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The Orava segment of the Pieniny Klippen Belt: Lithology, structure and stratigraphy based on the organic-walled dinoflagellate cysts (Šariš Unit)

MARÍNA MOLČAN MATEJOVÁ[1,✉] and PRZEMYSŁAW GEDL[2]

[1]Department of Geology and Paleontology, Faculty of Natural Sciences, Comenius University in Bratislava, Mlynská dolina G, 842 15 Bratislava, Slovakia; ✉marina.matejova@uniba.sk
[2]Institute of Geological Sciences, Polish Academy of Sciences, Research Centre in Kraków, Senacka 1, 31-002 Kraków, Poland; ndgedl@cyf-kr.edu.pl

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Abstract: The Pieniny Klippen Belt of the Western Carpathians is built up by Jurassic to Eocene Oravic units, with the Šariš, Subpieniny, and Pieniny Unit on the top. Major emphasis was placed on the dark fine-grained clastic deposits exposed in the vicinity of the villages of Beňova Lehota and Revišné (Orava sector of the Pieniny Klippen Belt). Through investigation of palynological material, the age of dark flysch strata was determined as predominantly uppermost Toarcian to Middle Aalenian and affiliated with the Szlachtowa and/or Skrzypny formations, belonging to the Šariš Unit. The results from the dinoflagellate cysts were supplemented by a structural investigation of the Šariš Unit. The complicated tectonic evolution of the Pieniny Klippen Belt is documented by intermixing of the soft shale deposits of Jurassic and Cretaceous age and by the presence of folds and cleavages. Based on the acquired data, the D_1 event records a compression with a NE–SW direction and is represented by folds with axial-plane cleavage. The younger D_2 phase is marked by the presence of south-vergent backthrusts, resulting from the ongoing compression and subsequent tilting of the originally north-vergent nappe stack of the Oravic units.

Keywords: Pieniny Klippen Belt, Šariš Unit, Orava region, Jurassic black flysch, biostratigraphy, dinoflagellate cysts

Introduction

The Pieniny Klippen Belt (PKB), as a significant tectonic zone of the Western Carpathians, shows a typical geological and structural complicity in its western Orava sector. In the studied area, various lithostratigraphic units of Mesozoic and Cenozoic ages representing three tectonic units – the Pieniny, the Subpieniny and the Šariš (Grajcarek) (Plašienka et al. 2021) occur across a relatively small area. These PKB units of the Orava sector were thrust over each other in several tectonic phases and were subjected to transpressional and transtensional tectonic regimes, which formed their present structure characterised by a mixture of imbricated tectonic units. In general, as in other areas of the PKB, hard carbonates of the Jurassic–Cretaceous age form klippen that are embedded in softer, less resistant Upper Cretaceous and Paleogene deposits. The Oravic units only include detached Jurassic to Lower Eocene strata, evolving from the Lower to early Middle Jurassic syn-rift clastic deposits followed by the Middle Jurassic–Cretaceous post-rift strata and terminated by the heterochronous Upper Cretaceous to Eocene syn-orogenic flysch deposits (Andrusov 1945; Birkenmajer 1977, 1986; Plašienka et al. 2012, 2021).

During our fieldwork in the western Orava part of the PKB, in the vicinity of the villages of Revišné and Beňova Lehota (Fig. 1), we revealed the presence of dark-coloured clastic deposits, occasionally of a turbiditic character, which we provisionally interpreted as being predominantly Jurassic strata of the Šariš Unit. This interpretation would widen the area of occurrence of the Šariš (Grajcarek) Unit in this part of the PKB, since this tectonic unit has been described so far only in a single locality (the klippe in Revišné; Molčan Matejová et al. 2019). To solve the problem of ages in lithologically similar rocks, we collected a set of samples studied for dinoflagellate cysts, which turned out to be an excellent tool for biostratigraphical studies of dark-coloured clastic strata of the PKB (e.g., Jaminski 1995; Gedl 2008; Barski et al. 2012; Gedl & Józsa 2015; Segit et al. 2015). The results of the palynological studies were supplemented by geological and tectonic observations in the area of study and compared to the surrounding region where the PKB structure crops out. Interpretations presented in this paper bring new age datings to the controversial so-called “black flysch”, proving in most samples its Jurassic age and allowing us to confirm a wider occurrence of the Šariš (Grajcarek) Unit.

Geological setting

The Pieniny Klippen Belt is a very narrow geological structure that stretches over a distance of 600 km from Vienna (Austria) in the west, then continues east through the territories of Poland and Slovakia, and finally extends to Ukraine and Romania in the south-east. Its width is occasionally reduced to only a few kilometres. The PKB separates two large regional domains: the Outer Carpathians to the north and the Central Carpathians to the south (Plašienka et al. 2020). The deposits that build the PKB structure represent sedimentary successions that span from the Lower Jurassic to Paleogene with Neogene volcanics and post-orogenic cover. The original accommodation space of the PKB was represented by a series of basins and rises, each differing by their facies character (Fig. 2). Three main sedimentation zones can be distinguished: (I) the northern oceanic realm, which is represented by the southern flanks of the Valais–Rhenodanubian–Magura Ocean and (II) the Czorsztyn Ridge, which forms

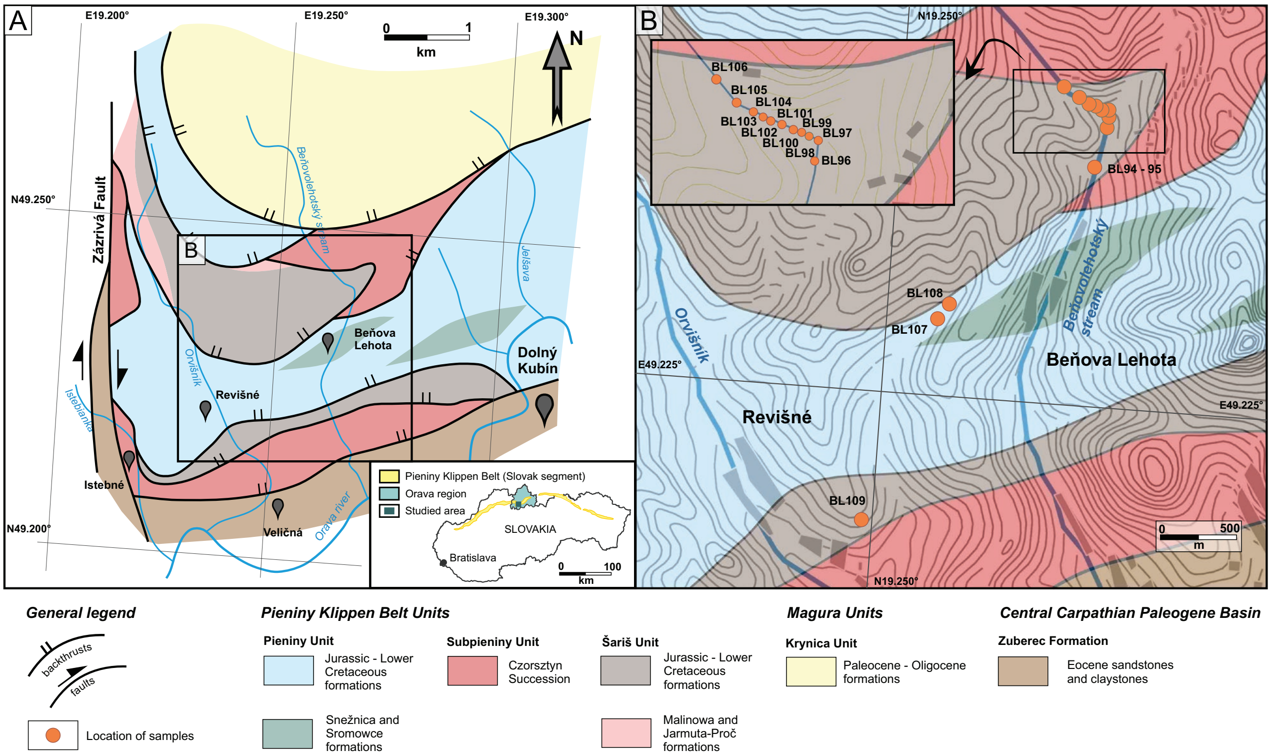

Fig. 1. Tectonic scheme of the studied area with location of samples (contour map exported from LLS: ÚGKK SR; tectonic map modified after Plašienka et al. 2021).

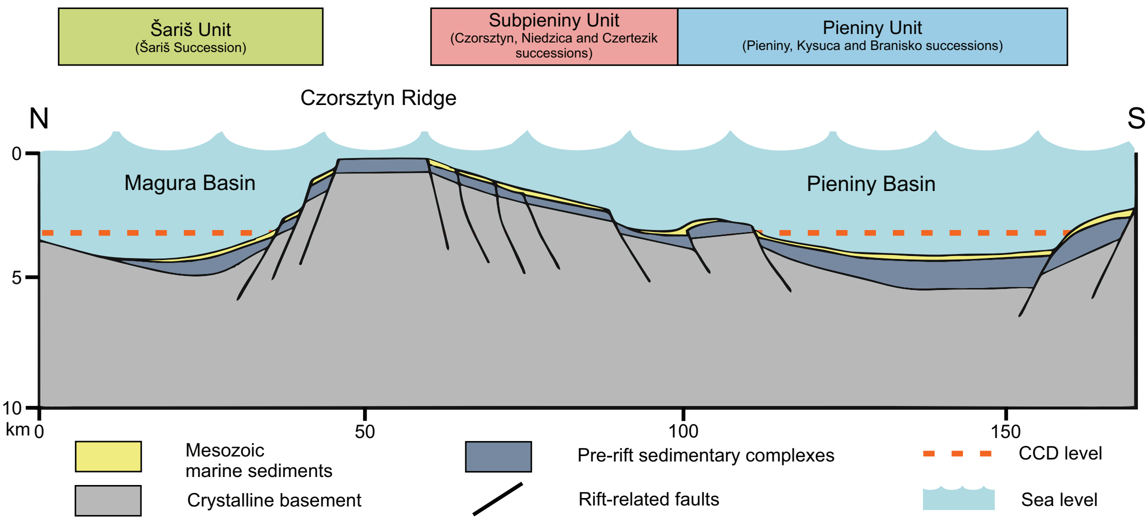

Fig. 2. Palinspastic reconstruction of the Pieniny Klippen Belt and adjoining areas during the Oxfordian (modified after Birkenmajer 1977).

an elevation that separated the Magura Ocean from (III) the South Penninic Ligurian–Piemont–Tauern–Rechnitz–Vahic Ocean spreading to the south (Plašienka et al. 2012). Each of these main facial zones (and further subzones) were transformed by orogenic movements into tectono-sedimentary units. The southern Penninic, deep-water deposits formed the Pieniny, Kysuca, and Branisko successions, and the deposits accumulated on the southern slopes of the Czorsztyn Ridge are distinguished (mainly in the Polish sector of the PKB) as the Niedzica and Czertezik successions (Birkenmajer 1977). The shallowest Czorsztyn Succession (Subpieniny Unit) sedimented in the shelf area close to the Czorsztyn Ridge. The strata deposited supposingly to the north from the Czorsztyn Ridge were accumulated in the southern part of the northern Penninic domain. They were named the Magura Succession by Birkenmajer (1958, 1965). These strata, which were tectonically incorporated into the PKB structure, were later distinguished in the Polish sector as the tectonic Grajcarek Unit (Birkenmajer 1970, 1977, 1979), spanning from the uppermost Lower Jurassic to the Paleogene (Birkenmajer & Gedl 2017; Fig. 3). In the eastern Slovak part of the PKB, it was renamed the Šariš Unit (Plašienka & Mikuš 2010), which is described by the authors as beginning with radiolarites (Callovian–Kimmeridgian). The older strata (the Szlachtowa and Opaleniec formations) were included in the Subpieniny Unit. In a recent ample publication about the PKB (Plašienka et al. 2021) in the easternmost part of the Varín PKB sector, the oldest recognised members of the Šariš Unit are turbidites and spotted marlstones of the Dutkov vrch and Allgäu formations of Sinemurian to Pliensbachian age, followed by the upper Toarcian to Bajocian Szlachtowa Formation (e.g., Birkenmajer & Gedl 2017 and references therein), which are composed of black dysoxic shales and siliciclastic turbiditic sandstones and often having a high content of clastic mica. In a section near Zazrivá (the Varín part of the PKB), Schlögl et al. (2012) and Suan et al. (2018) also interpret the Toarcian dark deposits of the Krempachy and Szlachtowa formations as belonging to the Šariš Unit. The most important element in the concept of the Šariš Unit is a normal stratigraphic succession of the Jarmuta and Proč formations (Jurewicz 2005, 2018; Plašienka & Mikuš 2010; Plašienka et al. 2012), which were previously considered as lying unconformably over deformed PKB units (Birkenmajer 1977, 1986). Lithostratigraphic division of the PKB successions, including the Grajcarek Unit (see Birkenmajer & Gedl 2017), was introduced by Birkenmajer (1977). This scheme, with subtle modifications, is still used today by Polish and Slovak geologists (Fig. 3).

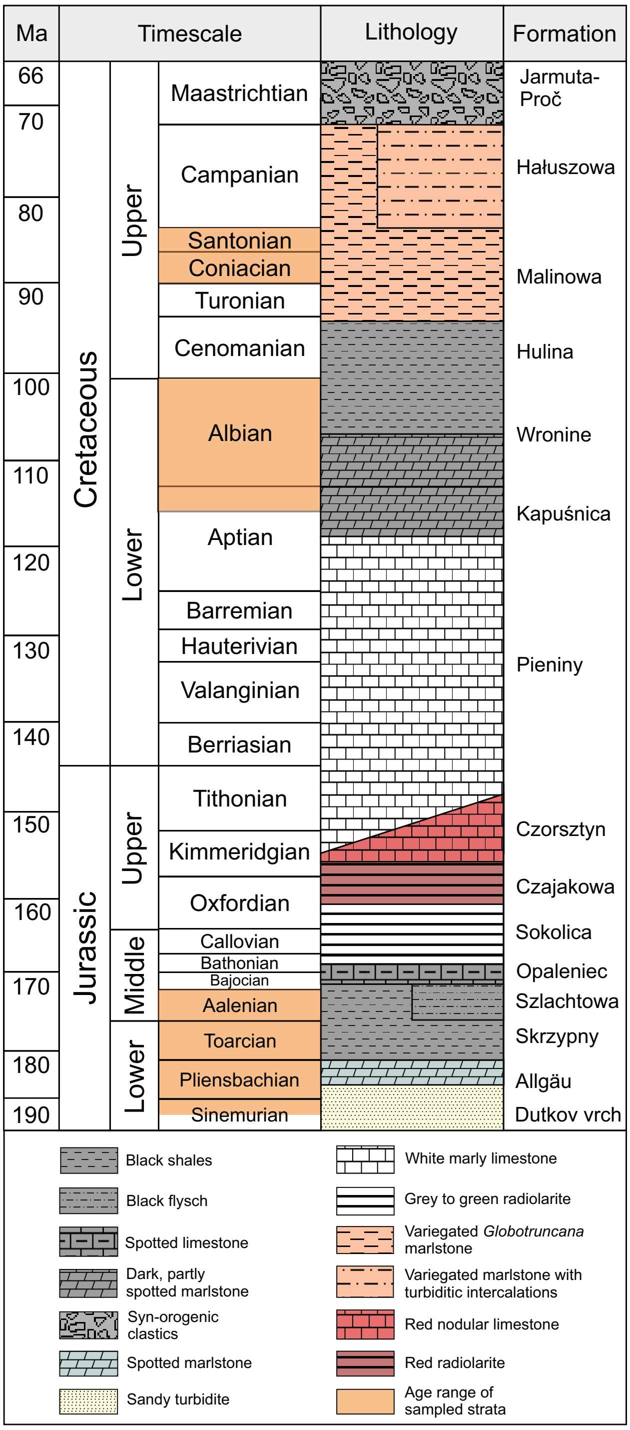

Fig. 3. Lithostratigraphic column of the Šariš Unit (modified after Plašienka et al. 2021).

Material

Sixteen samples from the area around the villages of Beňova Lehota and Revišné (Dolný Kubín district) were palynologically analysed and focused on the dinoflagellate cyst assemblages. Most of the samples (BL94–BL106) were taken from outcrops along the Beňovolehotský creek at Beňova Lehota (Figs. 1, 4, 5). Samples BL107 and BL108 were taken from outcrops situated in the valley of a small unnamed creek between the villages of Beňova Lehota and Revišné. One single sample, BL109, comes from an artificial outcrop, which had been dug out at Revišné (Fig. 1). The coordinates of all sampled locations are in Table 1.

Fig. 4. Field pictures. **A** — Soft, dark grey shale with neither concretions nor sandstone interlayers (BL94) of the Dutkov vrch Beds (?) exposed on the eastern bank of the Beňovolehotský creek; **B** — The same soft, dark shale as in A but exposed on the opposite, western creek bank (BL95) in contact with sandstone banks; **C** — Small exposure of the grey shale of the Dutkov vrch Beds (?) (BL96); **D** — Location of sample BL97 (left of the hammer) taken from greyish shale of the Hałuszowa Formation exposed to the right of a limestone block; **E** — A view on a scarp on the eastern bank of the Beňovolehotský creek from which samples BL98–BL101 were taken (sample BL98 comes from shale of the Wronine Formation in left hand lower corner of the photograph, sample BL99 was taken from black shales of presumably Kapuśnica Formation just behind it); **F** — A close-up of a shale (BL98); **G** — A view on a scarp built of shale and siltstones of the Kapuśnica Formation (sample BL100 was taken just left of the hammer); **H** — A close-up of shale (sample BL100 by the hammer).

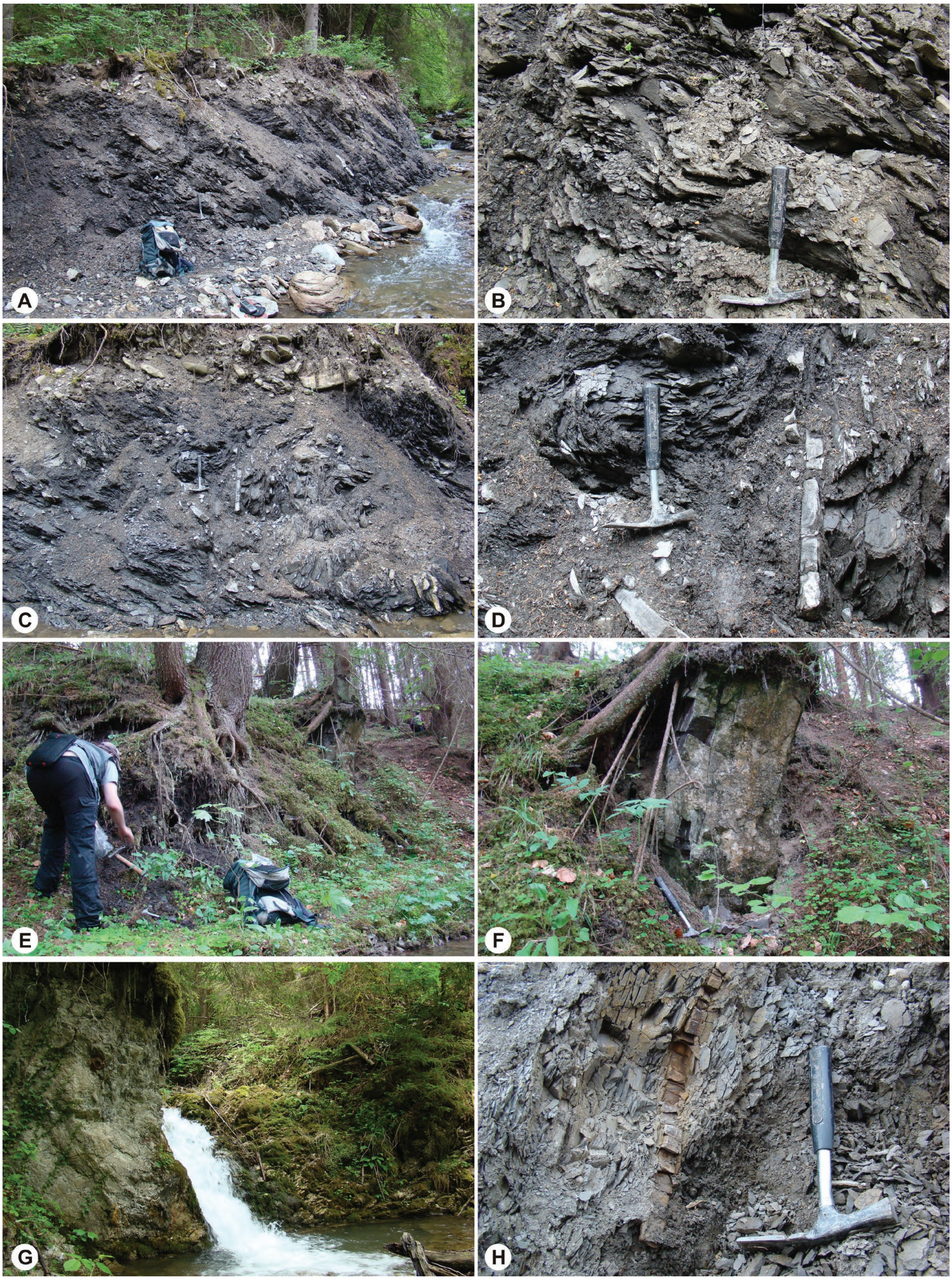

Fig. 5. Field pictures. **A** — An exposure of the Szlachtowa Formation, from which samples BL102–BL104 were taken; **B** — A close-up of a shale dominated, southern part of the same exposure and location of samples BL102 (arrowed); **C** — Northern part of the same exposure with more frequent thin-bedded sandstone layers, location of samples BL104; **D** — A close-up showing tectonic engagement of the rocks studied; **E** — Poorly-exposed outcrop (under the tree's roots) of black, micaceous shales of the Szlachtowa Formation and a thick-bedded sandstone layer a few metres farther; **F** — The same thick-bedded sandstone layer as in E; **G** — Small waterfall on a klippe built of limestones representing the Pieniny Limestone, the Czorsztyn Limestone and the Czajakowa Radiolarite formations; **H** — A close-up on black shale with siderite concretions and lenses of the Skrzypny Shale Formation exposed at Revišné (sample BL109).

Methods

Despite the lack of outcrops, the presence of soft light and dark pelagic deposits (mostly black shales and green and red marls) was documented during detailed geological mapping in the western part of the Orava segment of the PKB. Their position, with respect to the Jurassic-Cretaceous limestone klippen, was used as an important tool for the interpretation of the geological structure. Therefore, they were sampled, measured, and analysed in detail.

The collected samples were processed by following palynological procedure, including 38 % hydrochloric acid (HCl) treatment, 40 % hydrofluoric acid (HF) treatment, heavy liquid ($ZnCl_2$+HCl; density 2.0 g/cm^3) separation, ultrasound for 10–15 s, and sieving at 15 µm on a nylon mesh. No oxidation in fuming nitric acid (HNO_3) was applied. The quantity of processed rock was a constant 20 g for each sample. A single slide from each sample was made using glycerine jelly as a mounting medium; all dinoflagellate cysts from each slide were qualitatively determined using a Zeiss Axiolab microscope. The rock samples, palynological residues, and slides are stored in the archive of the Institute of Geological Sciences, Polish Academy of Sciences, Research Centre in Kraków.

For a better understanding of the tectonics that had influenced the strata, as well as to enhance interpretations of the evolution of the study area, structural measurements were collected from the outcrops. They included measurements of bedding planes, as well as all prospective mesoscopic brittle and ductile structures (cleavages and folds). The dataset is composed mostly of cleavage planes. Even though the cluster of measurements is small, the data were sufficient for interpretation and correlation with older, published results. Stereographic projections were made using the software Stereonet 11 and are projected in the lower hemisphere (Allmendinger et al. 2013; Cardozo & Allmendinger 2013).

Table 1: GPS coordinates of the sampled locations.

Sample	Coordinates (WGS84) X (N)	Coordinates (WGS84) Y (E)	Locality
BL94	49.23707°	20.26498°	*Beňovolehotský stream*
BL95	49.23707°	20.26498°	*Beňovolehotský stream*
BL96	49.23974°	19.26596°	*Beňovolehotský stream*
BL97	49.23976°	19.26583°	*Beňovolehotský stream*
BL98	49.24003°	19.26538°	*Beňovolehotský stream*
BL99	49.24003°	19.26538°	*Beňovolehotský stream*
BL100	49.24002°	19.26542°	*Beňovolehotský stream*
BL101	49.24042°	19.26457°	*Beňovolehotský stream*
BL102	49.24023°	19.26467°	*Beňovolehotský stream*
BL103	49.24023°	19.26467°	*Beňovolehotský stream*
BL104	49.24023°	19.26467°	*Beňovolehotský stream*
BL105	49.24052°	19.26378°	*Beňovolehotský stream*
BL106	49.24103°	19.26236°	*Beňovolehotský stream*
BL107	49.22988°	19.25372°	*Pod Lopušnym hill*
BL108	49.22962°	19.25340°	*Pod Lopušnym hill*
BL109	49.21795°	19.24922°	*Revišné*
DB23	49.22965°	19.23265°	*Revišné*

Palynological results

All samples yielded rich and diverse palynological organic matter. Their composition, which is described below, differs from sample to sample. Palynomorphs are present in all samples; in the majority, they are of aquatic origin. Dinoflagellate cysts predominate – their occurrence is shown in Table 2. They are variously preserved; however, in most cases, the preservation is moderate to poor, which results in a less precise taxonomic determination, commonly at the generic level only (particularly in the case of Cretaceous material).

Samples **BL94–BL96** yielded large amounts of palynological organic matter composed almost entirely of terrestrial elements (Fig. 6). The palynofacies is similar in all three samples, being dominated by black, opaque phytoclasts, commonly elongated, dark brown woody particles and sporomorphs (mainly spores; Fig. 6J, K). Cuticles are almost completely absent; if present, they occur as large fragments up to 0.5 mm. Marine sporomorphs are totally subordinate. Samples BL94 and BL95 yielded some acritarchs (mainly representatives of the *Veryhachium*-morphotype; Fig. 7A–D), whereas sample BL96 yielded foraminifera organic linings (Fig. 8A, E, F) and exceedingly rare acritarchs (Fig. 8B). All three samples also yielded delicate palynomorphs of uncertain, but quite likely, dinoflagellate affinity. These are thin-walled, single-layered, subsphaerical forms with an irregular opening and an adnate operculum. Interestingly, the latter feature causes them in some cases to resemble dinoflagellate cysts with multiparaplate archaeopyles like *Kallosphaeridium* and *Dissiliodinium* (Fig. 7F–O) or *Mendicodinium* (Fig. 8D). Samples BL94 and BL96 also yielded enigmatic palynomorphs (Fig. 9). They are elongated, dark brown, smooth, tube-shaped forms with a segmentic structure. The taxonomical affinity is unknown. Their dark colouration suggests animal origin and the segmented structure evokes possible arthropod affinity. The occurrence of these palynomorphs in the material collected from two remote outcrops suggests that both exposures represent the same lithostratigraphic unit.

Sample **BL97** yielded a much lower amount of palynological matter composed almost entirely of black, opaque, equidimensional phytoclasts (Fig. 10J). Rare sporomorphs (bisaccate pollen grains) and dinoflagellate cysts are also present. Pollen grains are dark coloured (Fig. 10K, M), whereas dinoflagellate cysts show bimodal preservation. *Palaeohystrichophora infusorioides*, which is a dominant taxon, is relatively well-preserved and has pale colouration (Fig. 10A–D). Other taxa, which are very rare, show rather worse preservation and their cyst walls are much darker (Fig. 10E–I, L, N–R). *Pterodinium* (Fig. 10L, N) and *Spiniferites* (Fig. 10E) are most frequent among these rare dark-coloured specimens.

Black, opaque phytoclasts are also a dominant element of palynofacies found in sample **BL98**, which yielded small amounts of palynological organic matter. In contrast to the preceding sample BL97, its palynofacies is characterised by

Table 2: Distribution of dinoflagellate cysts and some other aquatic palynomorphs in exposures at Beňova Lehota. F: frequent, above 10 specimens per slide; c: common, 3–9 specimens per slide; x: rare, 1–2 specimens per slide; ?: questionable occurrence. Species indicated with an asterisk (*) are most likely a contamination.

	Lithostratigraphy	**Dutkov vrch (?)**			**Haluszowa Formation**	**Wronine Formation**	**Kapuśnica Formation (?)**		**Szlachtowa Fm**							**Skrzypny Shale Fm**	
	Age	**Lower Jurassic?**			**Cretaceous**				**Uppermost Lower–lowermost Middle Jurassic**								
					Coniacian–Santonian	**Uppermost Albian–Cenomanian**	**Mid Albian**		**Upper Toarcian**	**Uppermost Toarcian–mid Aalenian**					**Mid–Upper Aalenian**	**Uppermost Toarcian–mid Aalenian**	
	Taxon / **Sample**	**BL 94**	**BL 95**	**BL 96**	**BL 97**	**BL 98**	**BL 99**	**BL 100**	**BL 101**	**BL 102**	**BL 103**	**BL 104**	**BL 105**	**BL 106**	**BL 107**	**BL 108**	**BL 109**
1.	*Micrhystridium* sp.	x	x	x		x			x		x		x	x			x
2.	*Incertae sedes* (multiplate archaeopyle dinoflagellate cysts?)	x	x	x					x								
3.	*Odontochitina cribropoda*				x												
4.	*Palaeohystrichophora infusorioides*				F	x											
5.	*Pterodinium* sp.				c	?	x	F									
6.	*Spiniferites ramosus*				c	c	c	F									
7.	*Scriniodinium campanula*				x												
8.	*Callaiosphaeridium asymmetricum*				c	x	c	x									
9.	*Xenascus*? sp.				x												
10.	*Cyclonephelium*? sp.				x	c											
11.	*Palaeohystrichophora ?cheit*					F	x	?									
12.	*Litosphaeridium conispinum*					x											
13.	*Achomosphaera* sp.					c											
14.	*Tanyosphaeridium* sp.					x	x										
15.	*Apteodinium* sp.					x											
16.	*Odontochitina operculata*					x		x									
17.	*Oligosphaeridium* sp.					c	F	c									
18.	*Tanyosphaeridium ?salpinx*					x											
19.	*Florentinia mantellii*					x											
20.	*Impagidinium* sp.					x											
21.	*Odontochitina* sp.					x											
22.	*Chlamydophorella ambigua*					x											
23.	*Ovoidinium*? sp.					x											
24.	*Circulodinium* sp.					c	c	x									
25.	*Gonyaulacysta ?diutina*						x										
26.	*Coronifera oceanica*						x										
27.	*Systematophora cretacea*						c	c									
28.	*Prolixosphaeridium conulum*						x										
29.	*Kiokansium*? sp.						x										
30.	*Subtilisphaera*? sp						x										
31.	*Pervosphaeridium pseudohystrichodinium*						x										
32.	*Occisucysta*? sp.						x	x									
33.	*Palaeoperidinium ?cretaceum*						x	x									
34.	*Litosphaeridium arundum*						x	c									
35.	*Cribroperidinium orthoceras*							x									
36.	*Apteodinium* sp.							x									
37.	*Protoellipsodinium touile*							x									
38.	*Protoellipsodinium* sp.							x									
39.	*Dapsilidinium* sp.							x									
40.	*Kleithrasphaeridium simplicispinum*							x									
41.	*Florentinia*? sp.							x									
42.	*Nannoceratopsis dictyambonis*								c	F	F	x	x	x	F	?	
43.	*Nannoceratopsis gracilis*								c	F	F	F	F	F	F	F	c
44.	*Batiacasphaera* sp.								c		c					x	
45.	*Escharisphaeridia* sp.								c	c							
56.	*Scriniocassis prisca*								x		?	x				x	
47.	*Scriniocassis weberi*								x								
48.	*Mancodinium semitabulatum*								x	x	x	x					
49.	*Sphaerical acritarchs*								c								
50.	*Phallocysta elongata*									F	F	F	c	x	c	F	x
51.	*Nannoceratopsis evae*									c	x						c
52.	*Wallodinium* sp.									F		x		x		?	
53.	*Dissiliodinium* sp.									c	F	F	c	x	F	F	x
54.	*Kallosphaeridium* sp.									c		x					
55.	*Nannoceratopsis spiculata*									x	x						
56.	*Valvaeodinium* sp.									x				x			

Table 2 (continued)

	Lithostratigraphy	Dutkov vrch (?)			Haluszowa Formation	Wronine Formation	Kapuśnica Formation (?)		Szlachtowa Fm							Skrzypny Shale Fm	
					Cretaceous				Uppermost Lower–lowermost Middle Jurassic								
	Age	Lower Jurassic?			Coniacian–Santonian	Uppermost Albian–Cenomanian	Mid Albian		Upper Toarcian	Uppermost Toarcian–mid Aalenian					Mid–Upper Aalenian	Uppermost Toarcian–mid Aalenian	
	Taxon / Sample	BL 94	BL 95	BL 96	BL 97	BL 98	BL 99	BL 100	BL 101	BL 102	BL 103	BL 104	BL 105	BL 106	BL 107	BL 108	BL 109
57.	*Nannoceratopsis plegas*									x	x						x
58.	*Nannoceratopsis deflandrei senex*									x							
59.	*Valvaeodinium koessenium*									x	x						x
60.	*Dissiliodinium ?lichenoides*									c	x	x		c	c	c	
61.	*Mendicodinium*? *spinosum*									x			x				
62.	*Moesiodinium*? sp.									x	x						
63.	*Valvaeodinium* cf. *koessenium*									x	x						x
64.	*Dapsilidinium* sp.*														x		
65.	*Nannoceratopsis ?ambonis*																x
66.	*Systematophora* sp.*														x		
67.	*Cordosphaeridium minimum**														x		
68.	*Spiniferites* sp.*														x		

a higher proportion of dark brown debris and generally larger dimensions of black phytoclasts (Fig. 11A). A noticeable feature is the occurrence of spores (Fig. 11E–I, P) and pollen grains (Fig. 11Q), which are almost completely absent in sample BL97. Dinoflagellate cysts found in this sample are pale-coloured and moderately preserved (Fig. 12G, H–J, K, R, V, W). Among them, *Palaeohystrichophora* (*P. cheit*?) is the most frequent (Fig. 12H).

The neighbouring sample **BL99** yielded a much larger amount of palynological matter with increased proportion of cuticles (Fig. 11B), yet still dominated by black phytoclasts. Dinoflagellate cysts are pale-coloured and moderately preserved. Their assemblage is diversified (Fig. 12C, F, L) with frequent *Oligosphaeridium*, *Systematophora*, *Spiniferites* and *Callaiosphaeridium asymmetricum*. Marine palynomorphs are represented also by foraminifera organic linings (Fig. 12D). Sporomorphs were present too (Fig. 11J, R)

A different palynofacies was found in sample **BL100**, which yielded large amounts of palynological organic matter distinguished by a high ratio of structureless particles (Fig. 11C, D). Dinoflagellate cysts in this sample are similarly preserved as in sample BL99 (Fig. 12A, E, M, P, Q, T, U); however, their assemblage is less diversified, being dominated by *Pterodinium* and *Spiniferites* (Fig. 12O, S). Rare foraminifera organic linings are also present (Fig. 12B). Sporomorphs are represented mainly by spores (Fig. 11K–O, S).

Sample **BL101** yielded small amounts of palynological organic matter composed mainly of black, opaque phytoclasts and palecoloured, very delicate and well-preserved thin-walled palynomorphs (Fig. 13G) resembling those from the samples BL94–BL96. Infrequent sporomorphs (Fig. 13B) and foraminifera organic linings occur. Beside the thin-walled forms (possibly dinoflagellate cysts), very rare true dinoflagellate cysts and acritarchs were found (Fig. 14B, C). The former is represented by *Nannoceratopsis* (mainly *N.* cf. *dictyambonis*; Fig. 14N) and rare *Scriniocassis* (*S. priscus*, *S. weberi*; Fig. 14A).

All three samples, **BL102– BL104,** which had been collected from a continuous outcrop, yielded large amounts of palynological organic matter dominated by terrestrial palynodebris (black, opaque particles and dark-brown, woody particles; cuticles are rare; Fig. 13G–I) and sporomorphs (mainly pteridophyta spores; pollen grains are rare; Fig. 13A, B). The highest proportion of terrestrial elements occurs in sample BL104 (Fig. 13I). Aquatic palynomorphs are represented by dinoflagellate cysts, foraminifera organic linings (Fig. 13E, F, I), acritarchs, rare prasinophyte *Tasmanites* (Fig. 13D), and a single scolecodont (Fig. 13C). One outstanding feature is the frequent occurrence of foraminifera, particularly large-sized and complete specimens (trochospiral specimens commonly occur with thick and dark initial chambers and much thinner, pale terminal chambers; Fig. 13E, I). Dinoflagellate cysts are moderately to well-preserved (Fig. 14); they are pale and show no trace of damage by pyrite crystallisation (pyrite crystals are present, but on a limited scale). Sample BL102 yielded dinoflagellate cysts represented mainly by *Phallocysta elongata* (Fig. 14D–F), *Wallodinium* (*laganum*?) and *Nannoceratopsis* (mainly *N. gracilis*; Fig. 14G, P–S). Smooth-walled specimens of *Dissiliodinium* and *Kallosphaeridium*? (Fig. 14J) are relatively common. Rare *Mancodinium semitabulatum*, *Valvaeodinium koessianum*, and *V*. cf. *koessianum* occur. Sample BL103 yielded a similar assemblage with predominantly frequent *Phallocysta elongata*, *Nannoceratopsis* (mainly *N. gracilis* and *N. dictyambonis*; Fig. 14T–V), and

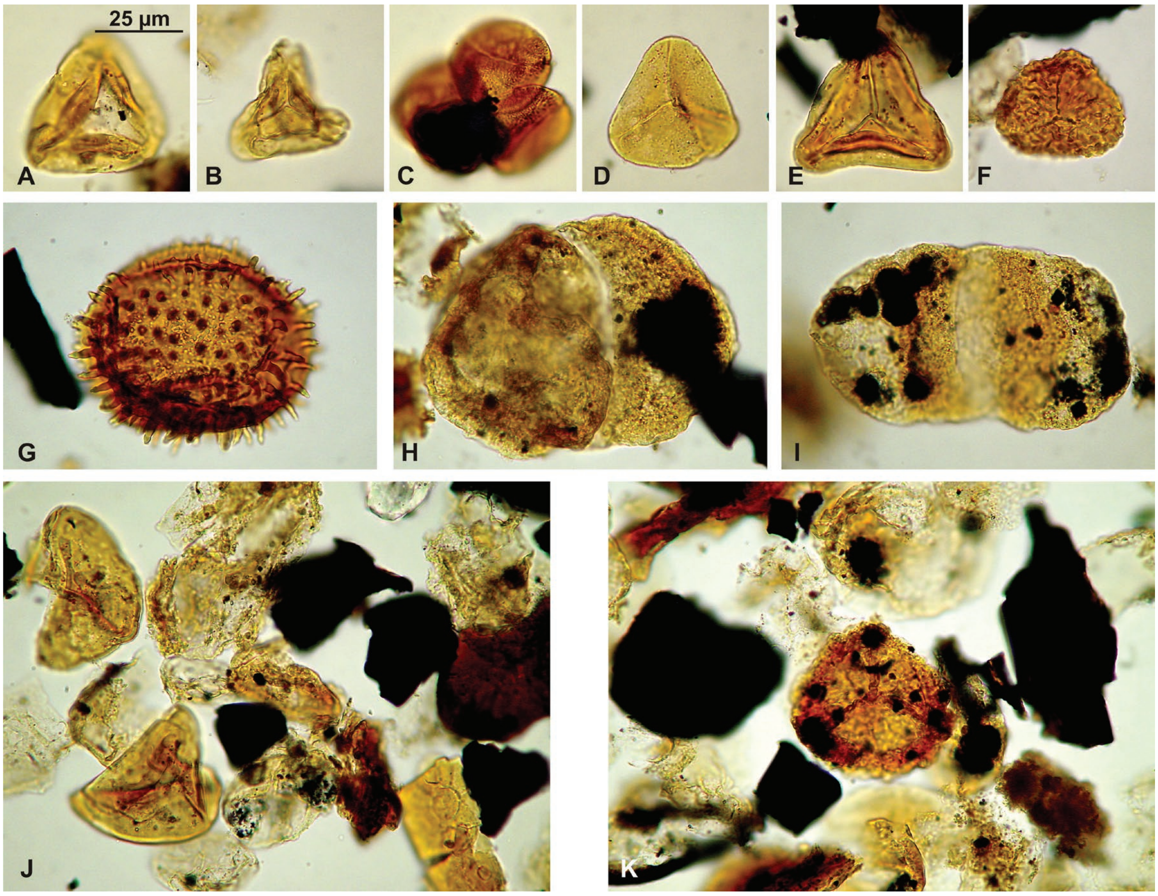

Fig. 6. Terrestrial elements of sample BL94. Scale bar in A refers to all other microphotographs. **A**–**G** — Spores; **H**, **I** — Bisaccate pollen grains; **J**, **K** — Palynofacies.

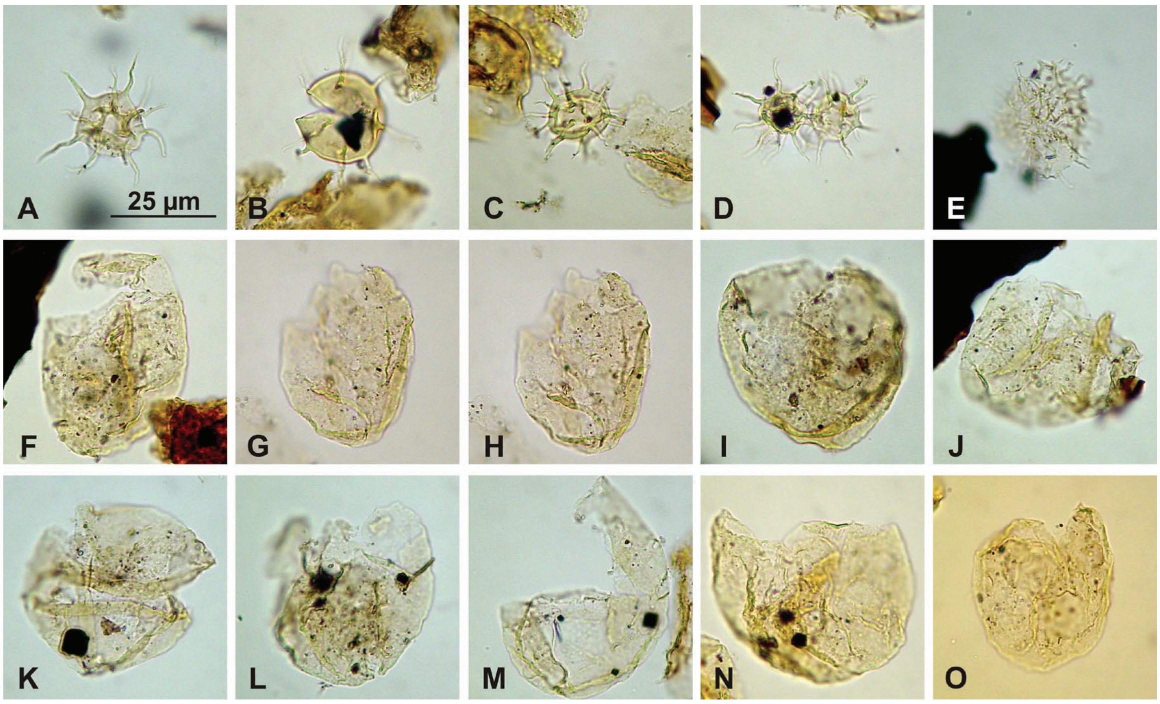

Fig. 7. Aquatic elements of sample BL94. Scale bar in A refers to all other photomicrographs. **A**–**E** — Acanthomorphic acritarchs, most of which represent *Veryhachium*-morphotype (A–D) and much rarer *Micrhystridium*-morphotype (E); **F**–**O** — Thin-walled forms, likely representing dinoflagellate cysts with multiparaplate archaeopyle *Kallosphaeridium*–*Dissiliodinium*.

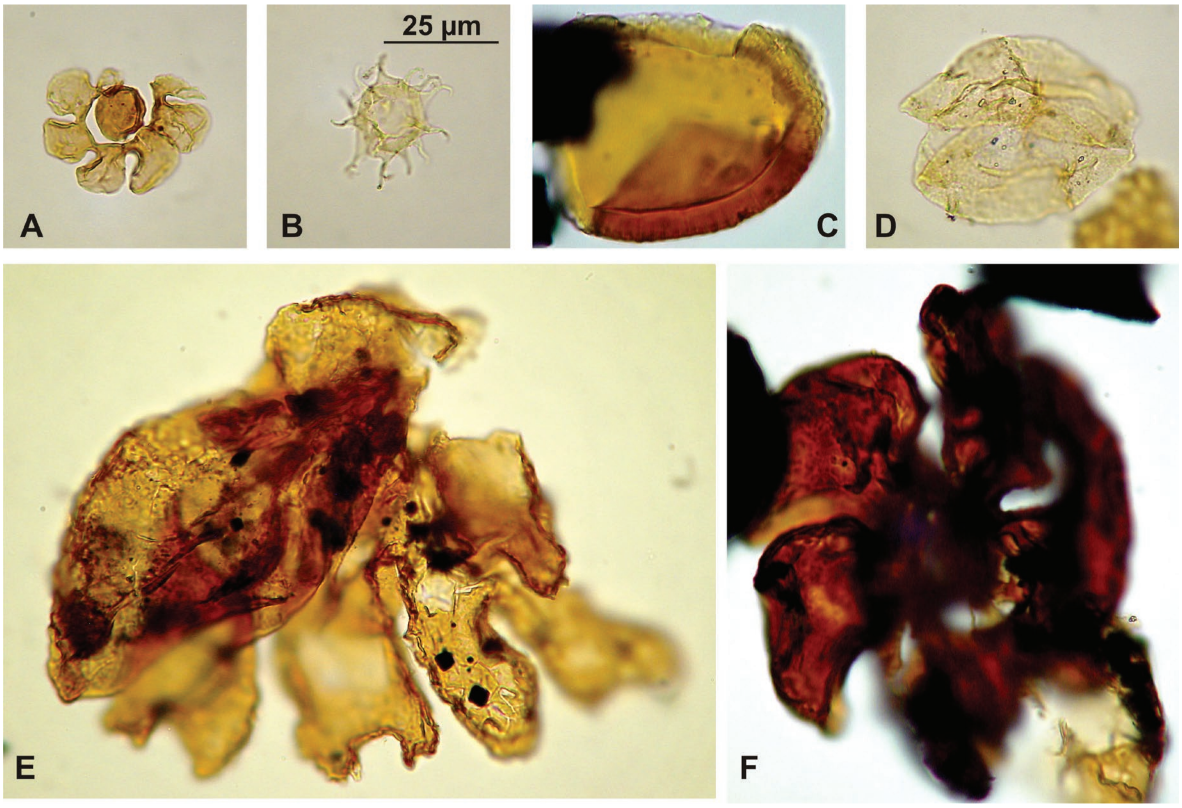

Fig. 8. Palynomorphs from sample BL96. Scale bar in B refers to all other photomicrographs. **A, E, F** — Organic foraminifera linings; **B** — Acanthomorphic acritarch of *Veryhachium*-morphotype; **C** — A prasinophyte (*Tasmanites*); **D** — Thin-walled form, presumably a dinoflagellate cyst *Mendicodinium*.

Dissiliodinium. Infrequent and single specimens of *Moesiodinium*?, *Mancodinium semitabulatum* (Fig. 14K), *Valvaeodinium koessianum*, and *V*. cf. *koessianum* (Fig. 14L) occur. Sample BL104 yielded the same dominating species, except for *N. dictyambonis*, which is quite rare. Single specimens of *Scrinocassis priscus* and *Mendicodinium*? (Fig. 14O) were also found.

Sample **BL105** yielded large amounts of palynological organic matter dominated by terrestrial elements (Fig. 13J), similar to samples BL102–BL104. These are mainly black opaque phytoclasts and dark brown woody particles (commonly elongated and occasionally very long); cuticles are rare; however, when present, they are quite large. Aquatic palynomorphs are represented almost entirely by dinoflagellate cysts (foraminifera and acritarchs are rare). Well-preserved, pale dinoflagellate cysts are dominated by *Nannoceratopsis gracilis* (*Phallocysta elongata* and *Dissiliodinium* are subordinate; infrequent *N. dictyambonis* occurs).

The same amount of palynological organic matter and the same type of palynofacies was found in sample **BL106**. Its composition differs slightly by a lower number of dinoflagellate cysts. Their assemblage is also taxonomically similar to the one found in sample BL105, but differs by an even higher domination of *N. gracilis*.

A different palynological content was found in sample **BL107**. It yielded high amounts of palynodebris (black and dark brown phytoclasts associated with minor amounts of cuticles) and structureless organic matter (mainly delicate, presumably of marine origin; Fig. 15K, L). Aquatic palynomorphs are represented by dinoflagellate cysts and rare acritarchs, foraminifera organic linings, and prasinophyte *Tasmanites*. Interesting is the composition of dinoflagellate cyst assemblages found in this sample, which seems to be composed of taxa of different ages. The most frequent are *Nannoceratopsis* (*N. dictyambonis* and *N. gracilis*; Fig. 15A) and *Dissiliodinium* sp. accompanied by rare *Phallocysta elongata*. In addition to these species, very rare, poorly-preserved specimens of *Systematophora* sp. and very well-preserved specimens of *Dapsilidinium* sp. (Fig. 15N) and *Cordosphaeridium minimum* occur.

Sample **BL108** yielded palynofacies dominated by black, opaque phytoclasts and small-sized palynodebris composed of translucent phytoclasts, sporomorphs, and palynomorphs of uncertain origin (Fig. 15M). No structureless, amorphous organic matter was found. Dinoflagellate cysts are frequent; the most common are *Phallocysta* (Fig. 15I) and *Dissiliodinium lichenoides* (Fig. 15F), while the less frequent is *Nannoceratopsis* (mainly *N. gracilis*, less common *N. deflandrei*; Fig. 15B). Rare acritarchs, foraminifera organic linings, and *Tasmanites* occur.

Palynofacies of sample **BL109** consist of terrestrial palynodebris and palynomorphs of various origin (algae?, zooclasts?,

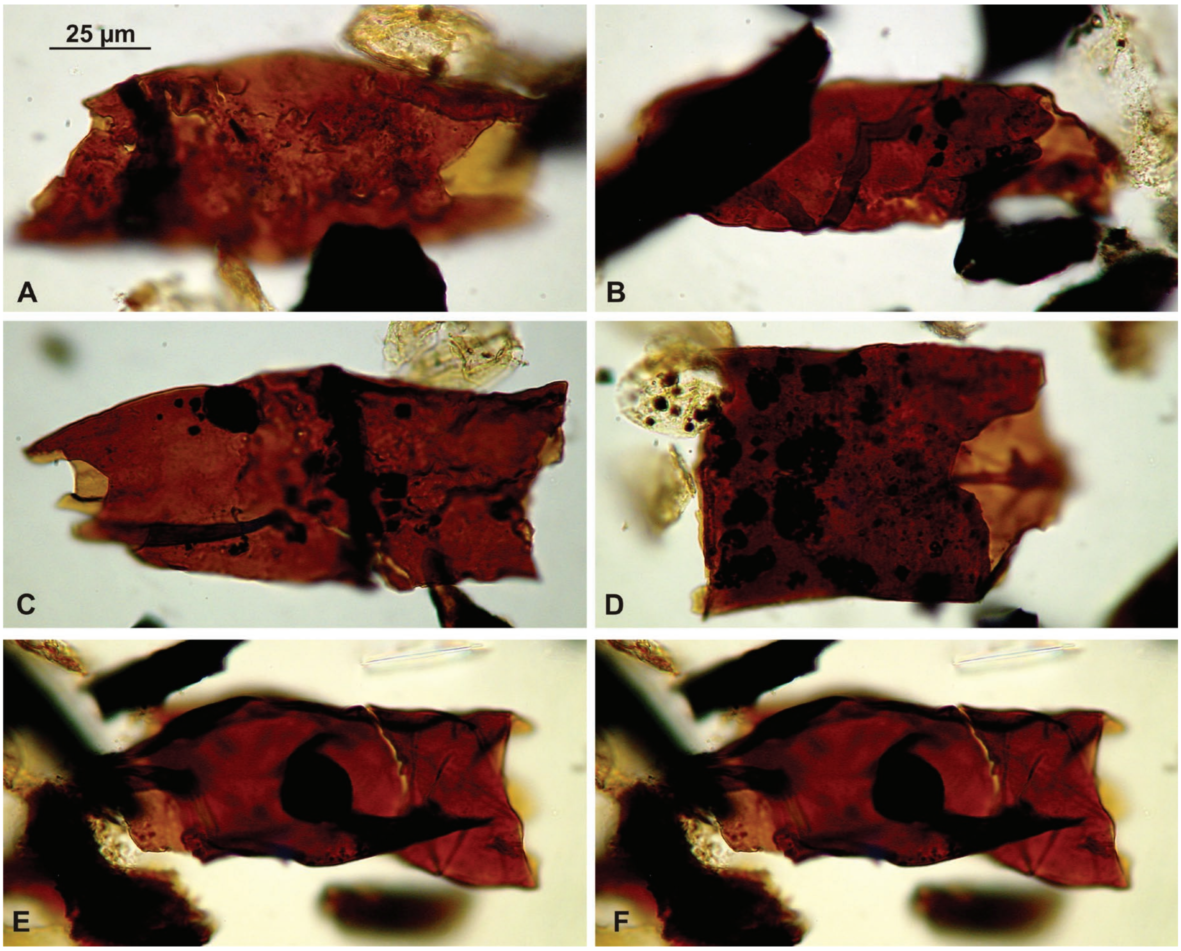

Fig. 9. An *incertae sedis* from samples BL94 and BL96. Scale bar in A refers to all other photomicrographs. **A**–**D** — Sample BL94; **E**, **F** — Sample BL96. Dark colouration and segmental structure suggest an animal (Arthropode?) origin.

some of uncertain origin), as well as marine palynomorphs (very frequent foraminifera organic linings, subordinate dinoflagellate cysts, rare acritarchs; Fig. 15J). Relatively infrequent dinoflagellate cysts (Fig. 15C–E) are dominated by *Nannoceratopsis*, mainly *N. evae* (Fig. 15C), as well as *N. ambonis*? and *N. gracilis*. Single specimens of *Phallocysta*, *Valvaeodinium* (Fig. 15E), *Dissiliodinium*, and *Luehndea spinosa* (Fig. 15D) were also found.

Age interpretation and lithostratigraphic assignment

Dark shales exposed and studied in a series of outcrops along the Beňovolehotský creek at Beňova Lehota, as well as in the neighbouring sites appeared to be barren of macrofossils, except for one location. Since organic-walled dinoflagellate cysts are the most widespread microfossil group in the Mesozoic and Paleogene dark, fine-clastic deposits of the PKB (e.g., Birkenmajer & Gedl 2004; E. Gedl 2007; Gedl 2008; Barski et al. 2012; Segit et al. 2015) we decided to examine the strata in question for palynology. Indeed, dinoflagellate cysts appeared in almost all of the studied samples. From a comparison of their known global age-ranges and their occurrences in previously-studied PKB sites, we proposed age dating and lithostratigraphic correlation of the studied deposits.

A black shale outcrop in the southernmost part of our section along the Beňovolehotský creek (samples BL94–BL96) yielded problematic aquatic palynomorph assemblages, which did not allow precise dating. They include long-ranging acritarchs and delicate, thin-walled forms (possibly multiparaplate archaeopyle dinoflagellate cysts *Kallosphaearidium*–*Dissiliodinium*). Similar forms are widespread in the oldest deposits of the Pieniny Klippen Belt in Poland, in the Toarcian Krempachy Marl Formation, and the Skrzypny Shale Formation (as “thin-walled forms” or “*incertae sedis*”: Gedl 2008, e.g., fig. 56F; fig. 65F–H; fig. 132T, V). Smooth-, thin-walled specimens of *Kallosphaeridium* (e.g., *K. capulatum*) are frequent in the same lithostratigraphic units (Gedl 2008). In the Polish material, they co-occur with other dinoflagellate cysts like *Nannoceratopsis*, which allowed their dating. *Nannoceratopsis* is also common in the oldest dinoflagellate cyst assemblage from the PKB described so far –

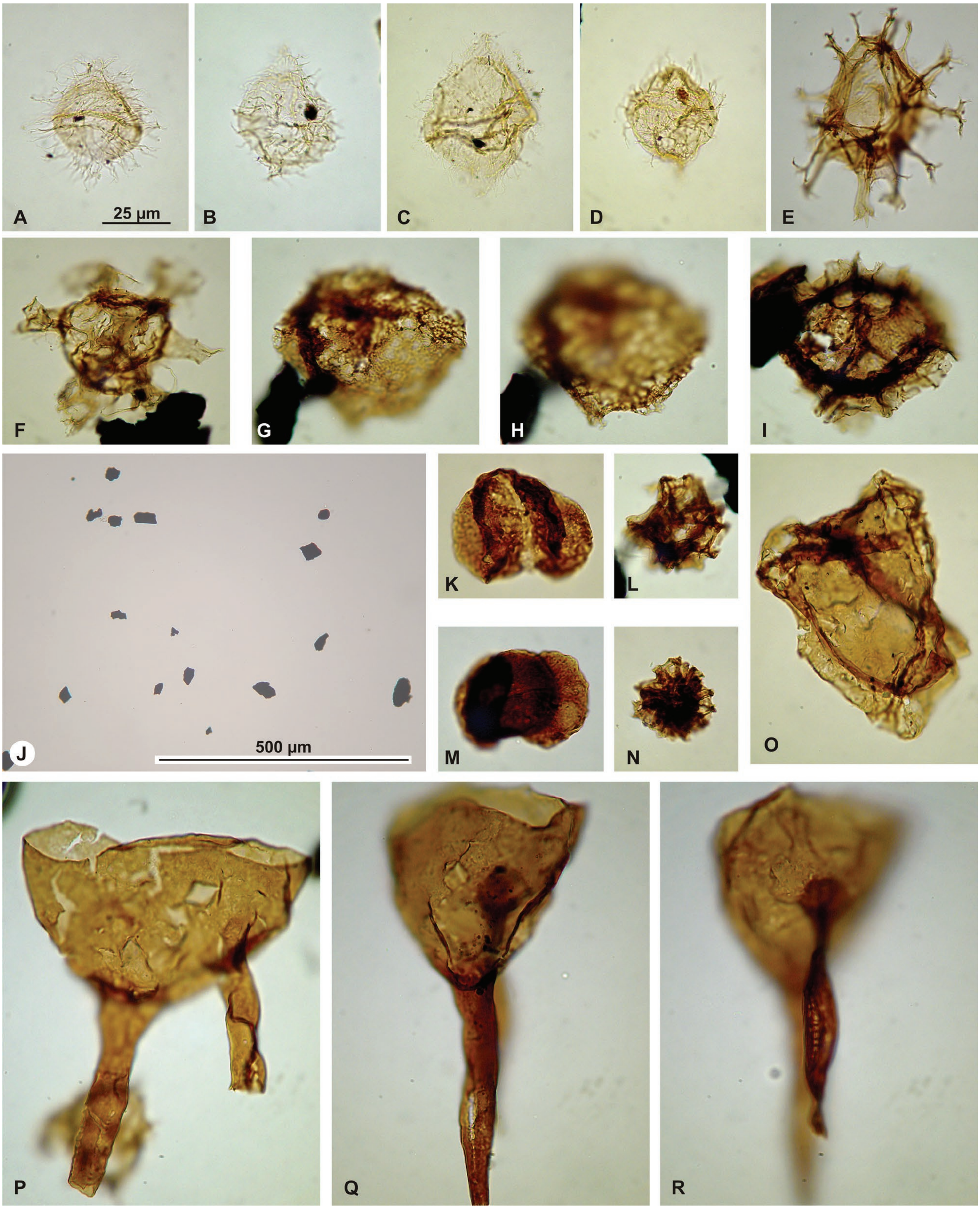

Fig. 10. Palynomorphs and palynofacies of sample BL97. Scale bar in A refers to all other photomicrographs except for P. **A**–**D** — *Palaeohystrichophora infusorioides*; **E** — *Spiniferites ramosus*; **F** — *Callaiosphaeridium asymmetricum*; **G**, **H** — *Circulodinium*? sp.; **I** — Dinocyst; **J** — Palynofacies composed almost entirely of black, opaque, equidimensional phytoclasts; **K** — Pollen grain; **L** — *Pterodinium* sp; **M** — Pollen grain; **N** — *Pterodinium* sp.; **O** — *Scrinodinium campanula*; **P**–**R** — *Odontochitina cribropoda* (Q, R: the same specimen, various foci).

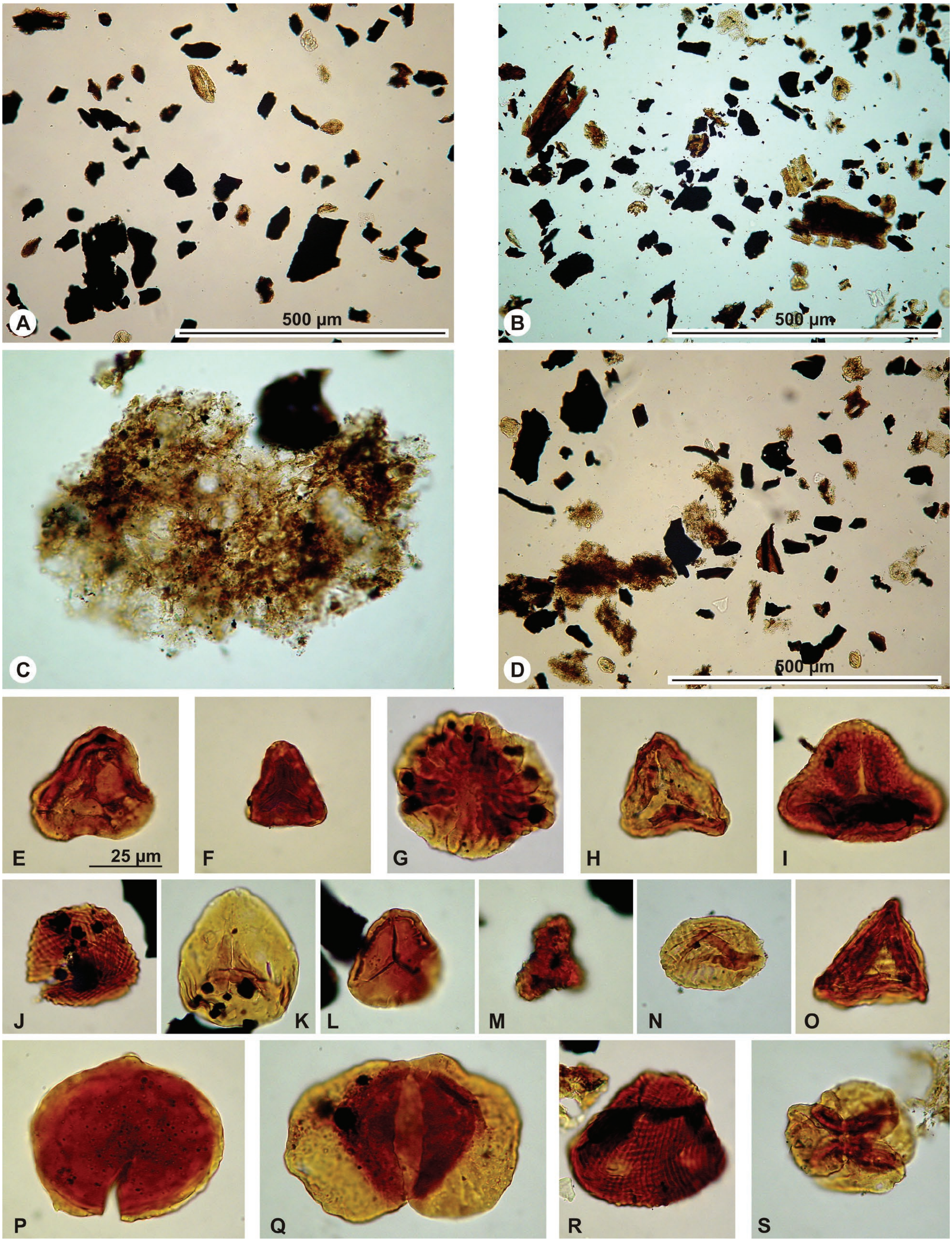

Fig. 11. Terrestrial palynomorphs, phytoclasts, and palynofacies of samples BL98–BL100. Scale bar in E refers to all other photomicrographs except for A–D. **A**, **B** — Palynofacies of samples BL98 (A) and BL99 (B) composed of terrestrial palynodebris; **C** — Structureless organic matter (BL100); **D** — Palynofacies of sample BL100 with opaque phytoclaststs associated by amorphic particles; **E–S** — Sporomorphs (E–I, P, Q: BL98; J, R: sample 99; K–O, S: BL100).

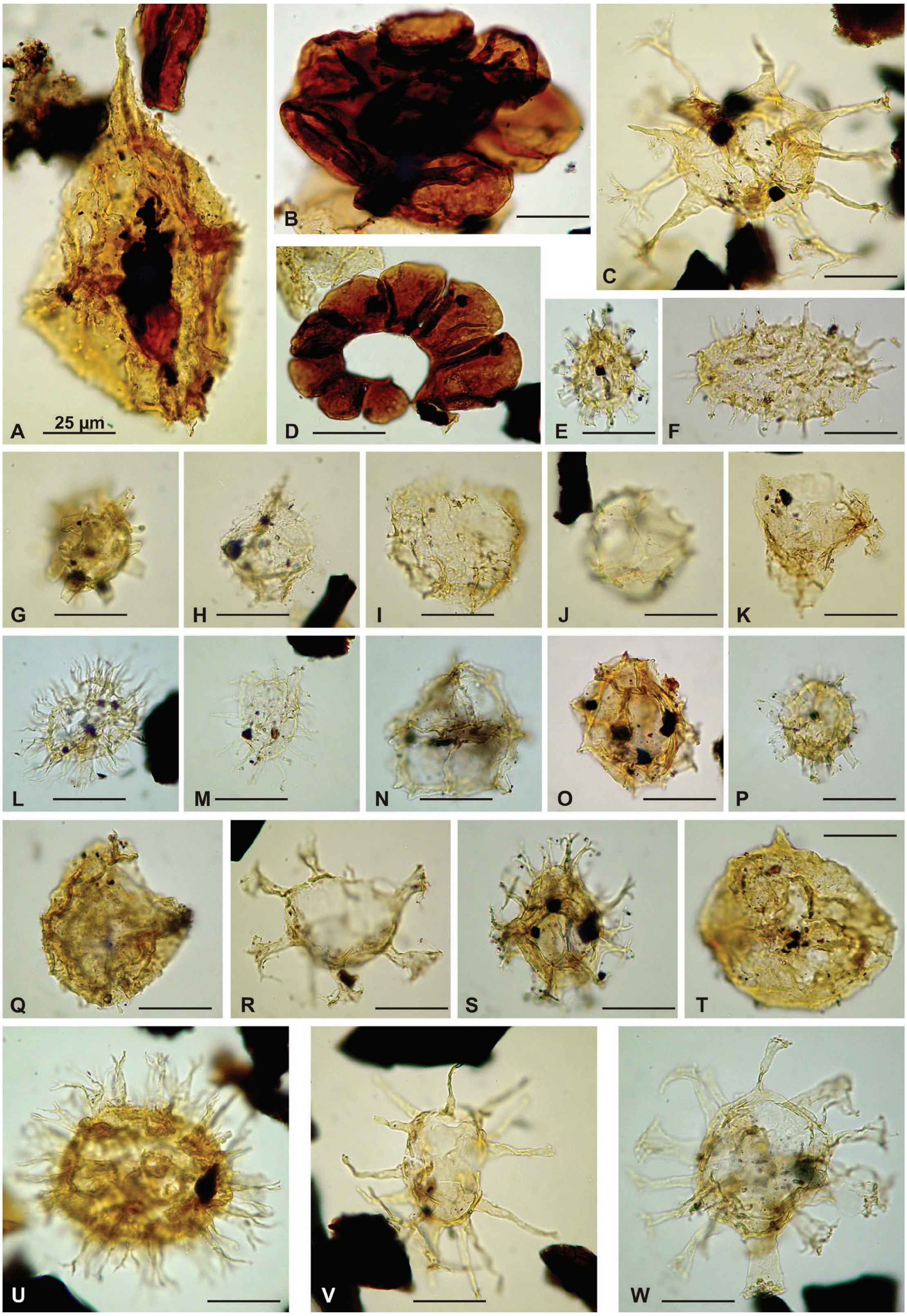

Fig. 12. Aquatic palynomorphs from samples BL98–BL100. Scale bar in A refers to all other photomicrographs. **A** — *Cribroperidinium orthoceras* (BL100); **B** — Organic foraminifera lining (BL100); **C** — *Oligosphaeridium complex* (BL99); **D** — Organic foraminifera lining (BL99); **E** — *Litosphaeridium arundum* (BL100); **F** — *Prolixosphaeridium conulum* (BL99); **G** — *Litosphaeridium conispinum* (BL98); **H** — *Subtilisphaera cheit*? (BL98); **I** — *Circulosphaeridium* sp. (BL98); **J** — *Impagidinium* sp. (BL98); **K** — *Odontochitina* sp. (BL98); **L** — *Coronifera oceanica* (BL99); **M** — *Tanyosphaeridium* sp. (BL100); **N**, **O** — *Pterodinium* sp. (BL100); **P** — *Litosphaeridium arundum* (BL100); **Q** — *Ocissucysta* sp. (BL100): **R** — *Callaiosphaeridum assymetricum* (BL98); **S** — *Spiniferites ramosus* (BL100); **T** — *Apteodinium* sp. (BL100); **U** — *Systematophora* sp. (BL100); **V** — *Oligosphaeridium* sp. (BL98); **W** — *Florentinia mantellii* (BL98).

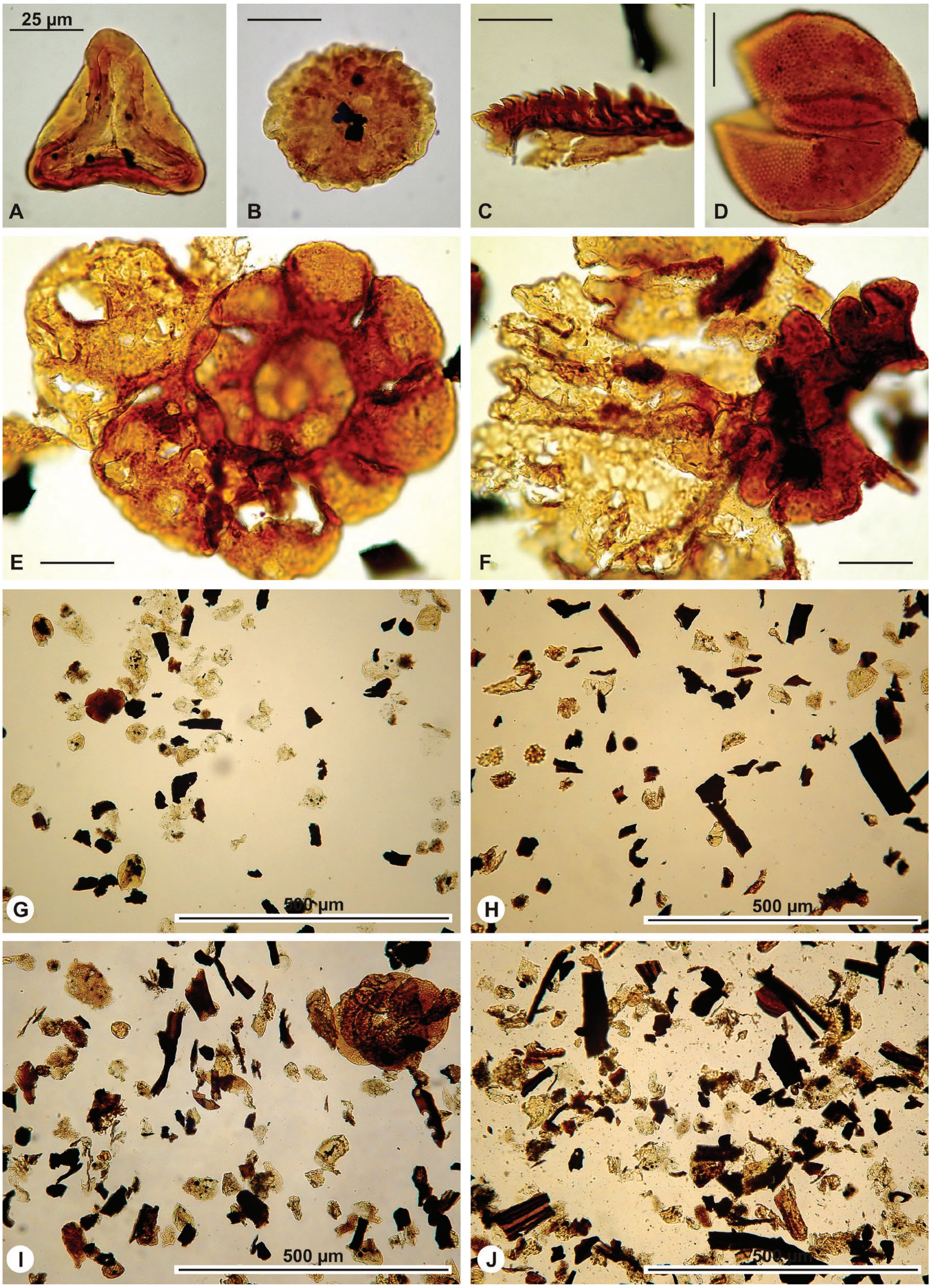

Fig. 13. Terrestrial and aquatic palynomorphs and palynofacies of samples BL101–BL105. Scale bar in A refers to all other photomicrographs except for G–J. **A, B** — Spores (A: BL103; B: BL101); **C** — Scolecodont (BL103); **D** — Prasinophyte (*Tasmanites*; BL102); **E, F** — Organic foraminifera linings (E: BL103; F: BL104); **G** — Palynofacies of sample BL101 composed of black, opaque phytoclasts and pale-coloured, delicate, thin-walled palynomorphs of uncertain origin, possibly dinoflagellate cysts; **H** — Palynofacies of sample BL102 with dominating black palynodebris with common elongated particles and relatively frequent dinoflagellate cysts; **I** — Palynofacies of sample BL104 dominated by terrestrial palynodebris (woody particles, sporomorphs); note the large foraminifera lining in the photomicrograph right hand upper corner; **J** — Palynofacies of sample BL105 dominated by terrestrial palynodebris composed of black, opaque phytoclasts, dark brown woody particles (commonly elongated), and highly dispersed transparent plant tissue remains.

the upper Pliensbachian Krempachy Marl Formation exposed in the Hryzeň section at Zázrivá, Slovakia (Gedl in Plašienka et al. 2021).

Similar palynological contents (a large number of terrestrial elements, very rare acritarchs, and thin-walled forms) were found in the thin shale intercalations within quartz sandstones and thick shale packages exposed in the upper parts of the Jedľovinka Hill near Zázrivá (Gedl in Plašienka et al. 2021; Gedl, unpublished). These strata are treated as Sinemurian by Aubrecht (1997), based on the presence of ammonites of this age. We suggest that the dark shale exposed in the southernmost parts of the Beňovolehotský creek represents the age counterparts of the Sinemurian strata known from the Jedľovinka Hill, which seems to be the oldest lithostratigraphic element of the Šariš/Grajcarek Unit (unknown so far in the Polish or Slovak sector of the PKB). If our interpretation is correct, the occurrence of Sinemurian strata in the Beňovolehotský creek section is limited to only two sites: the site with samples BL94/BL95 and the one with sample BL96. These two sites are located 200 m from each other; we have no evidence whether Sinemurian strata occur constantly in between. It is more likely that they are tectonically separated by other lithostratigraphic units, as is typical in the complicated structure of the PKB.

This is the case with the following sample BL97, which represents the Upper Cretaceous strata. The age of the greyish shale is based on the presence of the rare, but age-diagnostic species *Palaeohystrichophora infusorioides*, *Callaiosphaeridium asymmetricum*, and *Odontochitina cribropoda* (Fig. 10). The first two species are rather long-ranging (latest Albian–Early Maastrichtian and Hauterivian–Early Campanian, respectively; Stover et al. 1996); however, *O. cribropoda* is known to have appeared most likely during the Coniacian–Campanian (Mao & Mohr 1992) with its first appearance in the Late Coniacian (Riding & Crame 2002). Their co-occurrence suggests a Senonian age of the shales. Late Cretaceous dinoflagellate cysts from the PKB have so far not been studied comprehensively. However, they were reported from several sites and various lithostratigraphic units, including the Pomiedznik Formation (Jamiński 1990, 1995), the Malinowa Shale Formation (Gedl 2007a), the Hałuszowa Formation (Gedl 2007b; Birkenmajer & Gedl 2019), Jaworki Marl Formation (Birkenmajer & Gedl 2012), and the Hulina Formation (Birkenmajer & Gedl 2004). In most cases, the Late Cretaceous dinoflagellate cysts assemblages are quantitatively and taxonomically impoverished, being dominated by the peridinioids *Palaeohystrichophora* and *Subtilisphaera–Alterbidinium*, and the gonyaulacoids *Spiniferites* and *Pterodinium*. Hence, their dating is imprecise, being commonly limited to the Late Cretaceous or Senonian periods. This is also the case with the assemblage from sample BL97, which consists of rare and mainly long-ranging specimens. The Senonian age of this sample makes it coeval with two lithostratigraphic units of the Šariš/Grajcarek Unit: The Malinowa Shale Formation and the Hałuszowa Formation (Fig. 3). The first unit represents oceanic pelagic deposits, which are distinguished by red colouration, deposited during the latest Cenomanian–Early Campanian (Birkenmajer 1977; Birkenmajer & Gedl 2017). Dinoflagellate cysts are absent in these overhelmningly red abyssal clays (e.g., Birkenmajer & Gedl 2019), and they occur in very thin, darker coloured layers only (Gedl 2007a). Their characteristic feature is the predominance of *Palaeohystrichophora infusorioides* and *Alterbidinium*, with less frequent *Spiniferites ramosus* and *Pterodinium cingulatum*. Similar assemblages were found in the second coeval lithostratigraphic unit: the Hałuszowa Formation (Gedl 2007b). It was distinguished by Birkenmajer (1977) only in the Grajcarek Unit, a the upper Santonian–Campanian flyschoid to flysch strata, being transitional between the underlying red clay of the Malinowa Shale Formation and the overlying Jarmuta Formation (Fig. 3). Palynofacies of the samples from this formation have so far shown an almost 100 % dominance of black, opaque phytoclasts (Gedl 2007b; Birkenmajer & Gedl 2019), which resemble the palynofacies in sample BL97. Dinoflagellate cyst assemblages from the formation found at Hałuszowa (Gedl 2007b) contained rare *P. infusorioides*; however, they were dominated by another peridinioid – the *Subtilisphaera*-morphotype associated by *Pterodinium* and *Spiniferites*. Hence, lithology of the strata from which sample BL97 was taken (grey-greenish shale with red shale intercalations), together with its palynofacies and dinoflagellate cyst-based age allow the strata in question to be included in the Hałuszowa Formation.

Three samples, BL98–BL100, yielded Cretaceous dinoflagellate cysts. Sample BL98, which was taken from massive shale, yielded infrequent dinoflagellate cysts, among which *Litosphaeridium conispinum* was found. The age-range of this species is Late Albian–Cenomanian (Lucas-Clark 1984, 2007). Its presence, together with *Palaeohystrichophora infusorioides* (latest Albian–Early Maastrichtian; Stover et al. 1996) and *P. ?cheit* (Aptian–Campanian; Santos et al. 2019 and references therein; currently: *Subtilisphaera cheit* according to Santos et al. 2019) suggest an uppermost Albian–Cenomanian age of these steel-greyish shale. The proposed age, lithology, and rather small amounts of palynological organic matter suggest that this part of the exposure represents the Wronine Formation. This lithostratigraphic unit was established by Birkenmajer (Birkenmajer & Pazdro 1963; Birkenmajer 1977) as the pale-coloured Lower Cretaceous resting upon the black strata of the Kapuśnica Formation. Barremian–Aptian age of this unit was suggested based on the foraminifera (Birkenmajer & Pazdro 1963) and the Upper Aptian–Albian age was based on calcareous nannoplankton (Birkenmajer and Dudziak 1987; see Birkenmajer & Gedl 2017 for details). Subsequent dinoflagellate cyst studies show an even younger age of the Wronine Formation. E. Gedl (2007), on the basis of relatively rich assemblages, suggested various ages of this formation, ranging from the Upper Barremian to Cenomanian age. The author also noted common reworking of the Barremian–Aptian forms among Late Albian–Cenomanian taxa, which in these cases, may mask their true age. Despite the age interpretation, typical *Palaeohystrichophora infusorioides*

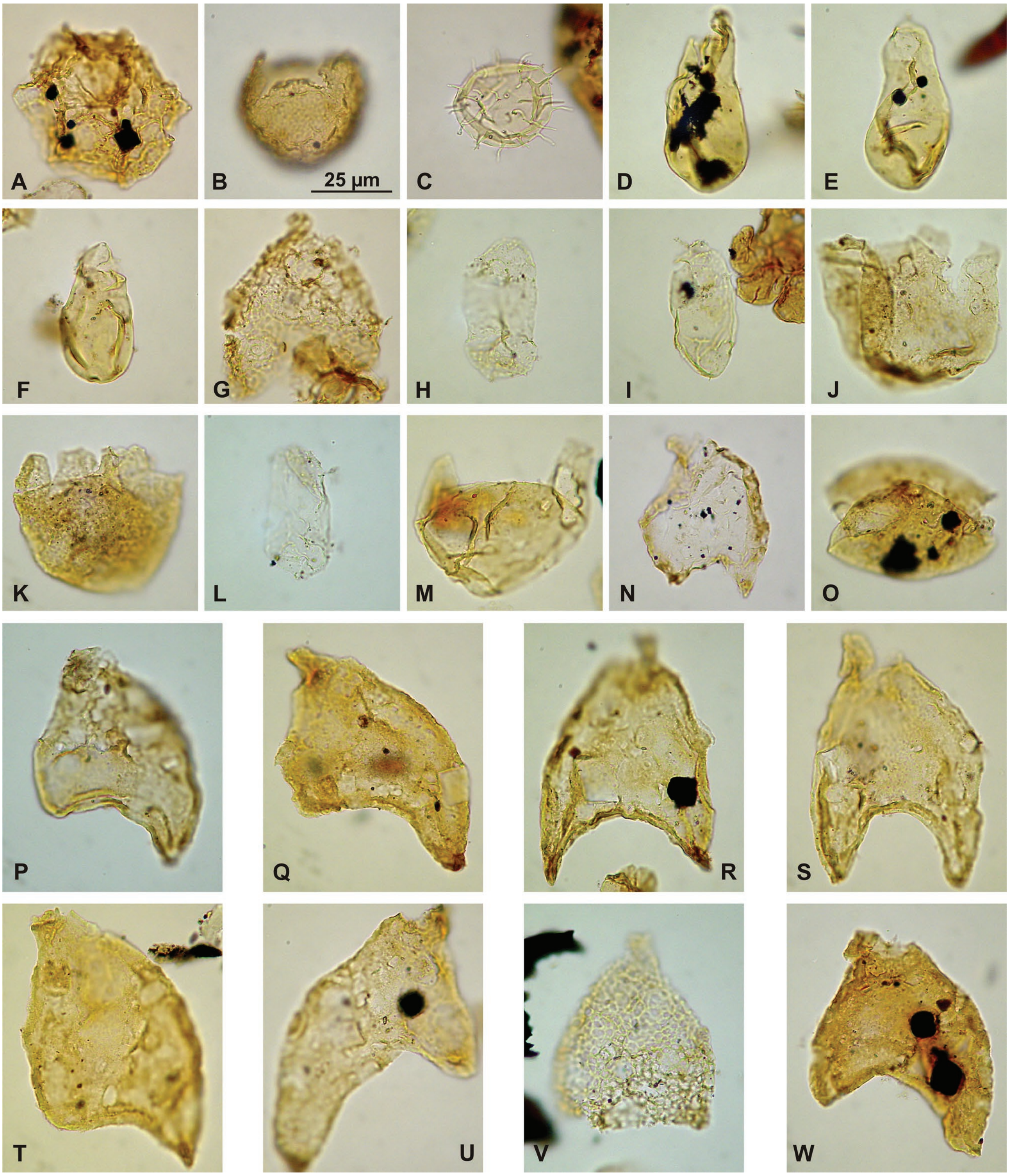

Fig. 14. Dinoflagellate cysts and acritarchs from samples BL101–BL104. Scale bar in B refers to all other photomicrographs. **A** — *Scriniocassis priscus* (BL101); **B** — *Batiacasphaera* sp. (BL101); **C** — Acanthomorphic acritarch of *Micrhystridium* morphotype (BL101); **D**–**F** — *Phallocysta elongata* (BL102); **G** — *Nannoceratopsis evae* (BL102); **H, I** — *Wallodinium* sp. (BL102); **J** — *Kallosphaeridium*? sp. (BL102); **K** — *Mancodinium semitabulatum* (BL103); **L** — *Valvaeodinium* cf. *koessenium* (BL103); **M** — *Kallosphaeridium*? sp. (BL103); **N** — *Nannoceratopsis* cf. *dictyambonis* (BL101); **O** — *Mendicodinium*? sp. (BL104); **P, Q** — *Nannoceratopsis gracilis* (BL102); **R** — *Nannoceratopsis spiculata* (BL102); **S** — *Nannoceratopsis* sp. (BL102); **T** — *Nannoceratopsis gracilis* (BL103); **U** — *Nannoceratopsis plegas* (BL103); **V** — *Nannoceratopsis evae* (BL103); **W** — *Nannoceratopsis gracilis* (BL104).

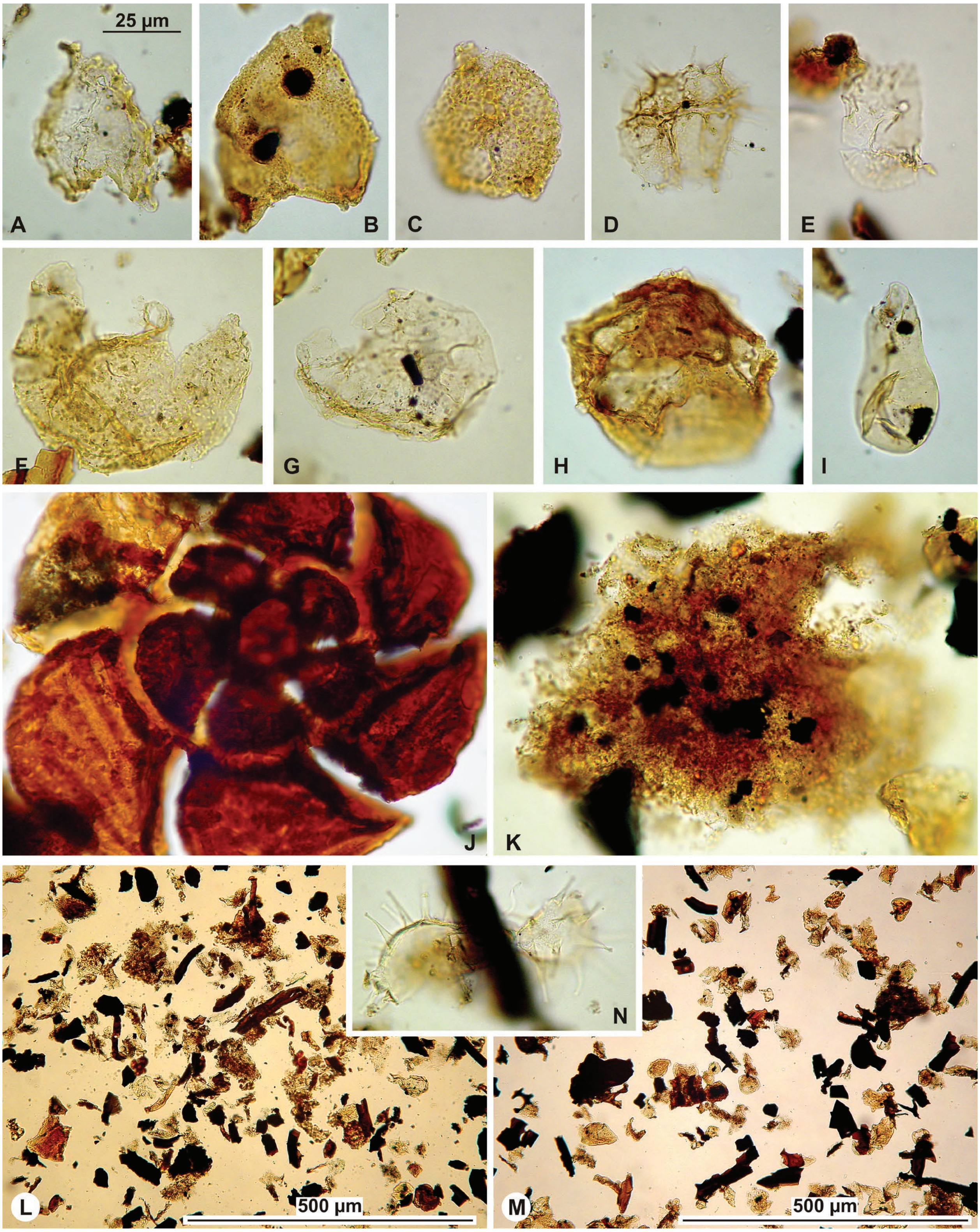

Fig. 15. Aquatic palynomorphs, phytoclasts, and palynofacies of samples BL107–BL109. Scale bar in A refers to all other photomicrographs except for L and M. **A** — *Nannoceratopsis dictyambonis* (BL107); **B** — *Nannoceratopsis deflandrei* (BL108); **C** — *Nannoceratopsis evae* (BL109); **D** — *Luehndea spinosa* (BL109); **E** — *Valvaeodinium* sp. (BL109); **F** — *Dissiliodinium lichenoides* (BL108); **G** — Smooth, thin-walled form, possibly *Dissiliodinium* (BL108); **H** — *Scriniocassis priscus* (BL108); **I** — *Phallocysta elongata* (BL108); **J** — Organic foraminifera lining (BL109); **K** — Structureless (amorphous) organic matter (BL107); **L** — Palynofacies of sample BL107 showing palynodebris associated with structureless organic matter; **M** — Palynofacioes of sample BL108 composed of palynodebris (mainly dark-brown and black, opaque phytoclasts), sporomorphs and dinoflagellate cysts; **N** — *Dapsilidinium* sp. (BL107).

were not found for this period (this species was found in the overlying Hulina Formation; E. Gedl 2007). The mentioned feature calls into question our correlation of sample BL98 with the Wronine Formation, since this sample yielded *P. infusorioides*. *Palaeohystrichophorida infusorioides* is absent in two neighbouring samples, BL99 and BL100, which on the other hand yielded *Litosphaeridium arundum*, an Albian (Lucas-Clark 1984) or Middle Albian–earliest Cenomanian (Stover et al. 1996) species. The presence of *L. arundum* and the lack of *P. infusorioides* may indicate Middle Albian age of both samples. These samples could be thus correlated with the Wronine Formation, especially since the remaining dinoflagellate cysts from the samples (i.a., *Pterodinium*, *Oligosphaeridium*, *Circulodinium*, *Spiniferites*; Table 2) are similar to those described in the formation by E. Gedl (2007) and Gedl (2013). A characteristic feature from the Wronine Formation samples studied so far is the rather low amount of palynological organic matter, which is dominated mainly by black opaque phytoclasts (E. Gedl 2007; Gedl 2013). Samples BL98 and BL99 yielded palynofacies that fit well with the characteristics of the Wronine Formation. Sample BL100 (black shale) yielded outstanding palynofacies where structureless organic particles dominate. This feature is typical for deposits accumulated in anoxic bottom conditions like the Hulina Formation or the Kapuśnica Formation. This may indicate that the black shales of sample BL100 represent the Kapuśnica Formation or that they belong to the generally pale-coloured Wronine Formation, but reflect a local, temporary anoxic event. Gedl (1997) described similar palynofacies from a black shale layer (sample Rzeźnia-7) within the greenish Wronine Formation at Szczawnica, Poland. This sample yielded Barremian–Aptian species co-occurring with the Albian *Ellipsodinium rugulosum*.

Further samples collected along the Beňovolehotský creek represent dark, fine-grained, Lower to Middle Jurassic strata. The ages differ slightly from sample to sample, but they generally represent the Toarcian–Aalenian period when accumulation of fine clastics took place in the Magura Basin during the dysoxic bottom conditions. The dinoflagellate cyst assemblages from the strata in question can be compared and correlated with the results from previous studies of the coeval Jurassic dinoflagellate cysts from the PKB of Poland and Slovakia (e.g., Gedl 2008; Gedl & Józsa 2015; Segit et al. 2015).

Sample BL101 cannot be precisely dated due to the scarcity of dinoflagellate cysts (Table 2). The presence of *Nannoceratopsis dictyambonis* (Late Toarcian–Early Bajocian; Bucefallo Palliani & Riding 1997a), *Scrinocassis prisca* (latest Toarcian–Middle Bajocian; Stover et al. 1996), and *S. weberi* (Late Pliensbachian–Aalenian; Stover et al. 1996) suggest that the host rock represents the uppermost Toarcian–Aalenian. A characteristic feature of the assemblage is the lack of *Phallocysta elongata*, which is a widespread species in the uppermost Toarcian–lowermost Bajocian dark strata of the PKB (e.g., Gedl 2008; see also further samples below). The lack of it may therefore indicate that the strata in question had accumulated during the final Toarcian, but prior to the first appearance of *P. elongata*.

Phallocysta elongata occurs in further samples of BL102–BL106, associated by various (Table 1) long-ranging species, which are all known from the Aalenian (e.g., *N. gracilis*, *N. dictyambonis*, and *Mancodinium semitabulatum*; e.g., Stover et al. 1996). From the latter, *N. dictyambonis* has the narrowest range limited to the Late Toarcian–Early Bajocian. One clue that suggests a more precise, uppermost Toarcian–Middle Aalenian age of the strata is again the lack of younger forms; in this case, *Dissiliodinium lichenoides*, which appeared for the first time in the Middle Aalenian (Feist-Burkhardt & Monteil 2001).

The rock series, from which samples BL102–BL106 were taken, most likely represent the Szlachtowa Formation. This lithostratigraphic unit is considered the oldest of the Grajcarek Unit (Polish part of PKB). The Szlachtowa Formation was formally described by Birkenmajer (1977; see also Birkenmajer 1963; Birkenmajer & Gedl 2017). It consists of dark grey to black, highly micaceous shale and sandstone layers. The ratio between the sandstones and shales vary both spatially and laterally, being the base for distinguishing between two facies: the black flysch facies and the black shale facies. The former is characterised by the more frequent occurrence of thin- to medium-bedded sandstone layers, which show a turbiditic character. The shale facies contain less frequent sandstones, and it is similar to the Skrzypny Shale Formation. According to Birkenmajer, the Szlachtowa Formation was a turbiditic fan with an eastern source area (e.g., Birkenmajer & Gedl 2017). This assumption could be true, since flysch facies are more frequent in the eastern sectors of the PKB (Polish sector: the Jaworki and Korścienko area; Birkenmajer 1963; Krawczyk & Słomka 1986; Gedl 2008; Barski et al. 2012; Slovak sector: Litmanová area; Gedl & Józsa 2015), whereas in the western sector of the PKB (the Slovak localities in Orava: this study), shale facies seem to predominate. The age of the Szlachtowa Formation was mainly based on microfossils, because the macrofossils, particularly ammonites, are very rare (see Birkenmajer and Gedl 2017 for details and references). The Middle Toarcian–Bajocian age was suggested on the base of dinoflagellate cysts (Gedl 2008; Barski et al. 2012; Gedl & Józsa 2015; Segit et al. 2015). Our interpretations show that these black shales represent the Upper Toarcian–Middle Aalenian Szlachtowa Formation developed in the black flysch facies.

A more complicated correlation is with sample BL107 (Fig. 1). This is due to its unusual lithology, consisting of black, soft shales intercalated with pale shales. Dinoflagellate cysts are composed of a mixture of Cretaceous and Early–Middle Jurassic species (Palaeogene taxa, due to their excellent preservation as shown in Fig. 15N, seem to be a contamination).

The age of the Jurassic species is similar to the assemblages found in the Szlachtowa Formation: latest Toarcian–Middle Aalenian (*Nannoceratopsis dictyambonis*, *N. gracilis*, *Dissiliodinium* sp., and rare *Phallocysta elongata*). However, the presence of highly damaged, but definitely Cretaceous forms associated by structureless organic particles, suggest that these rocks represent the Kapuśnica Formation, and the Jurassic species are recycled. Still, we cannot exclude that this outcrop exposes a tectonic melange of the middle Cretaceous (Kapuśnica Formation?) and the Lower–Middle Jurassic rocks (Szlachtowa Formation?, Skrzypny Shale Formation?).

The neighbouring outcrop (sample BL108) represents Jurassic strata. The sample yielded frequent specimens of *Nannoceratopsis*, *P. elongata*, and *D. lichenoides*; however, lacks *Dissiliodinium giganteum*, which is an Early Bajocian species (Feist-Burkhardt & Monteil 2001) widespread in the Lower Bajocian of the PKB (Gedl 2008; Barski et al. 2012; Segit et al. 2015). Therefore, a Middle Aalenian–Late Aalenian age of the host rock can be suggested. The outcropping shale most likely represents the Skrzypny Shale Formation, since we found neither micaceous shale nor sandstone. The presence of siderite concretions also points to the Skrzypny Formation. However, they cannot be treated as an unequivocal indicator because such concretions can also be found in the shale facies of the Szlachtowa Formation (e.g., Birkenmajer & Gedl 2017).

The same lithostratigraphic correlation can be suggested in the case of black shale exposed during the digging of the foundations at Revišné (sample BL109). They show features characteristic for the Skrzypny Shale Formation: siderite concretions and lenses (Fig. 5H). In this location, which was the only one from the studied outcrops, few specimens of thin-walled bivalves *Bositra buchi* Roemer were found. However, due to the small dimensions of the outcrop, we cannot exclude (e.g., the case of sample 108) that it does not represent the shale facies of the Szlachtowa Formation. The age of the dinoflagellate cyst assemblage seems to be coeval with ages from samples BL102–BL106: latest Toarcian–Middle Aalenian. This assumption is based on the frequent presence of *Nannoceratopsis evae* (latest Toarcian–Aalenian), rare occurrence of *Phallocysta elongata*, and the lack of *Dissiliodinium lichenoides* (first appearance in the Middle Aalenian). This sample yielded *Valvaeodinium* specimens as well, which are typical for Early Jurassic (mainly Pliensbachian-Early Toarcian) and *Luehndea spinosa* (Late Pliensbachian–Early Toarcian; e.g., Bucefallo Palliani & Riding 1997b, 1999). The origin of these taxa is uncertain. *Luehndea spinosa* is likely recycled (single, poorly-preserved specimen; Fig. 15D). *Valvaeodinium* occurs in samples BL101, BL102 and BL106 (Table 2) as well; in all of the samples, this taxon is pale-coloured and does not show any features of recycling (Fig. 15E).

Tectonics – results and structural interpretations

Systematic collection of meso-scale structural elements was carried out on the studied strata. Beddings (S_0) measured in the dark flysch sediments and on other younger marly deposits are represented by planes dipping generally to the NW. However, the orientation of dips of individual bedding planes often varies from the W to the N (Fig. 16A – contour diagram of all S_0). The beddings change slightly from outcrop to outcrop, which is visible in the map of the area with stereonet diagrams of S_0 (Fig. 17). The cluster of secondary structures is mostly represented by cleavages (S_1) (Fig. 16B – contour diagram of all S_1). Measured cleavage planes have more or less the same orientation (NW–SE) with slightly offsetting values of dips from their paired bedding planes.

The obtained structural results fit well with the existing understanding of the PKB structure and enhance the interpretation of the tectonic evolution of the area. From the S_0 dataset, it is visible how plastic softer layers of the PKB units were marked by folding accompanying brittle faulting of more rigid rock formations. Bedding planes clearly differ in their orientation based on their position in the folded complex. These

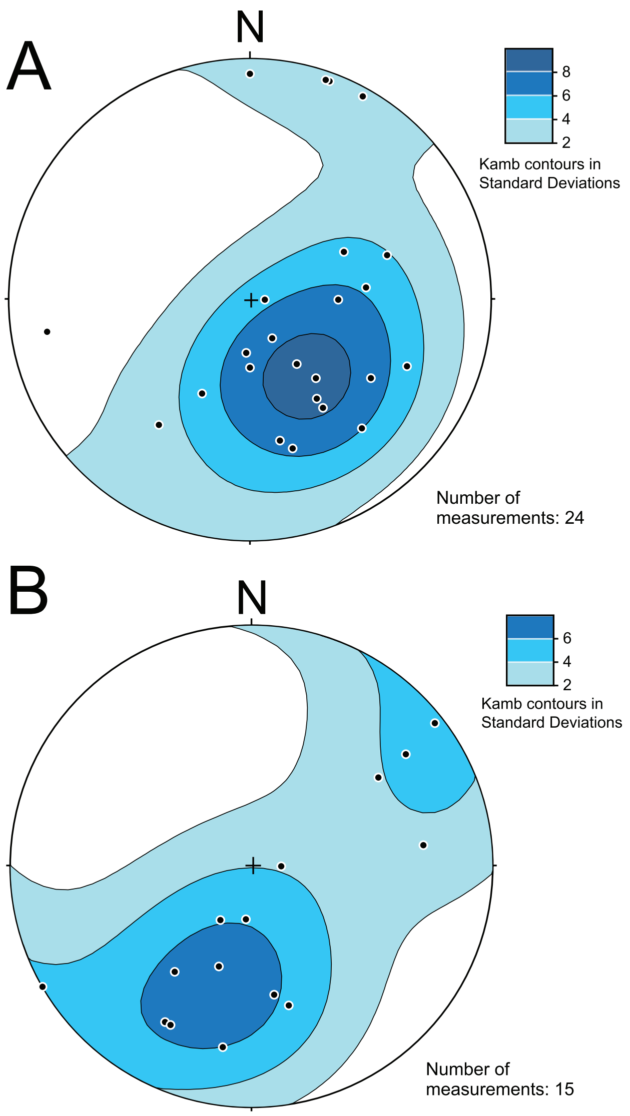

Fig. 16. Contour diagrams of bedding planes poles (**A**) and cleavages poles (**B**).

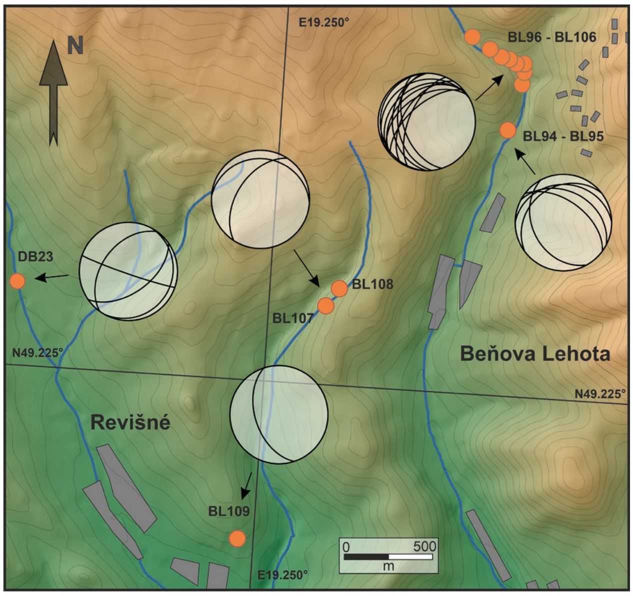

Fig. 17. Location map of meassured outcrops (orange circles and outcrop numbers in black) with stereograms of bedding planes (S0) (topographic and contour map exported from LLS: ÚGKK SR).

layers were often in overturned position and with occassional repeating of the strata. Based on bedding planes orientation, we could calculate axial plane of folded complex, which is identical with cleavage planes S_1.

Significant influence of deformation is also captured in the black shales by secondary structural fabrics. Observed pressure solution seams are usually bedding-parallel and may reflect compaction, i.e., volume reduction, due to the increasing weight of overburden. Dissolution occurs on grain-to-grain or layer boundaries at a rate controlled by the magnitude of normal stress across the boundary. The dissolved carbonate minerals reprecipitates on low-stress intergranular boundaries and opening veins. Secondly, polished anastomosing surfaces connected with the cleavage planes S_1 penetratively cut through the shales (scaly fabric) and are formed in tectonically active zones.

One challenging and complex situation of the area is visible not only in the section in the Beňovolehotský creek, where Cretaceous and Jurassic shales are mixed together, but also noted in an outcrop on the Pod Lopušným hill (BL107), where shales contain Cretaceous and Early-Middle Jurassic dinoflagellate species. The most probable explanation is that the Jurassic species are recycled. However, it is possible that the Kapuśnica Formation and Szlachtowa/Skrzypny Formation are folded together in highly-tectonised strata, similarly to those in the Beňovolehotský creek. This fact is supported also by the change in the colour of the shales (alternation of lighter and darker sections in the shales). Mixing of the dark, soft, and plastic Jurassic deposits (like the Szlachtowa, Opaleniec, or Skrzypny formations) with Cretaceous red (Malinowa Formation) and dark strata (the Wronine, Kapuśnica, or Haluszowa formations) is documented also in other parts of the PKB (Birkenmajer & Gedl 2017; Gedl 2013; Gedl & Józsa 2015) and often led to missinterpretations and discussions about the age of these strata (Oszczypko et al. 2003; Birkenmajer et al. 2008).

In addition to the sampled locations, an outcrop of black shales (DB23 - which no longer exists and could not be sampled) was documented in the Orvišník stream during geological mapping of the area. Layers of black shales with small blocks and lithoclasts of dark grey sandstones were positioned subverticaly and slightly inclined to the S with cleavages showing the same trend as other measured outcrops.

Discussion

The strata, which built up the PKB in western Orava, crop out sporadically and are strongly imbricated and mixed together. Despite uncertainties resulting from tectonic complications, some of the deposits likely belong to the Šariš Unit, which crops out in two of the three subparallel strips – in the northern area as well as in the southernmost area (Fig. 1; modified after Plašienka et al. 2021). In the northern part of the Orava PKB zone, the Šariš Unit is exposed in the Beňovolehotský creek (analysed in this paper) along with other studied outcrops of dark shales accompanied by the carbonate klippe of the Pieniny Limestone Formation with condensed layers (Fig. 18). Moreover, it is supported by the vast presence of the Jarmuta Formation (possibly Jarmuta–Proč Formation) in the area, which was assigned by Plašienka and Mikuš (2010) to the Maastrichtian–Eocene of the Šariš Unit.

In the southern strip, in the village of Revišné, a bottom part of a large klippe belongs to the Šariš Unit with lithostratigraphic units that are strongly reduced in thickness (Molčan Matejová et al. 2019). In the described klippe, the Czorsztyn Limestone Formation and the Revišné Limestone Formation are stratigraphically the oldest (Tithonian) (the latter is a lithofacial variation of the Pieniny Limestone Formation; see Aubrecht 1994). The light grey, partially spotted Pieniny Limestone Formation provided biostratigraphic evidence for the Late Tithonian, Late Valanginian, and the latest Barremian or Barremian/Aptian boundary interval ages. The youngest determined layers are grey-spotted marlstones of the Kapuśnica and Wronine formations (Aptian-Albian). Moreover, in the southern strip, there are multiple outcrops of dark grey micaceous shales surrounding small Lower Cretaceous klippe, as well as Upper Cretaceous synorogenic clastic sediments also belonging to the Šariš Unit.

Confirmation of the presence of the Šariš Unit in the western Orava part of the PKB is relatively new. In older studies, its formations were solely attributed to the Pieniny Unit (Andrusov 1938a, b; Gross et al. 1993a, b; Haško & Polák 1979). Only the recent work of Molčan Matejová (2019) in the area describes the Upper Cretaceous synorogenic sediments of the Jarmuta Formation (possibly Jarmuta-Proč Formation) as belonging to the Šariš Unit, and consequently also the other formations (Kysuca, Lalinok, Tisalo), which were previously

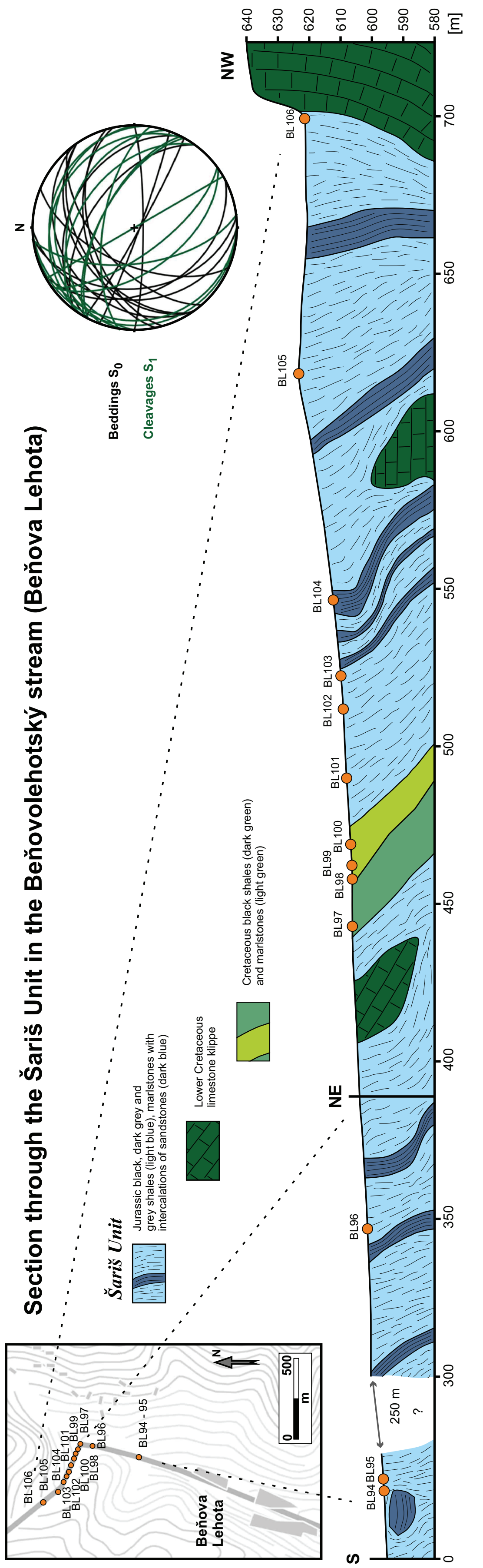

Fig. 18. Geological cross-section across the subsurface strata of the Šariš Unit exposed along the Beňovolehotský stream (Beňova Lehota) with stereogram of all measured beddings (S0) and cleavages (S1) on the outcrops BL94–BL106.

thought to be from the Pieniny Unit, are now described as belonging to the Šariš Unit (now the Wronine and Malinowa formations). Common outcropping of black shales affiliated with the Šariš Unit completes the geological picture of the area. The Toarcian-Aalenian black micaceous shales belong to the turbidite Skrzypny and Szlachtowa Formation and represent the oldest lithostratigraphic members recognised in the Šariš Unit in the studied area.

Some of the latest publications (Barski et al. 2012; Segit et al. 2015; Suan et al. 2018) affiliate the Szlachtowa Formation only with the pre-Late Albian Magura Basin (Šariš Unit) based on the determined Early Bajocian age, and they state that other successions contain only the Skrzypny Formation of the Aalenian, followed by Early Bajocian hiatus. In other publications, as well as in our research, Szlachtowa micaceous sandstones and mudstones were dated as Aalenian, or even Sinemurian; however, in this paper, mostly uppermost Toarcian–Aalenian (Birkenmajer & Gedl 2004, 2017; Birkenmajer et al. 2008; Gedl 2008, 2013; Gedl & Józsa 2015).

The confusing nature of the present-day structure of the PKB in the Orava region is the result of transpressional and transtensional tectonics characterised by polyphase brittle faulting and accompanying semi-brittle flexural slip folding (Gross et al. 1993a; Nemčok & Nemčok 1994; Ratschbacher et al. 1993; Kováč & Hók 1996). The deformation of Oravic units began during the Late Cretaceous by NW thrusting and stacking of sedimentary units detached from their basement. Tectonic processes continued by detachment of the basinal Pieniny-type successions and their thrusting over the elevated part of the Czorsztyn Ridge (Subpieniny Unit). The Subpieniny and Šariš units were sequentially detached and accreted to the front of the growing accretionary wedge. These tectonic events were not recognised during the field works due to the fact that the original nappe structure was significantly modified and overprinted by younger deformation events. Interpretation of our measurements of cleaveage planes and bedding planes from numerous outcrops show the presence of folds (not always clearly visible in the field). The axial plane of the folded complex calculated from the beddings S_0 is oriented in the NW–SE direction, and it is identical with cleavage planes S_1. Thus, these planes represent axial plane cleavage, indicating compression in the NE-SW direction, which we interpret as the D_1 deformation phase. Compressional and transpressional tectonic regimes produced by NE–SW-NNE–SSW compression were also documented in the studied area in limestone klippen, as well as in the Paleogene formations of the Central Carpathian Paleogene Basin (Molčan Matejová 2019). Continuing primary NW thrusting and shortening rotated the bedding planes and pre-existing deformation structures of the PKB strata into a steep, vertical or even overturned position. During the Late Oligocene to early Middle Miocene, significant south-vergent backthrusting occurred with a change of the maximum compression direction from NW–SE to the N–S orientation (Plašienka et al. 2020). Results of this deformation phase are visible also in the studied area in the westernmost part of the Orava sector of the PKB by the presence of south-verging bedding planes of the sedimentary units, often in subvertical or overturned position. In our work, we characterise the backthrusting stage as a D_2 event. One of the products of south-verging tectonics is the occurrence of folds and brittle structures, mostly reverse faults (back-thrusts), which have also been documented by recent works (Marko et al. 2005; Pešková et al. 2007, 2009, 2012; Sentpetery 2012; Molčan Matejová 2019). The Middle to Late Miocene structural record of the Oravic units reflects a transtensional regime with shifting of the orientaion of maximum horizontal stress axis from the N–S to the NE–SW (Kováč 2000; Pešková et al. 2009; Plašienka et al. 2020).

In conclusion, the question arises regarding the Jurassic age of the black shales, as well as their vast presence near and under the limestone klippe. Is it correct to use the frequent statement about the PKB, that "harder Jurassic to Middle Cretaceous klippe lay in softer, less resistant Middle to Upper Cretaceous sediments"?

Conclusions

In this study, we examined dark grey to black fine-clastic micaceous deposits, also called the "black flysch", which are a common lithostratigraphic unit outcropping in the Orava sector of the Pieniny Klippen Belt. Determined dark flysch strata of the Szlachtowa or Skrzypny formations were deposited mostly during the uppermost Toarcian to Middle Aalenian, with a few samples pointing presumably to Sinemurian age. The studied Jurassic clastics were often tectonically incorporated together with Creatceous marly deposits, seemingly forming a consistent sedimentary succession, which reflects the complicated tectonic evolution of this part of the PKB. All of the examined formations were affiliated with the Šariš Unit, thus widening the area of its occurrence. Intricated tectonic situation of this area is the result of several different tectonic stages, which commenced by northward nappe thrusting of the Oravic units; however, these early thrust structures were overriden by younger compression and transpression with the main compression axis being oriented NE to SW. This phase (D_1) is characterised by formation of lateral folds connected with axial plane cleavege. Ongoing compressional regime and shortening of the Oravic units caused subsequent backthrusting of older structures and backward tilting of sedimentary units (D_2).

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