney, 1968; Książkiewicz, 1972). According to some authors, the term Stebnik Unit refers to the folded and overthrust Miocene in the Przemyśl sigmoid only; the folded Miocene to the west of Przemyśl represents the Zgłobice Unit (see, e.g., Kotlarczyk, 1988; Połtowicz, 2004; Oszczypko *et al*., 2008).

The deepest element, penetrated by the NS-1 Borehole, is the crystalline basement (v), which is a part of the Małopolska Massif, in this area composed of Precambrian phyllites (Karnkowski, 1997). The orography of the crystalline basement was shaped by tectono-erosional processes during the latest Cretaceous–Paleogene (Karnkowski and Ozimkowski, 2001). During this time, the northern surroundings of Carpathian basins were a land, in which denudation processes predominated. Evidence for them takes the form of palaeovalleys that were cut into the pre-Paleogene basement, approximately perpendicular to the present-day Carpathian edge (Moryc, 1995; Karnkowski, 1997; Gedl and Worobiec, 2020). The products of the erosional processes are conglomerates, composed of phyllitic clasts that rest upon the crystalline Precambrian basement (a depth of 5,478.5–5,568 m; Fig. 2; Tab. 1). Conglomerates in a similar stratigraphic position, resting upon the crystalline basement, are known from several wells in the Carpathian Foredeep (e.g., the Racławówka Conglomerate Formation or the Albigowa Conglomerate; see Moryc, 1995). However, their correlation with those from the NS-1 Borehole is uncertain, owing to differences in petrographic composition and the lack of precise dating (see also Gedl and Worobiec, 2020).

The marine Miocene of the Carpathian Foredeep overlies the conglomeratic strata (Fig. 2). This is the autochthonous unit, the strata of which are tectonically undisturbed (except for the uppermost part; see below). It shows a tripartite development of facies, similar to that in the greater part of

Table 1

Lithostratigraphy and main tectonic units penetrated by the NS-1 Borehole.

Depth [m]	Tectonic units	Lithostratigraphic units	Age	
0–20	Quaternary			
20–3,950	Stebnik Unit	Balych Beds and Stebnik Beds	Miocene (Karpatian–Badenian)	
3,950–4,020		Sloboda Conglomerate (? clasts of Jurassic–Cretaceous ages)	Oligocene	
4,020–4,137		Polyanitse Beds and Menilite Beds	Eocene–Oligocene	
4,137–4,395		Stebnik Beds	Miocene (Karpatian–Badenian)	
4,395–4,455	Autochthonous Miocene	Tectonically disturbed uppermost part	Miocene	Badenian
4,455–5,422		Machów Formation		upper Badenian–Sarmatian
5,422–5,444		Evaporitic series (Krzyżanowice Formation)		middle Badenian
5,444–5,478.5		Skawina/Baranów formations		lower Badenian
5,478.5–5,568	Sub-Miocene strata	Conglomerates (composed of clasts derived from crystalline basement)	(?)	
> 5,568	Crystalline basement		Precambrian	

the Foredeep Basin. The lowermost part is composed of lower Badenian fine clastics (the Skawina/Baranów formations). Above, a characteristic feature of the entire Foredeep Basin evaporitic horizon occurs (the Wieliczka and Krzyżanowice formations; middle Badenian), which passes upwards into upper Badenian and Sarmatian clastics (the Machów Formation). The uppermost part of the autochthonous Miocene (4,395–4,455 m) shows tectonic disturbances of different magnitudes, caused by tectonic dislocations of the overlying Stebnik Unit during the overthrusting of it (the so-called "disturbed Miocene"; Fig. 2; Tab. 1).

The Stebnik Unit (i.e., the Sambir Unit, in the Ukrainian sector of the foredeep), distinguished by Tołwiński (1937), consists of folded and overthrust Miocene and presumably Paleogene strata (e.g., Karnkowski, 1994, 1997), both probably for the most part of continental origin (Fig. 2). The precise age of the rocks forming this unit is difficult to define, as various authors suggest different ages; moreover, some units are believed to represent the Borislav-Pokuttya Nappe and not the Stebnik Unit. These controversies refer to the salt-bearing Miocene strata (e.g., Garlicki, 1973; Karnkowski, 1994) and to the Paleogene part of the Stebnik succession, which for example according to Zieliński (1963) include the Carpathians elements, the Eocene Hieroglyphic and Popiele beds and the Oligocene Menilite Beds. Other authors (e.g., Garecka and Olszewska, 1997) claim that the Stebnik Unit is composed only of Miocene strata, including the Dubnik Conglomerate, the Stebnik Beds, the Balych Beds, the Przemyśl Beds, the Evaporitic Beds, and the Radych Conglomerate. According to several authors, the main difference between the Stebnik and Zgłobice units is that the former is made up of older strata (Lower–Middle Miocene) and the Zgłobice Unit consists of Middle–Upper Miocene (e.g., Kotlarczyk, 1988; Oszczypko *et al*., 2008). However, the newest, unpublished data (Staryszak, 2021) indicate that the Stebnik Unit includes Paleogene strata, separated from the Miocene by a hiatus. The strata that comprise the Stebnik Unit accumulated on the Carpathian foreland, perhaps also partly within the northernmost extent of the flysch basin (Kotlarczyk, 1988). Their thickness in the study area is very variable, showing a gradual reduction towards the north, from 40 m in the vicinity of Przemyśl (the Przemyśl-130 Borehole) to 4,375 m in the NS-1 Borehole.

MATERIAL AND METHODS

The NS-1 Borehole was drilled by the Polish Oil and Gas Company (PGNiG) in 2021. It is located at the village of Sierakośce, south-east of the road between Sierakośce and Zawiar, north-west of the Wiar River (plot no 155; Fig. 1C).

A total of nine samples, including six core samples and three cuttings samples, was taken from the NS-1 Borehole for palynological analysis (Fig. 2). Core samples were taken from the five intervals cored: 4,750–4,768 m, 5,130–5,140 m, 5,458–5,467 m, 5,525–5,531.8 m, and 5,559–5,568 m. Cuttings samples were taken from 3,950 m, 4,030 m, and 5,200 m (Fig. 2). Sample depths, their lithology and presumed stratigraphic-tectonic affinity are shown in Table 2.

Core lithology

Cored interval 4,750–4,768 m (autochthonous Miocene). This interval is heterolithic, composed of predominantly dark greyish, marly mudstones, alternating with thin-bedded (1–2 cm), fine-grained, dark steel-greyish sandstone layers (Fig. 3A). The sandstones exhibit horizontal lamination without bioturbation; cross-bedding and ripple marks are rare. The tops and soles of sandstone layers are sharp. Frequent clasts were found in the sandstones: these are clasts from sedimentary rocks, most likely the Oligocene Menilite Beds in the Carpathians and crystalline clasts, derived from the Eocambrian basement. Material from this interval appeared to be barren of microfauna.

Cored interval 5,130–5,140 m (autochthonous Miocene). The entire cored interval is composed of loamy rocks, including claystones, mudstones and sandy mudstones with subordinate sandstones intercalations. A few layers of pelitic marls and altered (calcified) bentonites, up to 12 cm in thickness, were found. Sandstones are mainly fine-grained, less frequent are middle-grained. The thickness of their layers varies between 2 and 5 cm, rarely reaches up to 18 cm.

Table 2

A list of samples from the NS-1 Borehole investigated with regard to palynology, their lithology and structural origin.

Sample depth [m]	Sample type	Lithology	Stratigraphic-tectonic unit
3,950	Cuttings	Small amount of tiny pieces of dark mudstones and sandstones	Stebnik Unit
4,030	Cuttings	Small amount of tiny pieces of dark mudstones and sandstones	
4,760.80	Core (4,750–4.768 m)	Greyish, calcareous claystone	Autochthonous Miocene
5,139.20	Core (5,130–5,148 m)	Greyish, calcareous mudstone	
5,200	Cuttings	Very small amount of tiny pieces of mudstones and sandstones	
5,458.35–50	Core (5,458–5,467 m)	Dark greyish, poorly calcareous mudstone	
5,465.70–85	Core (5,458–5,467 m)	Dark greyish, poorly calcareous mudstone	
5,561	Core (5,559–5,568 m)	Cherry-red, non-calcareous clay matrix	Conglomerates
5,561	Core (5,559–5,568 m)	Dark greenish to willow-green, non-calcareous clay matrix	

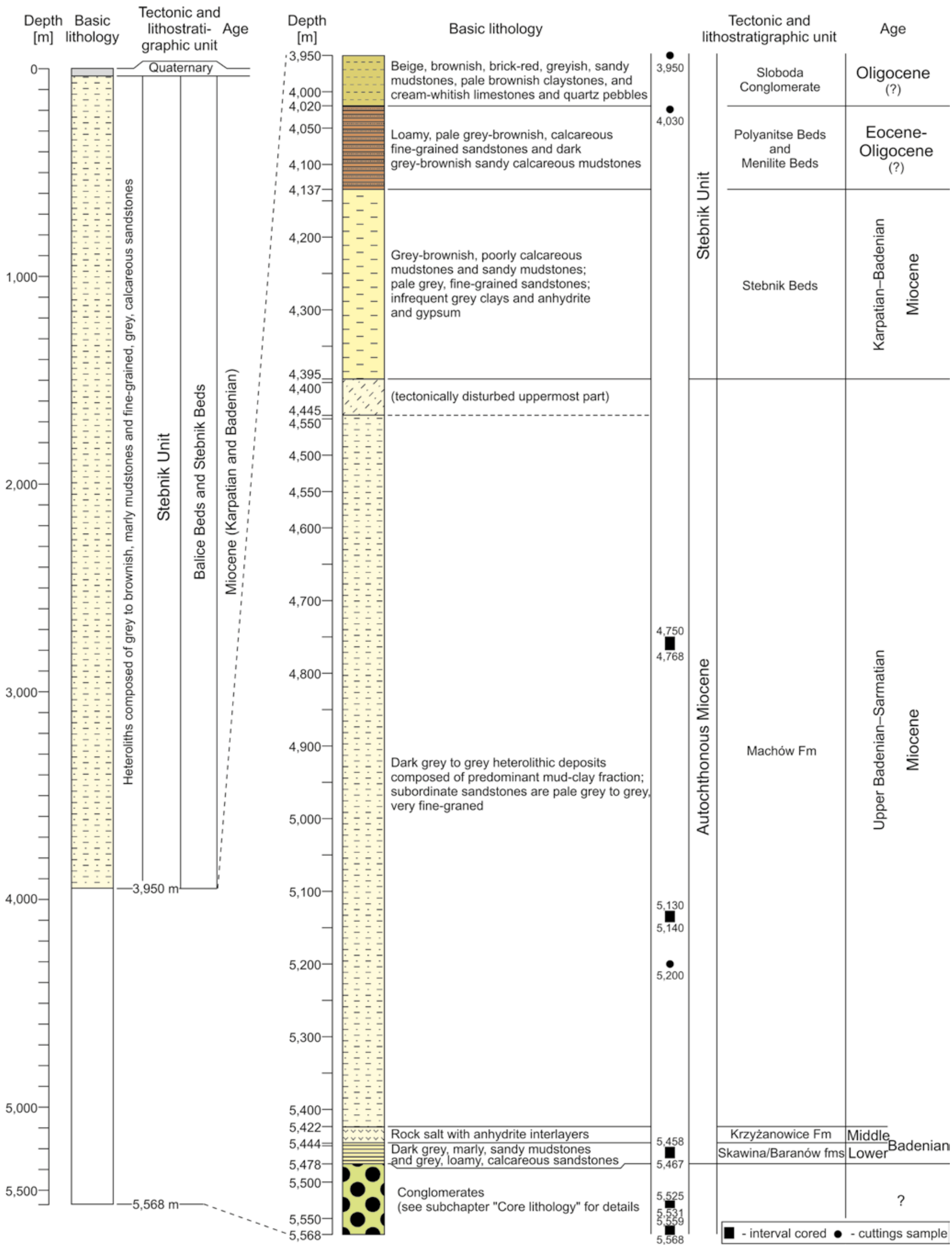

Fig. 2. The NS-1 Borehole succession: basic lithology, tectonic unit, lithostratigraphy and age (after Kendra, 2021).

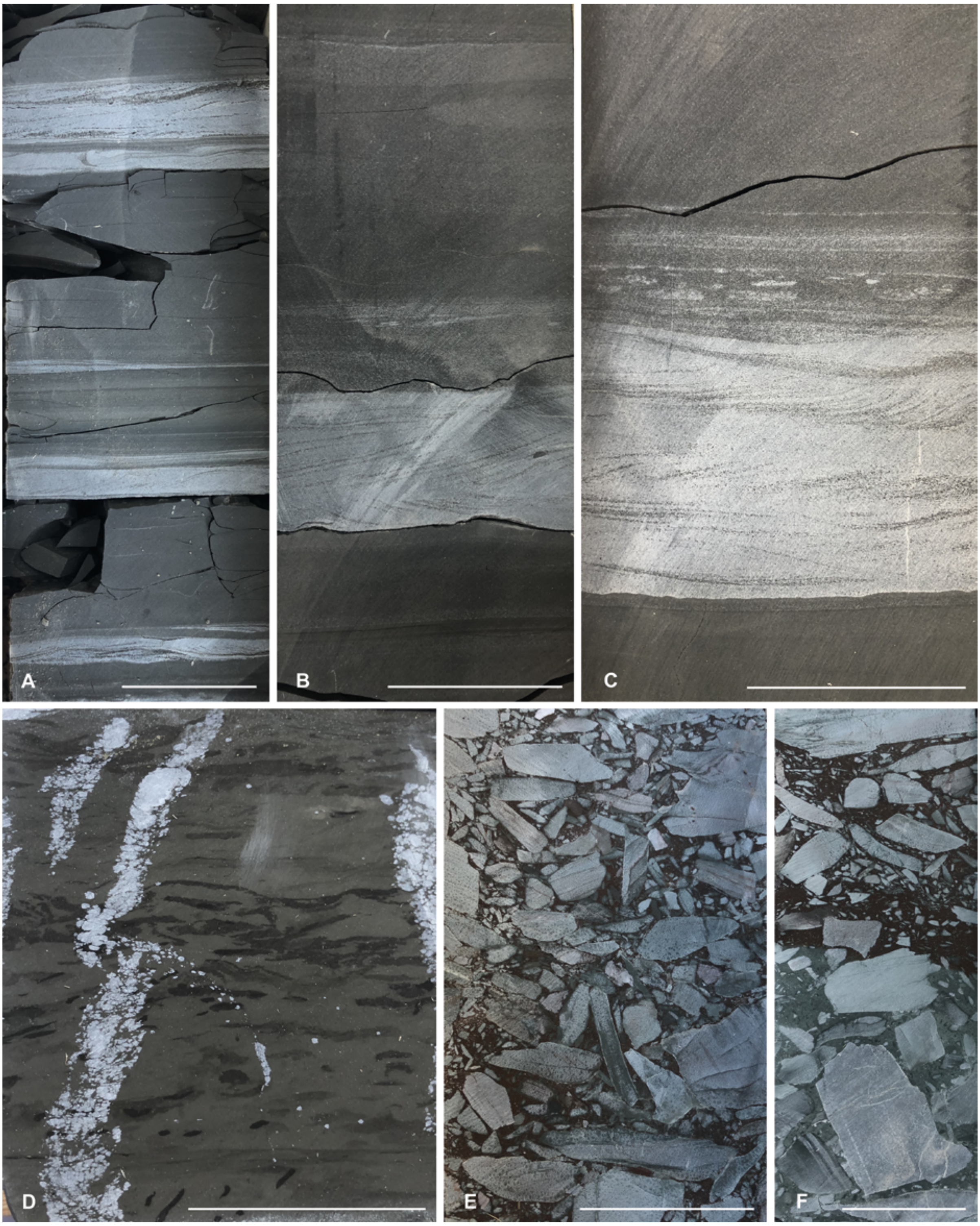

Fig. 3. Lithology of cores from the NS-1 Borehole (photograph – P. Śmist). Scale bars indicate 5 cm. **A.** Core 4,750–4,768 m, core box III (the upper Badenian Machów Formation, autochthonous Miocene). Heterolithic lithofacies dominated by mudstones. Sandstones layers are up to 2 cm thick (1–2 cm on average). **B.** Core 5,130–5,148 m, core box XVII, 26–30 cm (the upper Badenian Machów Formation, autochthonous Miocene). Sandstone with herringbone cross-bedding; rare in drilled Miocene rocks, an example of cross-stratification that resulted from currents moving in opposite directions. **C.** Core 5,130–5,148 m, core box XVIII, 85–91 cm (the upper Badenian Machów Formation, autochthonous Miocene). Sandstone with small-scale cross-lamination with angular and tangential dip directions of laminae. **D.** Core 5,458–5,467 m, core box IX (the lower Badenian Skawina Formation, autochthonous Miocene). Very intense bioturbation in marly claystone. Ichnofacies *Chondrites* and *Planolites* are rare in Miocene of Carpathian Foredeep. White vertical veins are anhydrite, which cut the ichnofossils; this indicates early diagenetic origin of the anhydrite, possibly during early stages of burial and lithification. The source of sulphates was presumably the early Badenian sea water. **E.** Core 5,525–5,531.8 m, core box V. Conglomerate composed of densely packed angular clasts. **F.** Core 5,525–5,531.8 m, core box VII. Conglomerate with visible change in matrix colour; greenish in the lower part of photomicrograph (lighter shade) and darker (cherry-red) in the upper part.

The sandstone layers display various types of bedding, i.a., horizontal bedding, cross-bedding, ripple marks, and graded bedding (Fig. 3B, C). Thicker sandstone layers are of turbiditic origin, with several parts of the Bouma sequence visible, from low-angle lamination through horizontal and convolute lamination at the top. The most frequently observed sequences are T_{cde}, T_{cd}, T_{bce}. Among the clasts identified, both crystalline material from the eroded Precambrian basement and sedimentary rocks (carbonates, radiolarites, and cherts) occur; the latter may partly come from Carpathian sedimentary sequence. This cored interval yielded infrequent foraminifera and calcareous nannoplankton.

Cored interval 5,458–5,467 m (autochthonous Miocene). This cored interval is composed of dark greyish marls and marly clays with carbonate content of over 30%. A characteristic feature is the presence of olive-greyish layers with frequent bioturbation traces of *Chondrites* and *Planolites* (Fig. 3D). The marls contain frequent calcareous foraminifera *Globigerinoides*, the marly clays contain abundant *Globigerinoides* and *Orbulina*, and *Candorbulina suturalis* is present. The last-mentioned feature makes the interval studied similar to the Baranów Beds, which differ in having a higher ratio of clastic material. Marls from this interval also contain some limestone layers, a few centimetres thick, and anhydrite lenses. Anhydrite occurs also as veins, vertical or oblique to the bedding. These veins have soft, gradational edges indicating that the anhydrite grew during the early stages of burial.

Cored intervals 5,525–5,531.8 m and 5,559–5,568 m (conglomerates). Both core intervals contain conglomerates, composed of greenish, less frequently reddish clasts, in a reddish and/or green-willow green, fine clastic matrix. Clasts, even over 10 cm in diameter, are angular only and commonly elongated and rectangular with sharp edges (Fig. 3E, F); no rounded clasts occur. In places, clasts display preferred orientation, although in greater part clasts are randomly distributed and filling all of the available space. Clast lithology is uniform; macroscopically the following rock types can be distinguished: greenish and reddish claystones and mudstones, fine-grained greenish sandstones, pink sandstones, and rare quartz grains.

Petrographic analysis confirms the low diversity of clast composition. These are mainly fine-grained, quartzose sandstones with iron oxide-calcite cement, weakly metamorphosed chlorite shales with marked foliation (greenschist facies), chloritized sericitic claystones, and quartzose sandstones with chlorite. The last-mentioned mineral is responsible for general greenish colour of clasts and matrix.

The matrix is made up of finely ground clasts. Its colour (greenish or reddish) reflects either the dominating colour of the source clasts and/or it reflects various weathering conditions, influencing the occurrence of iron oxides and hydroxides. The greenish colour comes from chlorite; the red colour of the matrix and rarely of clasts is a result of weathering and oxidation of the rock components (biotite and chlorites).

Palynological processing

The samples were processed in the Institute of Geological Sciences, Polish Academy of Sciences, Kraków. The palynological procedure included treatment with 38% hydrochloric-acid (HCl), 40% hydrofluoric-acid (HF), heavy-liquid ($ZnCl_2$+HCl; density 2.0 g×cm^{-3}) separation, an ultrasound bath for 10–15 s and sieving at 10 µm on a nylon mesh. No nitric-acid (HNO_3) treatment was applied. The quantity of rock processed was 30 g for core samples and between 4 and 10 g for cuttings samples.

Palynological slides were made for each sample, using glycerine jelly as a mounting medium. As a standard, two slides were made from each sample, except for the samples from the Stebnik Unit, which yielded very small amounts of palynological organic matter; in their case, six to eight slides were made, using almost all of the material extracted. Palynological residues and slides are stored in the collection of the Institute of Geological Sciences, Polish Academy of Sciences, Kraków.

RESULTS

A short description of palynological organic matter from samples studied is given below. Dinoflagellate cyst frequencies are shown in Table 3, whereas sporomorph occurrences are given in Table 4. Photomicrographs of selected palynomorphs are shown in Figures 4–10.

Sample 3,950 m (Stebnik Unit). The sample yielded very small amounts of palynological organic matter. It must be taken into account that sample weight was only 4 g. The palynofacies is composed of terrestrial elements, mainly black, opaque phytoclasts with frayed edges. Some fragments of very delicate tissue occur; they are presumably a recent contamination. Infrequent sporomorphs, represented by both pollen grains (*Cathayapollis* sp. and *Pinuspollenites* sp.) and spores, occur. They show various states of preservation, ranging from specimens of dark-coloured and highly altered wall structure (Fig. 4D, Q, S), from ones with dark-coloured, but relatively intact structure (Fig. 4A, B, E), to lighter-coloured and relatively well-preserved specimens (Fig. 4C, R). Dinoflagellate cysts are even less frequent and very poorly preserved; these are mainly indeterminate specimens (Fig. 4F, J, P), while some show recognizable features, such as archaeopyle types (Fig. 4K, L). A single, questionably determined *Homotryblium* was found (Fig. 4G, H). Another single specimen is slightly better preserved and represents a *Systematophora-Areoligera* morphotype (Fig. 4N, O).

Sample 4,030 m (Stebnik Unit). This sample yielded very small amounts of palynological organic matter, similar to the sample from a depth of 3,950 m. It also weighted only 4 g. The palynofacies also resembles the one from sample 3,950 m. It is composed almost entirely of black, opaque phytoclasts with characteristically frayed edges (Fig. 5E, F). Palynomorphs are represented by infrequent pollen grains, usually moderately preserved (Fig. 5A–D) and very rare dinoflagellate cysts. The latter include mainly indeterminate gonyaulacoids; among better preserved cysts *Rhombodinium* sp. (Fig. 5G) and *Enneadocysta pectiniforme* are noteworthy. Preservation of remaining dinoflagellate cysts identified varies between poor and moderate: *Spiniferites*, *Homotryblium*, *Polysphaeridium* (Fig. 5I–O),

Table 3

Frequencies of dinoflagellate cysts in the NS-1 Borehole.

Tectonic unit:	**Stebnik Unit**		**Autochthonous Miocene**			
Sample depth:	**[m]**					
Dinoflagellate cysts	**3,950**	**4,030**	**4,750**	**5,139**	**5,458**	**5,465**
Homotryblium sp.	1		7	5		
Systematophora? sp.	2			2		
Undetermined gonyaulacoids	5	12	15	6		
Rhombodinium sp.		1	1			
Chiropteridium? sp.		1				
Spiniferites spp.		5	4	8	12	17
Enneadocysta sp.		1	2	1		
Polysphaeridium sp.		3				
Homotryblium tenuispinosum		1				
Enneadocysta pectiniformis		2				
Homotryblium ?plectilum		1				
Impletosphaeridium sp.			8			
Oligosphaeridium? sp.			2			
Lingulodinium? sp.			1			
Impagidinium spp.			3		9	19
Nematosphaeropsis labyrinthus			1		13	21
Minidinium? sp.			1			
Deflandrea sp.			5	10		
Wetzeliella spp.			1	2		
Caligodinium? sp.			1			
Glaphyrocysta sp.			1			
Distatodinium? sp.			1			
Hystrichokolpoma sp.			1			2
Spiniferites ramosus				22	30	54
Operculodinium sp.				9		
Lingulodinium machaerophorum				11	4	6
Isabelidinium? sp.				2		
Cribroperidinium? (operculum)				1		
Dapsilidinium? sp.				1		
Apteodinium? sp.				1	1	2
Cribroperidinium sp.					3	11
Spiniferites pseudofurcatus					2	5
Operculodinium centrocarpum					5	23
Unipontidinium aquaeductum					7	11
Hystrichokolpoma rigaudiae					2	7
Operculodinium piaseckii					3	4
Palaeocystodinium striatogranulosum					4	15
Pentadinium ?goniferum					1	
Hystrichosphaeropsis obscura					2	4
Apteodinium ?spiridoides					4	3
Reticulatosphaera actinocoronata						12
Thalassiphora sp.						2
Melitasphaeridium choanophorum						7
Pyxidiniopsis sp.						5
Palaeocystodinium golzowense						1
Dapsilidinium pseudocolligerum						3
Sum	8	27	55	81	102	273

Table 4

Frequencies of sporomorphs in the NS-1 Borehole.

	Tectonic unit:	**Stebnik Unit**		**Autochthonous Miocene**			
	Sample depth:	**[m]**					
Fossil taxa	**Botanical affinity**	**3,950**	**4,030**	**4,750**	**5,139**	**5,130–48**	**5,458–67**
cf. *Cicatricosisporites* sp.	Schizaeaceae?			1	1		
Corrugatisporites sp.	Lygodiaceae: *Lygodium*			1			
other trilete spores	ferns?	1		2	2	1	1
cf. *Abiespollenites* sp.	Pinaceae: *Abies*?			1		2	
Cathayapollis sp. + cf. *Cathayapollis* sp.	Pinaceae: *Cathaya*	2	5	9	14	9	37
Piceapollis sp. + cf. *Piceapollis* sp.	Pinaceae: *Picea*			2	3	1	3
Pinuspollenites sp. + cf. *Pinuspollenites* sp.	Pinaceae: *Pinus*	4	12	116	146	127	175
Sciadopityspollenites sp. + cf. *Sciadopityspollenites* sp.	Sciadopityaceae: *Sciadopitys*			2	1	1	
Zonalapollenites sp.	Pinaceae: *Tsuga*			11	9	8	2
Alnipollenites sp.	Betulaceae: *Alnus*				1		
Ericipites sp.	Ericaceae			2		1	
Polyatriopollenites sp.	Juglandaceae: *Pterocarya*					1	
Zelkovaepollenites sp.	Ulmaceae: *Zelkova*					1	
corroded small tricolporate pollen grains	Fagaceae?					1	
corroded triporate pollen grains	Juglandaceae?			1			
other corroded angiosperm pollen grains	Angiosperms			3	3	3	1
Sum		7	17	151	180	156	219

and *Chiropteridium*? sp., which was questionably included in this genus, as its processes appear to have been torn off (Fig. 5H).

Sample 4,760.80 m (autochthonous Miocene). This core sample yielded large amounts of palynological organic matter, composed almost exclusively of terrestrial elements. The predominant elements are dark brown and black phytoclasts, while phytoclasts with preserved plant structures and cuticles are subordinate. Terrestrial elements are represented also by pollen grains that are much more frequent than in previous samples (*Pinuspollenites*, *Zonalapollenites*, and *Cathayapollis*; Tab. 4). Dinoflagellate cysts are present, but they are infrequent and rather poorly preserved. Their assemblage is composed mainly of chorate gonyaulacoids, partly indeterminate, partly poorly preserved (*Impletosphaeridium*, *Spiniferites*, *Hystrichokolpoma*, *Homotryblium*; Figs 6, 7); peridinioids, represented by *Deflandrea*, *Wetzeliella* and *Rhombodinium*, are also present (Fig. 7). A few specimens of *Impagidinium* and a single specimen of *Nematosphaeropsis labyrinthus* were found. Rare prasinophytes *Tasmanites* are present. The preservation of palynomorphs is noteworthy. They are pale-coloured, but their wall structure is poorly preserved showing significant alternation, which causes problems for precise taxonomic determination.

Sample 5,139.20 m (autochthonous Miocene). This core sample, like the one from a depth of 4,760.80 m, yielded large amounts of palynological matter, which is almost entirely of terrestrial origin. The palynofacies is composed of predominant cuticles and phytoclasts with visible plant tissue structures, dark brown and black phytoclasts are common but not predominant. Hyalinous phytoclasts, presumably resin particles, and sporomorphs are present. The latter are composed mainly of pollen grains, among which the same taxa as in sample 4,760.80 m predominate (*Pinuspollenites*; Tab. 4). Dinoflagellate cysts are relatively frequent but highly dispersed in the mainly terrestrial material. They are poorly to moderately preserved (Fig. 8). Most frequent are representatives of *Spiniferites*, *Operculodinium*, *Deflandrea*, and *Lingulodinium machaerophorum*. Less frequent are representatives of *Homotryblium*, single, poorly preserved *Exochosphaeridium*, *Pentadinium*, *Enneadocysta*, *Dapsilidinium*?, *Systematophora*?, and *Isabelidinium*? were found. The presence of two specimens of *Wetzeliella* is noteworthy.

Sample from a depth of 5,200 m, a very small amount of rock particles, yielded no palynological organic matter after dissolution.

The palynological analysis of two samples from the autochthonous Miocene from depths of **5,458.35–50 m** and **5,465.70–85 m** gave almost identical results. The difference is the slightly higher proportion of dinoflagellate cysts in sample 5,465.70–85 m). The palynofacies of both samples is characterized by high proportions of dinoflagellate cysts,

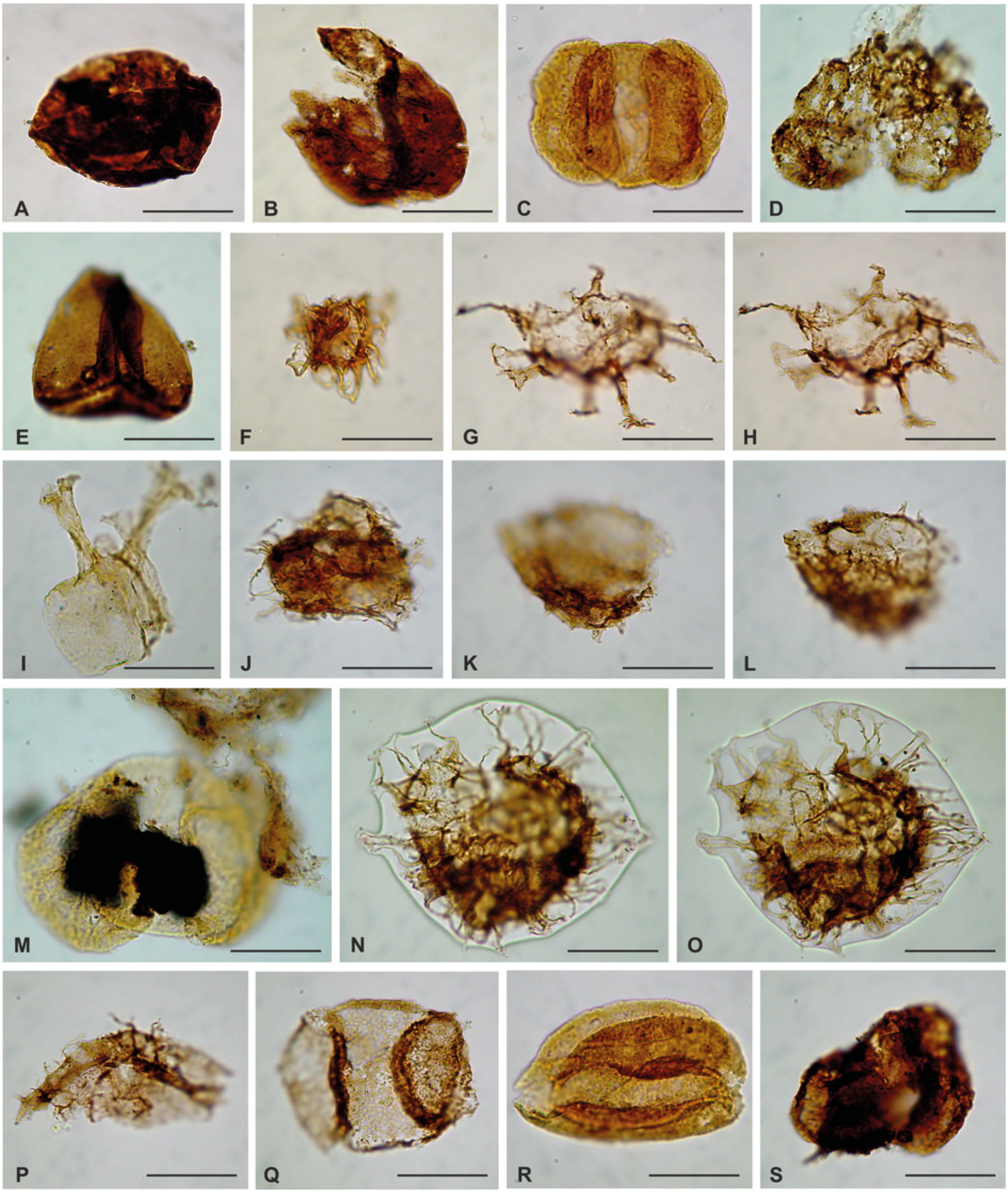

Fig. 4. Palynomorphs from the Stebnik Unit, NS-1 Borehole, depth 3,950 m (photograph – P. Gedl). Scale bars indicate 25 μm. **A.** Highly altered palynomorph, presumably a spore. **B.** Poorly preserved spore. **C.** Relatively well-preserved bisaccate pollen grain. **D.** Highly corroded bisaccate pollen grain. **E.** Well-preserved although dark coloured spore. **F.** Indeterminable dinoflagellate cyst. **G, H.** Poorly preserved dinoflagellate cyst, presumably *Homotryblium* (same specimen, various foci). **I.** Fragmentarily preserved chorate gonyaulacoid. **J.** Poorly preserved, indeterminable chorate gonyaulacoid. **K, L.** Poorly preserved dinoflagellate cyst, presumably with epicystal archaeopyle; K – focus on a short process in antapical area; L – focus on archaeopyle. **M.** Bisaccate pollen grain, black, opaque phytoclast and a fragment of matured organic particle (plant tissue?). **N, O.** Chorate gonyaulacoid, presumably with apical archaeopyle showing general similarity to the *Systematophora-Areoligera* morphotype (same specimen, various foci). **P.** A fragment of a dinoflagellate cyst of uncertain taxonomy. **Q, R.** Bisaccate pollen grains. **S.** Highly altered spore.

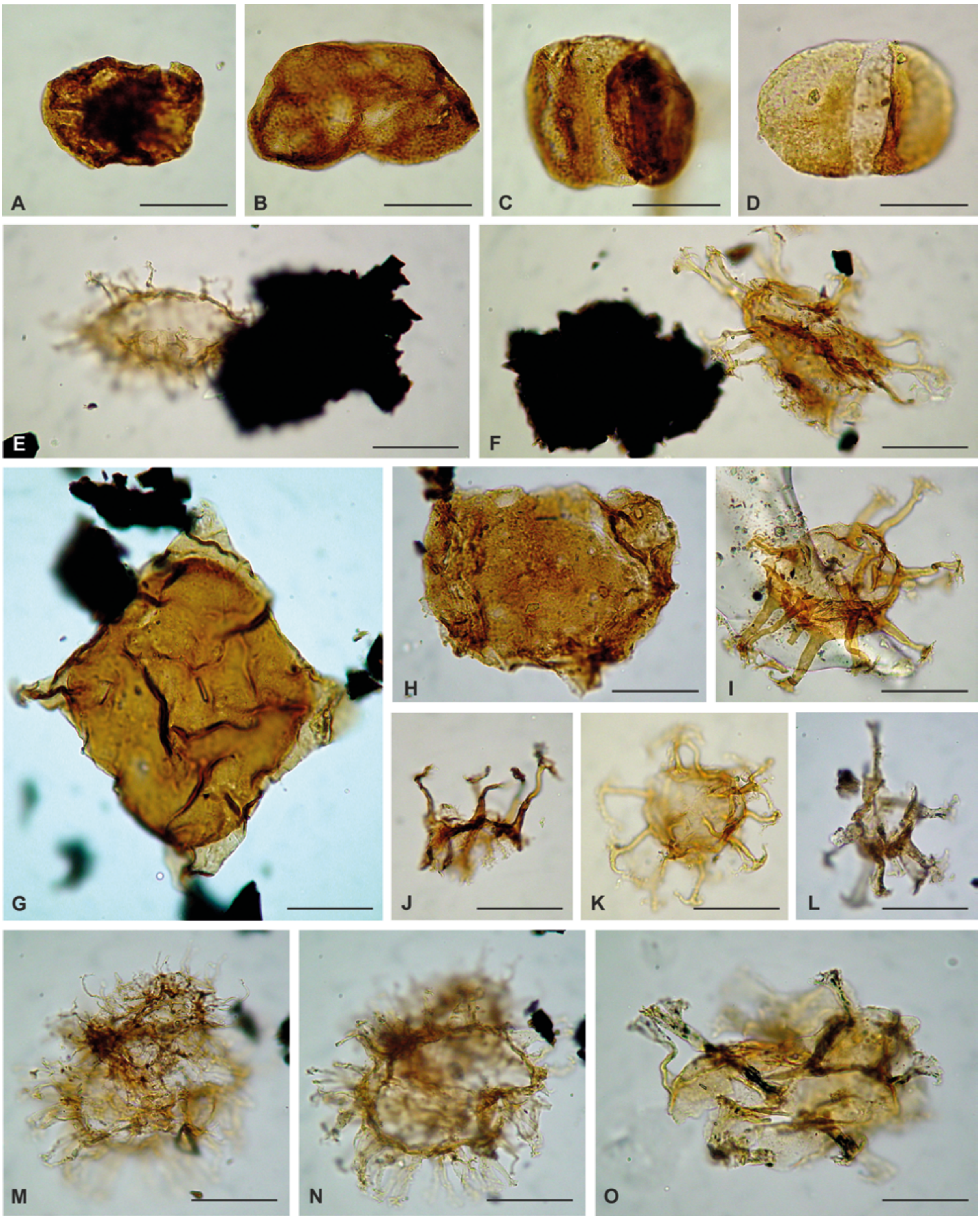

Fig. 5. Palynomorphs and phytoclasts from the Stebnik Unit, NS-1 Borehole, depth 4,030 m (photograph – P. Gedl). Scale bars indicate 25 µm. **A–D.** Sporomorphs. **E.** Dinoflagellate cyst with presumably epicystal archaeopyle (*Polysphaeridium*? sp.) and a black, opaque phytoclast with frayed edges. **F.** Another black, opaque phytoclast with frayed edges and an undetermined chorate gonyaulacoid. **G.** *Rhombodinium* sp. – specimen showing relatively good state of preservation. **H.** *Chiropteridium*? sp. **I.** Relatively pale-coloured specimen of presumably *Homotryblium* sp. **J.** A fragment of highly altered, dark-coloured dinoflagellate cyst, most likely an apical operculum. **K.** Another pale-coloured specimen although showing some wall structure alternation (*Enneadocysta*? sp.). **L.** Poorly preserved but pale coloured dinoflagellate cyst (*Homotryblium*? sp.). **M, N.** Two specimens of dinoflagellate cysts: poorly preserved and darker-coloured one above (focused in M in the upper part of the photomicrograph), and lighter-coloured but also poorly preserved specimen below, with numerous tubular processes resembling the ones of *Polysphaeridium zoharyi* (lower part of the photomicrograph, focused in N). **O.** Mechanically torn off and wrinkled, poorly preserved but relatively pale-coloured specimen; shape of processes similar to *Homotryblium plectilum*.

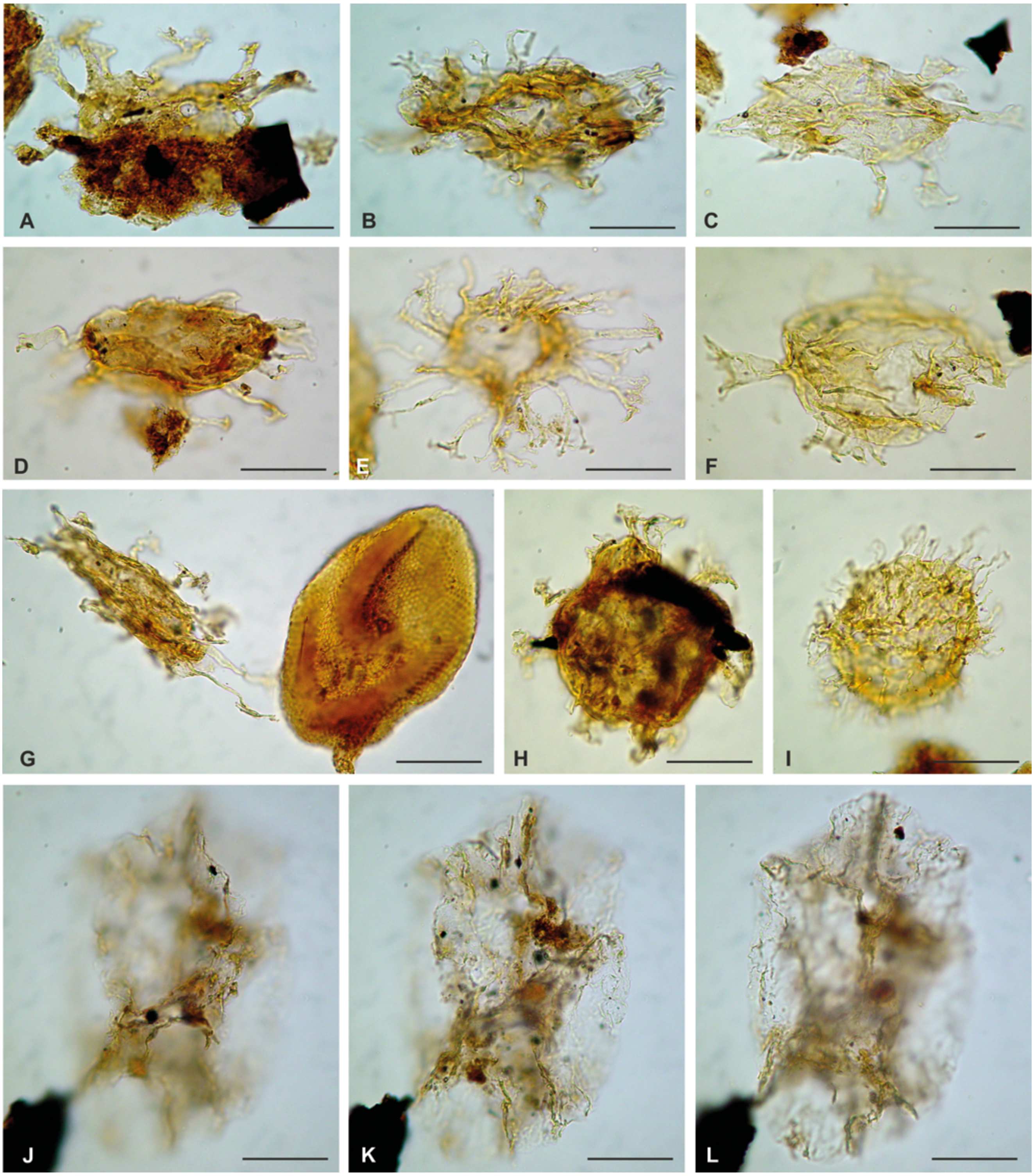

Fig. 6. Aquatic palynomorphs from the autochthonous Miocene, NS-1 Borehole, depth 4,760.80 m (photograph – P. Gedl). Scale bars indicate 25 μm. **A–I.** poorly preserved chorate gonyaulacoids (G – Prasinophyceae *Tasmanites* on the right-hand side of the photomicrograph). **J–L.** Poorly preserved specimen of a large murochorate gonyaulacoid (*Impagidinium*?; same specimen, various foci).

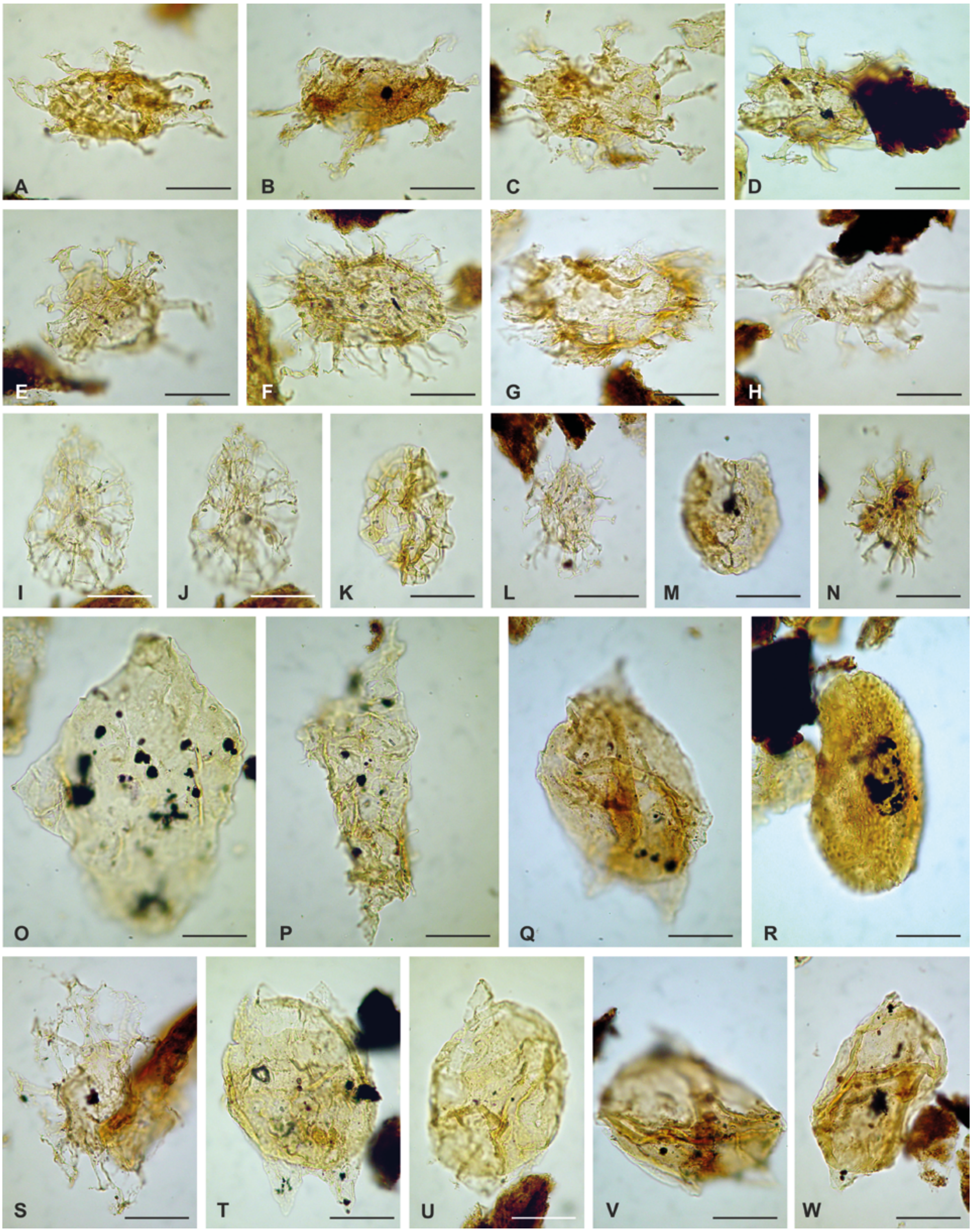

Fig. 7. Aquatic palynomorphs from the autochthonous Miocene, NS-1 Borehole, depth 4,760.80 m (photograph – P. Gedl). Scale bars indicate 25 µm. **A.** *Homotryblium*? sp. **B.** *Homotryblium*? sp. **C.** Chorate gonyaulacoid with presumably apical archaeopyle and intratabular processes, similar to *Enneadocysta* and *Oligosphaeridium*. **D.** *Homotryblium*? sp. **E.** Chorate gonyaulacoid with hollow processes, presumably *Homotryblium*. **F.** Chorate gonyaulacoid with uncertain archaeopyle type and non-tabular, solid processes, some of which are distally expanded. **G.** *Glaphyrocysta*-type dorso-ventrally compressed cyst. **H.** *Homotryblium* sp. **I, J.** *Nematosphaeropsis* ?*labyrinthea* (same specimen, various foci). **K.** *Impagidinium* sp. **L.** Small chorate gonyaulacoid, *Spiniferites*?-*Achomosphaera*? morphotype. **M.** *Caligodinium*? sp. **N.** Small chorate gonyaulacoid with solid processes, distally expanded (*Reticulatosphaera*? sp.). **O.** Incomplete specimen of *Rhombodinium* sp. **P.** Fragmentarily preserved specimen of *Wetzeliella* with solid, distally closed processes. **Q.** *Deflandrea* sp. **R.** *Tasmanites*? sp. **S.** *Distatodinium*? sp. **T–W.** *Deflandrea* spp.

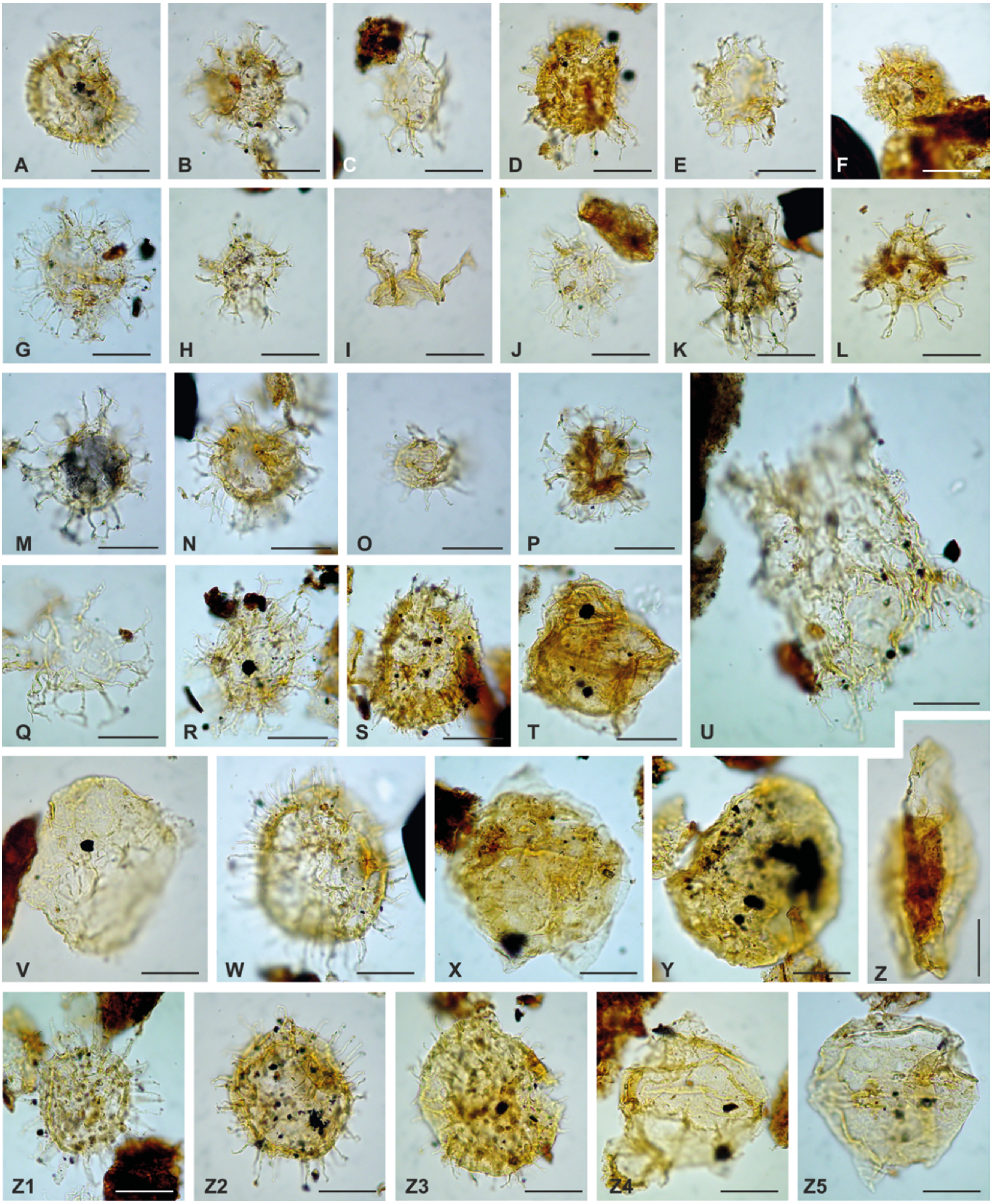

Fig. 8. Dinoflagellate cysts from the autochthonous Miocene, NS-1 Borehole, depth 5,139.20 m (photograph – P. Gedl). Scale bars indicate 25 µm. **A.** *Operculodinium* sp. **B–E.** *Spiniferites* spp. **F.** *Dapsilidinium*? sp. **G, H.** *Spiniferites* spp. **I.** Apical operculum. **J–N.** *Spiniferites* spp.**O.** *Dapsilidinium*? sp. **P.** *Spiniferites* sp. **Q.** *Enneadocysta* sp. **R.** *Spiniferites* sp. **S.** *Operculodinium* sp. **T.** *Pentadinium*? sp. **U, V.** *Wetzeliella* spp. **W.** *Operculodinium* sp. **X.** *Deflandrea* sp. **Y.** Unidentified species with 1P archaeopyle. **Z.** *Deflandrea* (?) in a lateral compression. **Z1.** *Lingulodinium machaerophorum*. **Z2, Z3.** *Operculodinium* spp. **Z4, Z5.** *Deflandrea* spp.

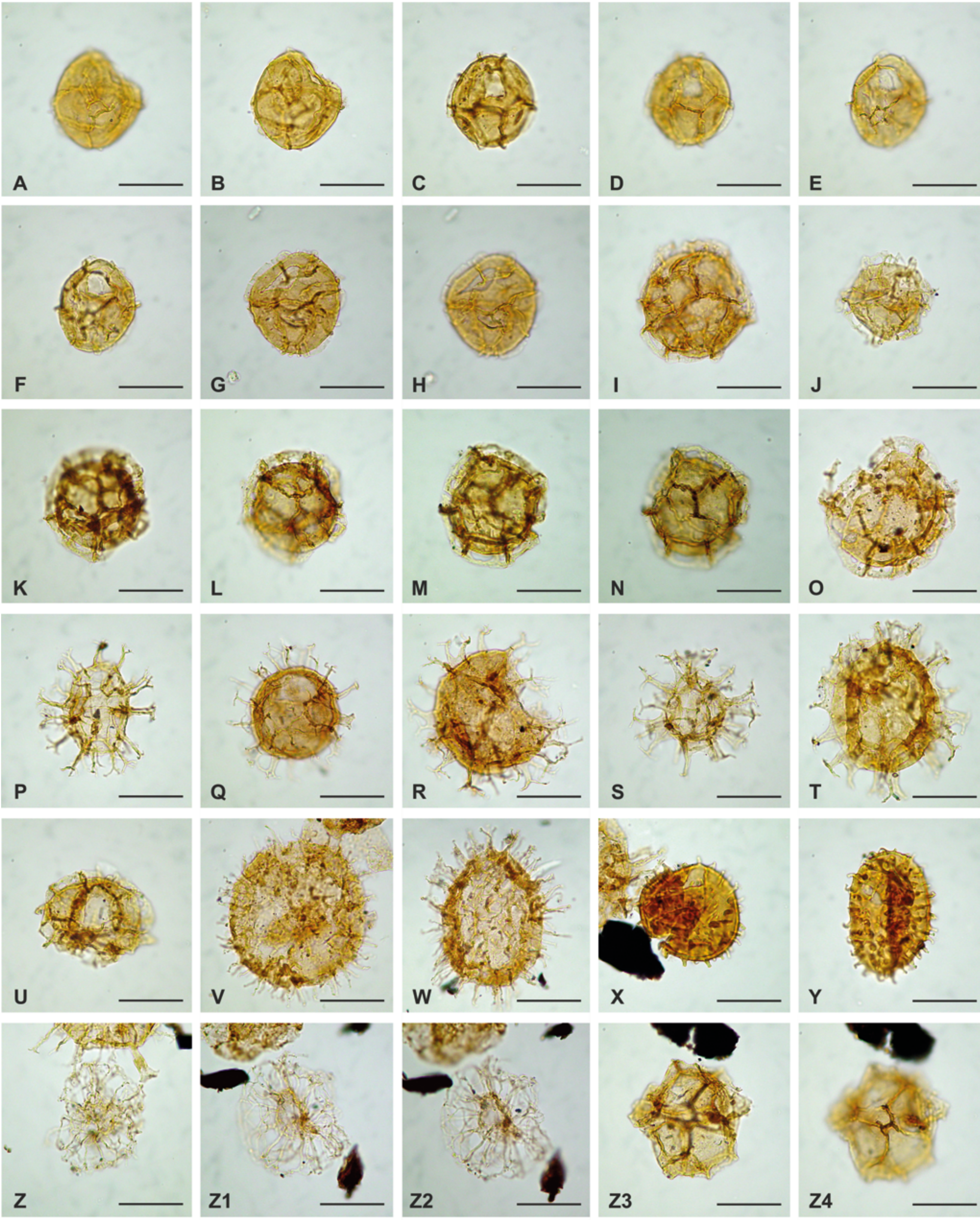

Fig. 9. Dinoflagellate cysts from the autochthonous Miocene, NS-1 Borehole, depth 5,458.35–50 m (photograph – P. Gedl). Scale bars indicate 25 µm. **A–H.** *Impagidinium* sp. (A and B, C and D, E and F, G and H – same specimens, various foci). **I.** *Impagidinium*? sp.; specimen with relatively high septa, some showing arch-like shape similar to the ones of *Unipontidinium aquaeductum*. **J.** Small specimen of *Unipontidinium aquaeductum*. **K–O.** *Unipontidinium aquaeductum* (K and L, M and N; same specimens, various foci). **P–T.** *Spiniferites* spp. **U.** *Unipontidinium aquaeductum*. **V.** *Lingulodinium multivirgatum*? sp. **W.** *Operculodinium* sp. **X.** *Operculodinium piaseckii*?. **Y.** *Operculodinium*? sp. **Z–Z2.** *Nematosphaeropsis labyrinthea* (same specimen, various foci). **Z3, Z4.** *Impagidinium aculeatum*? (same specimen, various foci).

Fig. 10. Dinoflagellate cysts from the autochthonous Miocene, NS-1 Borehole, depth 5,458.35–50 m (photograph – P. Gedl). Scale bars indicate 15 µm. **A, B.** *Hystrichokolpoma rigaudiea* (lateral view; same species, various foci). **C.** *Hystrichokolpoma rigaudiea* (polar view). **D–E.** *Lingulodinium machaerophorum*: long-process specimen with 1P archaeopyle (same species, various foci). **F, G.** *Cribroperidinium* sp. (same species, various foci). **H.** *Apteodinium* sp. **I, J.** *Cribroperidinium*? sp. (same species, various foci). **K, L.** *Spiniferites* sp. (large specimen with high membrane joining the processes in apical and antapical areas (same specimen, various foci). **M.** *Spiniferites pseudofurcatus*. **N.** *Spiniferites* sp. **O.** *Hystrichokolpoma rigaudiea*. **P.** *Spiniferites pseudofurcatus*. **Q.** *Spiniferites ramosus*; **R, S.** *Operculodinium centrocarpum* (same specimen, various foci). **T.** *Operculodinium* sp. **U, V.** *Palaeocystodinium striatogranulosum* (same specimen, various foci). **W, X.** *Pentadinium* sp. (same specimen, various foci). **Y.** *Chatangiella*? sp. **Z–Z2.** *Hystrichosphaeropsis obscura* (same specimen, various foci). **Z3.** *Lingulodinium*? sp. **Z4.** *Spiniferites pseudofurcatus*.

which amount to 60–80% (Figs 9, 10). The remaining elements are pollen grains and black, opaque phytoclasts. Both samples yielded rich, well-preserved and taxonomically diversified dinoflagellate cyst assemblages. The most frequent are *Spiniferites ramosus s.l.*, *Nematosphaeropsis labyrinthus*, *Lingulodinium machaerophorum*; the other common taxa include *Impagidinium* spp., *Hystrichokolpoma* spp., *Cribroperidinium* sp., *Apteodinium* sp., and *Unipontidinium aquaeductum*. *Palaeocystodinium striatogranulosum*, *Melitasphaeridium choanophorum*, *Reticulatosphaera actinocoronata*, *Hystrichosphaeropsis obscura*, and *Spiniferites pseudofurcatus*, are present in lower numbers.

Two samples from a depth of 5,561 m, conglomerate matrix. Both samples representing the loamy matrix and different in colour (greenish and cherry-red), yielded no palynological organic matter.

PALYNOMORPH COLOURATION

Palynomorph colouration undergoes significant changes with increasing temperature. This is due to molecular changes that occur within each organic particle during heating: light, immature particles become darker with a source of increasing heat, up to the transition of their structure into graphite carbon (e.g., Batten, 1996). In practical palynology, this phenomenon is widely used to determine the hydrocarbon potential of source rocks and to differentiate recycled palynomorphs that usually are darker than forms found *in situ*. The sources of heat in sedimentary successions are mainly related to the weight of the overlying strata, since the temperature increases with burial depth, or to magmatic intrusion.

In case of the NS-1 Borehole, it might be expected that the deepest part of the borehole should yield dark-coloured palynomorphs. This, however, is not the case: palynomorphs from the deepest intervals studied (autochthonous Miocene from depths of 5,458.35–50 m and 5,465.70–85 m; Figs 9 and 10) are of the same colour, or even lighter than the ones from shallower depths. This points to the fact that temperature at a depth of almost 5.5 km did not display significantly altered organic particles in the NS-1 Borehole. Moreover, it shows that factors affecting the darkening of some palynomorphs from shallower depths (e.g., the Stebnik Unit; see Figs 4, 5) were much more intense. These could be tectonic effects on their host strata, which prior to final placement were subjected to much stronger heating than the temperature that affected the autochthonous Miocene strata at a depth of 5.5 km.

AGE INTERPRETATION AND LITHOSTRATIGRAPHIC CORRELATION

Stebnik Unit

In general, the palynological material from two samples from the Stebnik Unit of the NS-1 Borehole (3,950 m and 4,030 m) is poor and does not allow precise dating; the differences in aquatic and terrestrial palynomorph age interpretations do not make solving this problem any easier. Moreover, these are cuttings samples, which increases the risk of contamination and further complicates the dating.

The age-interpretations of dinoflagellate cysts found at a depth of 4,030 m indicate a late early Oligocene (i.e., late Rupelian) age of the assemblage. This assumption is based on co-occurrence of three taxa determined.

A single specimen of *Rhombodinium* indicates Paleogene at this depth, as the stratigraphic range of this genus is limited to the Paleogene, mainly Eocene–Oligocene (e.g., Gocht, 1955; Bujak, 1979; Stover *et al*., 1996; Williams *et al*., 2004; Köthe and Piesker, 2008). However, this specimen resembles *Rhombodinium* sp. A from the Szaflary Beds (the Lower Oligocene part of the Podhale Flysch; see Gedl, 2000b). Another species from a depth of 4,030 m, *Enneadocysta pectiniformis*, has a Priabonian–Rupelian age-range (e.g., Williams *et al*., 2004). Another taxon found at this depth is a poorly preserved specimen of questionably determined *Chiropteridium*, a genus typical for higher part of the Rupelian and Chattian in the Polish Carpathians (e.g., Gedl, 2000a, b; Barski and Bojanowski, 2010; Suchocka *et al*., 2019).

Also, dinoflagellate cysts found in a sample from a depth of 3,950 m cannot precisely date this interval, as they are even less age-distinctive. The presence of poorly preserved *Homotryblium*? sp. indicates an Eocene–Lower Miocene age. But the similarity of palynofacies to the one from the depth of 4,030 m may indicate that also this sample represents the Oligocene.

If the assumption that these dinoflagellate cysts are *in situ* were to be accepted, then the Stebnik Unit at depths of 3,950 m and 4,030 m is Paleogene, most likely the upper Lower Oligocene. This assumption would allow correlation of strata from the samples with the Menilite Beds, the organic-rich, informal lithostratigraphic unit of the Flysch Carpathians. But the samples of the present authors yielded none of the amorphous organic matter, which is so very widespread in the Menilite Beds and characteristic of this facies (e.g., Gedl, 2004; Barski and Bojanowski, 2010; Suchocka *et al*., 2019). Possibly, the strata under consideration represent the Polanica Beds (also known as the Polyanytsa/Polyanitsa Formation), an informal lithostratigraphic unit that occurs just above the Menilite and Krosno Beds in the succession of the Stebnik Unit (see e.g., Oszczypko, 1998; Oszczypko *et al*., 2006; Gozhyk *et al*., 2015). However, the latest results of palynological studies indicate a Lower Miocene age for this unit (see Discussion).

It is not possible to resolve the issue of whether these dinoflagellate cysts are *in situ* by comparison with the ranges of the remaining taxa found in this sample. They all are long-ranging, although their spectrum also fits the late Early Oligocene. No younger taxa have been found. A particular premise, pointing to the possible reworking of dinoflagellate cysts in question is the variable state of preservation indicating different modes of origin. However, that does not solve the question as to which forms are reworked: those better preserved (e.g., *Rhombodinium*, *Enneadocysta pectiniformis*), or those worse preserved (the predominating forms, including, i.a., *Chiropteridium*?), or all of them?

Another issue in this topic is the spectrum of sporomorphs, which although infrequent and rather poorly preserved, indicate a younger, namely Miocene age of the strata in question. This assumption is based on the relatively common occurrences of *Zonalapollenites*, which appeared in such frequencies in the Miocene (or younger times; Stuchlik *et al*., 2002). Some elements, e.g., cf. *Cicatricosisporites* sp., are most likely reworked from Paleogene (Eocene–Oligocene) strata. The Paleocene is excluded, as there are no pollen grains from the Normapolles group. Acceptance of an undivided Miocene age, based on sporomorphs, results for two scenarios. One possibility is that this would have to be the earliest Miocene (Aquitanian): on the basis of poorly preserved specimens, including *Chiropteridium*? The last appearance in the mid Aquitanian of the northern hemisphere mid-latitudes according to Williams *et al*., 2004. *Homotryblium*? also could indicate the earliest Miocene. The highest occurrences of this particular genus in the Miocene; Stover *et al*., 1996; Williams *et al*., 2004; see also Gedl, 2016) could be *in situ*. Better preserved specimens, representing *Rhombodinium* and *Enneadocysta*, could have been recycled from Paleogene strata in clasts, assuring their better preservation. On the other hand, this part of the Stebnik Unit might represent younger Miocene strata (Middle Miocene?) but accumulated in a non-marine environment, devoid of marine cysts *in situ*, all considered to have been reworked.

Autochthonous Miocene

Two samples, taken from intervals cored in the upper part of the autochthonous Miocene (depths 4,760.80 m and 5,139.20 m), yielded palynological assemblages, the age of which can be interpreted in two ways; as in a case of the Stebnik Unit samples: they can be either Paleogene or Miocene, with reworked Paleogene elements.

The higher sample (depth 4,760.80 m) yielded a poorly preserved gonyaulacoid-dominated assemblage, with infrequent peridinioids. Some of the taxa encountered have stratigraphic ranges limited to Paleogene or older (*Rhombodinium*, *Wetzeliella*, *Enneadocysta*, and *Glaphyrocysta*), mostly being characteristic for the Eocene–Oligocene. No typical Middle Miocene taxa were found. Among those known also from the Miocene, *Deflandrea* has the shortest post-Paleogene range, being limited to the lower Aquitanian. Assuming that the Paleogene taxa are recycled, then a lower Aquitanian age can be proposed on the basis of the presence of *Deflandrea*, again assuming that it was not recycled. The highest occurrence is in the lower Aquitanian.

A similar, two-way age interpretation can be assumed on the basis of the relatively richer, but moderately preserved dinoflagellate cyst assemblage from a depth of 5,139.20 m (Tab. 3). Most of the taxa identified indicate an Eocene–Early Miocene time span. These are *Enneadocysta* and *Wetzeliella* only, the age-ranges of which are limited to Eocene–Oligocene exclusively (e.g., Stover *et al*., 1996). The remaining taxa, determined at the generic level, are long-ranging and appeared both in the Paleogene and the Early Miocene. However, an Early Miocene age can be supported by the relative taxonomic impoverishment of the assemblage, which is dominated by chorate gonyaulacoids, such as *Operculodinium*, *Spiniferites*, and *Lingulodinium*. All of these are important parts of the Miocene dinoflagellate cyst assemblages from the Carpathian Foredeep (e.g., Gedl, 1996, 1998, 1999). Many other taxa, which are typical for the Paleogene, i.a., *Areosphaeridium*, *Glaphyrocysta*, *Enneadocysta*, *Areoligera*, *Thalassiphora*, *Phthanoperidinium* or *Rhombodinium*, are missing. The presence of *Deflandrea*, if not it is recycled, may indicate that the strata in question are not younger then the lower Aquitanian, as this genus appeared for the last time in the early Aquitanian (as *D. phosphoritica*; Williams *et al*., 2004). A Middle Miocene age is excluded, as there are no species typical for this time interval, which are widespread in the Carpathian Foredeep (see below).

The interpretation of sporomorph analysis, although also ambiguous, favours a Miocene age for both samples. The sporomorphs, found in the samples from depths 4,760.80 m and 5,139.20 m, include abundant *Pinuspollenites*, *Zonalapollenites*, and *Cathayapollis* (Tab. 4), which make them similar to the samples from the Stebnik Unit, described above. The latter differ, however, in terms of the much lower frequencies of pollen grains.

This interpretation is supported by the infrequent foraminifera *Condorbulina s*p. and *Praeorbulina glomerosa*, found in the 5,130–5,140 m core interval (Mijal, 2021); their presence points to a Karpathian–Badenian age. The calcareous nannoplankton, in turn, is mainly reworked (Cretaceous and Eocene–Oligocene taxa). The Miocene forms are very poorly preserved and do not allow precise dating (Mijal, 2021). Their occurrence may resemble the mode of occurrence of dinoflagellate cysts and this explains their origin.

A Miocene age for this interval also can be favoured indirectly by the mode of occurrence of clasts (see the subchapter on core description, depths 4,750–4,768 and 5,130–5,140 m) that most likely originated from the Paleogene strata of the neighbouring Carpathians.

The two lowermost samples from the autochthonous Miocene, penetrated by the NS-1 Borehole (5,458.35–50 m and 5,465.70–85 m), yielded very abundant dinoflagellate cysts that precisely date the basal part of this unit. The presence of *Unipontidinium aquaeductum* indicates a latest Langhian–early Serravalian (early Badenian) age of accumulation for them. This species is known to have appeared during this time interval in the mid-latitudes of the Northern Hemisphere mid-latitudes (Williams *et al*., 2004). *U. aquaeductum* is typical only for the lower Badenian sub-evaporitic strata of the Carpathian Foredeep (e.g., Gedl, 1996, 1998, 1999; Peryt and Gedl, 2010). It does not occur in the upper Badenian strata overlying the evaporitic series (e.g., Peryt *et al*., 2014). Jiménez-Moreno *et al*. (2006) report a similar range of this species, correlated with NN5 (except for its basal part) and the lower part of NN6 calcareous nannoplankton zone of the Central Paratethys in Central Europe. Both the presence of this species and the general character and taxonomic richness of the assemblage allow the correlation of these basal strata of the autochthonous Miocene, penetrated by the NS-1 Borehole, with assemblages known from the sub-evaporitic strata (the Baranów Beds and the Skawina Beds) in other areas of the Carpathian Foredeep.

Rich and well-preserved foraminifera assemblages, composed of *Globigerinoides* and *Orbulina* and containing

Candorbulina suturalis, allow dating of the cored interval 5,458–5,467 m as lower Badenian (Moravian; Mijal, 2021), which is in good agreement with the age based on dinoflagellate cysts.

Conglomerates

The age of the conglomerates, penetrated by the NS-1 Borehole, is uncertain; both of the samples studied are barren. The petrographic composition of the clasts and their uniformity indicate a single source area for their origin that probably was the top of the Precambrian basement. No younger clasts have been identified. Angular clast shapes indicate a relatively short distance of transportation. The lack of microfossils and the red colouration of some parts of matrix indicate a continental sedimentary setting. All these data, although not without some degree of doubt, could indicate that the conglomerates drilled by the NS-1 Borehole originated as a result of erosion of the Precambrian basement in a terrestrial environment between the Precambrian and the Miocene. The lack of Paleozoic–Mesozoic clasts indicates that the accumulation of the conglomerates took place in pre-Paleozoic times, but any younger, pre-Miocene age cannot be excluded with certainty.

PALAEOENVIRONMENTS

The palynological data allow in many cases precise palaeoenvironmental interpretation of the ancient sedimentary settings. This method is based mainly on the analysis of various groups (including forms that are continental, aquatic, marine, etc.) and tracing changes in their proportions. Furthermore, a detailed analysis can be carried out on the basis of the known or supposed palaeoenvironmental preferences of particular palynological elements, their ability to withstand specific sedimentological processes, and their taphonomic resistance. The NS-1 Borehole material includes both continental and marine palynological organic matter, occurring in different proportions, which reflect a variety of sedimentary settings. A complication affecting the above-mentioned method in the present study is the possible occurrence of reworked material. The presence of this could significantly obscure the *in situ* contribution of particular groups of palynological elements and, as a consequence, it may falsify the true palaeoenvironmental interpretation.

Two samples analysed from the Stebnik Unit (3,950 m and 4,030 m) are cuttings samples and so their palynology cannot be supported by the sedimentological analysis of a core. The presence of marine dinoflagellate cysts, probably of Oligocene age, points to a marine sedimentary setting with some terrestrial influences. Interestingly, the majority of Oligocene strata in the Outer Carpathian marine basins were characterized by anoxic conditions, reflected in the palynological record by the presence of amorphous matter (e.g., Gedl, 2004; Barski and Bojanowski, 2010; Suchocka *et al*., 2019; see chapter above). Meanwhile, the NS-1 Borehole samples lack amorphous organic matter that excludes anoxic bottom conditions in the Stebnik basin during the accumulation of the samples under consideration. This in turn resembles the Oligocene strata of the Inner Carpathian basin, which lack amorphous organic matter (e.g., Gedl, 2000a, b).

However, the assumption that the marine dinoflagellate cysts in this part of the Stebnik Unit are reworked and they represent the Lower Miocene shows a purely continental environment or a very nearshore marine setting, characterized by conditions, hostile to motile dinoflagellates and/or the preservation of their cysts.

A similar situation occurs in the upper part of the autochthonous Miocene strata (samples from depths of 4,760.80 m and 5,139.20 m). Dinoflagellate cysts found there are of uncertain origin. They might be partly Paleogene, but some also might be Miocene, whereas sporomorph data indicate a Miocene age. This, along with the abundance of clasts from the Carpathian orogen (see core description), indicates that most, if not all, dinoflagellate cysts may be reworked. The lack of species that clearly could be treated as Miocene, as in the case of the samples from the Stebnik Unit, may indicate a sedimentary setting that was unfavourable for organic phytoplankton. The hostile conditions, responsible for this, may have resulted from the intense influx of terrigenous clastics along with terrestrial organic particles (present in the material of the present authors as the overwhelmingly predominant phytoclasts) leading to high turbidity of the water and/or possible changes in its salinity.

Completely different palaeoenvironmental conditions predominated during the accumulation of the lower part of the autochthonous Miocene succession, seen in the NS-1 Borehole (samples from depths of 5,458.35–50 m and 5,465.70–85 m). The predominance of dinoflagellate cysts, which represent up to 80% of the palynofacies in these intervals, indicate a pelagic mode of sedimentation. Terrestrial organic elements, which are so common in the upper part of the autochthonous Miocene, are represented here almost exclusively by bisaccate pollen grains, known for their high buoyancy and common airborne mode of transportation.

DISCUSSION

The Stebnik Unit and the autochthonous Miocene succession of the Carpathian Foredeep have been the subjects of geological studies for years. Their ages were primarily based on studies of foraminifera and calcareous nannoplankton. The results of palynological studies in this paper are presented for the first time. However, the previous age interpretations, particularly in a case of the Stebnik Unit, differ significantly, depending on the author, the method used and the study area. These differences are caused partly by the very frequent occurrence of reworked Cretaceous and Paleogene microfossils that are excellently preserved and commonly outnumber the poorly preserved *in situ* ones.

The latest and most complex biostratigraphic studies of the units under consideration are those by Garecka and Olszewska (1997) and Garecka and Jugowiec (1999) in which a summary of older studies is given and regional correlations with more western and eastern areas (i.e., Ukraine) are discussed.

Stebnik Unit

The presence of Oligocene dinoflagellate cysts in the samples of the present authors from the Stebnik Unit, if they were not reworked, indicates that at least part of this unit was deposited during the late Paleogene. Such an interpretation would be in favour of the theory that the Stebnik Unit consists of Miocene (Eggenburgian–Badenian) strata, folded together with the Paleogene flysch of the Skole Unit of the Carpathians (e.g., Zieliński, 1963; Karnkowski, 1994, 1997). However, this is in contrast with the interpretations postulated by other authors (e.g., Garecka and Olszewska, 1997), who claim an exclusively Miocene age for the Stebnik Unit. A possible explanation for this contradiction would be that both of the samples studied represent the Polyanitse Beds, which are believed to be the oldest unit of the Stebnik Unit. These strata occur mainly in the territory of Ukraine and rest upon the Carpathian Menilite Beds. There are, however, some inconsistences, concerning the age of these strata, their affiliation to the Stebnik Unit, and their relationship to the underlying Menilite Beds. In the older literature, their age is commonly correlated with the Oligocene, owing to their superposition above the Menilite Beds, which traditionally are regarded as Oligocene. However, subsequent studies showed that the top of the latter can represent even the Lower Miocene, meaning the NN2–NN3 calcareous nannoplankton zones (Andreyeva-Grigorovich *et al*., 1997; see also Gozhyk *et al*., 2015). Several authors believe that the Paleogene flysch strata of the Skole Unit are folded within the Stebnik Unit (e.g., Karnkowski, 1994). If this interpretation were to be accepted, then the dinoflagellate cysts of the present authors could be *in situ*. However, another, indirect clue in favour of a Miocene age of the strata under consideration is the micropalaeontological results from the Vorotyshche Beds, the succeeding lithostratigraphic unit of the Stebnik Unit. Garecka and Olszewska (1997) reported from this unit calcareous nannoplankton, not older then NN3 (vicinity of Aksmanice). An older age, correlated with NN1 and NN2, was suggested for the lower part of this unit in the Ukrainian part of the Carpathian Foredeep (Andreyeva-Grigorovich and Stupnickij, 1976 and Andreyeva-Grigorovich *et al*., 1997, respectively), and NN3 for its upper part (Andreyeva-Grigorovich and Stupnickij, 1976). However, it must be noted that many samples from the lower part of the Stebnik Unit are either barren or they commonly yielded only rich and well-preserved pre-Miocene material (Garecka and Olszewska, 1997; Garecka and Jugowiec, 1999).

The latter features are also characteristic for the overlying Stebnik Beds: Miocene taxa are commonly absent or greatly exceeded in number by Cretaceous and Paleogene forms. The former, if present, indicate an age, correlated with NN3–NN4 (Andreyeva-Grigorovich and Stupnickij, 1976; Andreyeva-Grigorovich and Savitska, 1996; Andreyeva-Grigorovich *et al*., 1997). The lack of Early Miocene fossils in the very numerous samples from this unit may indicate that some horizons of the Stebnik Unit accumulated during conditions that were temporarily hostile for the majority of marine microfossils. The precise nature of these conditions is uncertain. They could be related to water depth and/or chemistry. During these periods, freshwater or brackish conditions could have prevailed and might have been related to an intense influx of reworked Paleogene and Cretaceous fossils.

Autochthonous Miocene

The lower part of the autochthonous Miocene sequence studied is correlated by means of dinoflagellate cyst assemblages with the upper part of the NN5 and the lower part of the NN6 calcareous nannoplankton zones, on the basis of the presence of the stratigraphically important *Unipontodinium aquaeductum* (e.g., Gedl, 1996, 1998, 1999). This age interval corresponds in the Polish sector of the Carpathian Foredeep to the Skawina Beds and the Baranów Beds (and their local counterparts, such as the Korytnica Clays), in which calcareous nannoplankton allow their correlation with NN5 and NN6 (Martini, 1977; Dudziak and Łuczkowska, 1992; Gaździcka, 1994) and with the Paratethyan stage, the Badenian (upper Langhian to lower Serravalian, according to Lourens *et al*., 2004). Only in the westernmost part of the Polish Carpathian Foredeep, the base of the Skawina Beds can be as old as the top of NN4 (Garecka and Jugowiec, 1999).

Correlation of the lower part of the autochthonous Miocene in the NS-1 Borehole with the Skawina/Baranów beds of the Foredeep Basin, is further supported by the taxonomical similarity of the dinoflagellate cyst assemblages (e.g., Gedl, 1995, 1996, 1999). Their composition and predominance over terrestrial elements shows that the Foredeep Basin during the early Badenian in Poland was fully marine, characterized by similar sedimentary conditions, being a vast basin with predominantly pelagic deposition.

The pelagic mode of sedimentary accumulation ceased during subsequent stages of evolution of the Foredeep Basin. Samples from the higher part of the succession drilled clearly show increased terrestrial influx and taxonomic impoverishment in planktonic phytoplankton. A similar trend was observed in the central part of the Foredeep Basin, where the pre-evaporitic series yielded predominantly dinoflagellate cysts, whereas the post-evaporitic strata contained impoverished assemblages and frequent reworked taxa (Gedl, 1999). This part of the drilled autochthonous Miocene probably represents the Machów Formation, i.e., the post evaporitic series. The calcareous nannoplankton investigation from this lithostratigraphic unit gave slightly differing results, from NN5 to even possibly NN9 (Gaździcka, 1994; Garecka and Jugowiec, 1999).

Conglomerates

The superposition of the conglomerates drilled resembles the position of the conglomerates, known from neighbouring borings in the Carpathian Foredeep and below the Carpathian overthrust. Moryc (1995) described and discussed the age and origin of conglomerates (the Racławówka Conglomerate Formation) that occur in the vicinity of Sędziszów Małopolski and Rzeszów (some 90 km north-west of the study area; see Fig. 1A). Moryc (1995) described them as the basal fills of palaeovalleys, cut into the Carpathian foreland during the Laramian phase of the Alpine orogeny. In these valley floors, they rest upon basement of various ages, from Precambrian through Carboniferous to Jurassic, and are covered by presumably Paleogene fine-grained strata of the Czudec Formation and/or the Badenian strata of the Carpathian Foredeep Basin (see also Gedl and Worobiec, 2020).

A similar origin was tentatively suggested by Moryc for the more eastward-occurring Albigowa Conglomerates, known from the vicinity of Przemyśl, although their precise ages have not yet been determined (see Czernicki and Szafran, 1978; Szafran, 1980). However, in case of the NS-1 conglomerates, no incised structure has been detected in the site of deposition; moreover, their petrographic composition is completely different from that of the Racławówka Conglomerate Formation. The latter are polymictic, being composed of highly rounded clasts, representing Devonian, Carboniferous and Jurassic limestones, mixed with Precambrian quartzites and meta-argillites. The presence of the former and their high degree of roundness clearly distinguish the Racławówka Conglomerate Formation from the NS-1 material. These differences indicate different ages and/or conditions of formation. The lack of Mesozoic and Paleozoic clasts indicates that they accumulated even in pre-Paleozoic times. But the possibility cannot be excluded that they are of the same age and the petrographic differences are only the result of differences in the distance of transportation and the type of source rock subjected to erosion.

CONCLUSIONS

1. A total of nine samples was investigated for palynology from a Foredeep Basin sequence, penetrated by the NS-1 Borehole at the front of Carpathian overthrust: the Stebnik Unit (two samples), the autochthonous Miocene (five samples), and the basal conglomerates (two samples).
2. Cuttings samples from the Stebnik Unit yielded very low amounts of palynological organic matter, including very rare and poorly preserved dinoflagellate cysts and sporomorphs. Core samples from the upper part of the autochthonous Miocene yielded much greater amounts, dominated by terrestrial phytoclasts; abundant palynological material, although dominated by dinoflagellate cysts, was found in samples from the lower part of this unit. No organic matter was found in samples from the matrix of the basal conglomerates.
3. The age interpretations of the material from the Stebnik Unit and from the upper part of the autochthonous Miocene succession are not in complete agreement: some dinoflagellate cysts are Paleogene or long-ranging, but the composition of pollen grains rather points to a Miocene age. This indicates reworking of Paleogene material, presumably during the Early in the case of the Stebnik Unit and the Middle Miocene for the autochthonous Miocene. A similar phenomenon of increased reworking of Paleogene and Cretaceous microfossils relative to the *in situ* forms of the strata in question is widely known from the literature. The above is contrasted with the lack of redeposition observed in the lower part of the autochthonous Miocene succession, which yielded purely *in situ* Middle Miocene dinoflagellate cyst assemblages. The lack of organic matter in the matrix binding the conglomerate clasts does not allow their dating. However, clast petrography indicates that they were formed earlier than the other conglomerates, known from this area, possibly even in pre-Paleozoic times.
4. The lower part of the autochthonous Miocene, penetrated by the NS-1 Borehole, represents pelagic strata accumulated during the early Badenian (upper part of NN5 and lower part of NN6) correlated with the Skawina Beds and the Baranów Beds of the Foredeep Basin. Higher intervals, studied with regard to palynology most likely represent the Machów Formation, characterized by an increased influx of terrestrial material, including land plant remains and reworked dinoflagellate cysts, derived from eroded Carpathian strata. The Stebnik Unit at each of the depths studied represents deposits that accumulated in non-marine conditions or in a marine setting, not inhabited by dinoflagellates, most likely during the Early Miocene.
5. The analysis of palynomorph maturity, based on colouration, shows that even the deepest parts of the borehole from depths of almost 5.5 km (autochthonous Miocene) were not affected by a high temperature regime that would have led to significant darkening of their organic structures. Interestingly, much darker are some palynomorphs from the Stebnik Unit at shallower depths indicating that they have experienced much higher temperatures, probably during tectonic processes, before being buried at their current position.

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