

## Dinoflagellate cyst stratigraphy of the Popiele Member and Menilite Formation in the Boryslav–Pokuttya Nappe (Aksmanice, SE Poland)

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In the Paratethys Sea, isolation, the development of anoxia and stratification of the water column resulted in deposition of organic-rich sediments. In the Western Carpathians (Central Paratethys) these sediments now lie within the Menilite Formation. Whereas the Eocene–Oligocene transition has been studied in the Western Carpathians and is documented by dinoflagellate cyst assemblages, the dinoflagellate cyst stratigraphy of the Menilite Formation members has been uncertain. The Popiele Member and the Menilite Formation exposed at Aksmanice (Boryslav–Pokuttya Nappe, Western Outer Carpathians) reflect palaeogeographic changes at the beginning of the Oligocene. These previously studied deposits have been assigned to lithostratigraphic units, though without biostratigraphic documentation. The age of the Menilite Fm. in the Carpathian sedimentary succession is particularly interesting due to the diachronous character of the facies development. In this study we provide biostratigraphic data based on well-preserved organic-walled dinoflagellate cyst assemblages. The marker taxa recovered indicate a Rupelian age (Early Oligocene) for the Menilite Fm. A different assemblage occurs in the Popiele Member underlying the Menilite Fm. Here, the dinoflagellate cysts are more diverse and abundant, and represented by typical Eocene taxa attributed to *Areosphaeridium* spp. and *Charlesdowniea* spp. The Popiele Member may be assigned to the Priabonian (Late Eocene).

Key words: dinoflagellate cysts, biostratigraphy, Oligocene, Menilite Formation, Outer Carpathians, flysch.

### INTRODUCTION

During the Early Oligocene a significant part of Europe and Central Asia was covered by the Paratethys Sea, which was divided into two domains (1) the large Eastern Paratethys (southern Russia and Central Asia) and (2) the relatively small-scale Western and Central Paratethys (Central Europe). The Western and Central Paratethys comprised the Alpine Foreland Basin, the Carpathian basin and the Pannonian basin (Sachsenhoffer et al., 2018). Restricted marine oxygen-poor conditions in the Paratethys were caused by (1) significant tectonic activity leading to (2) gradual isolation that coincided with (3) global cooling at the Eocene/Oligocene (E/O) boundary at about 33.9 My bp (Gradstein and Ogg, 2004; Gradstein et al., 2004), following a prominent greenhouse–icehouse transition (Báldi, 1980; Rusu, 1988). In these restricted basins organic-rich shales were deposited during the Oligocene and

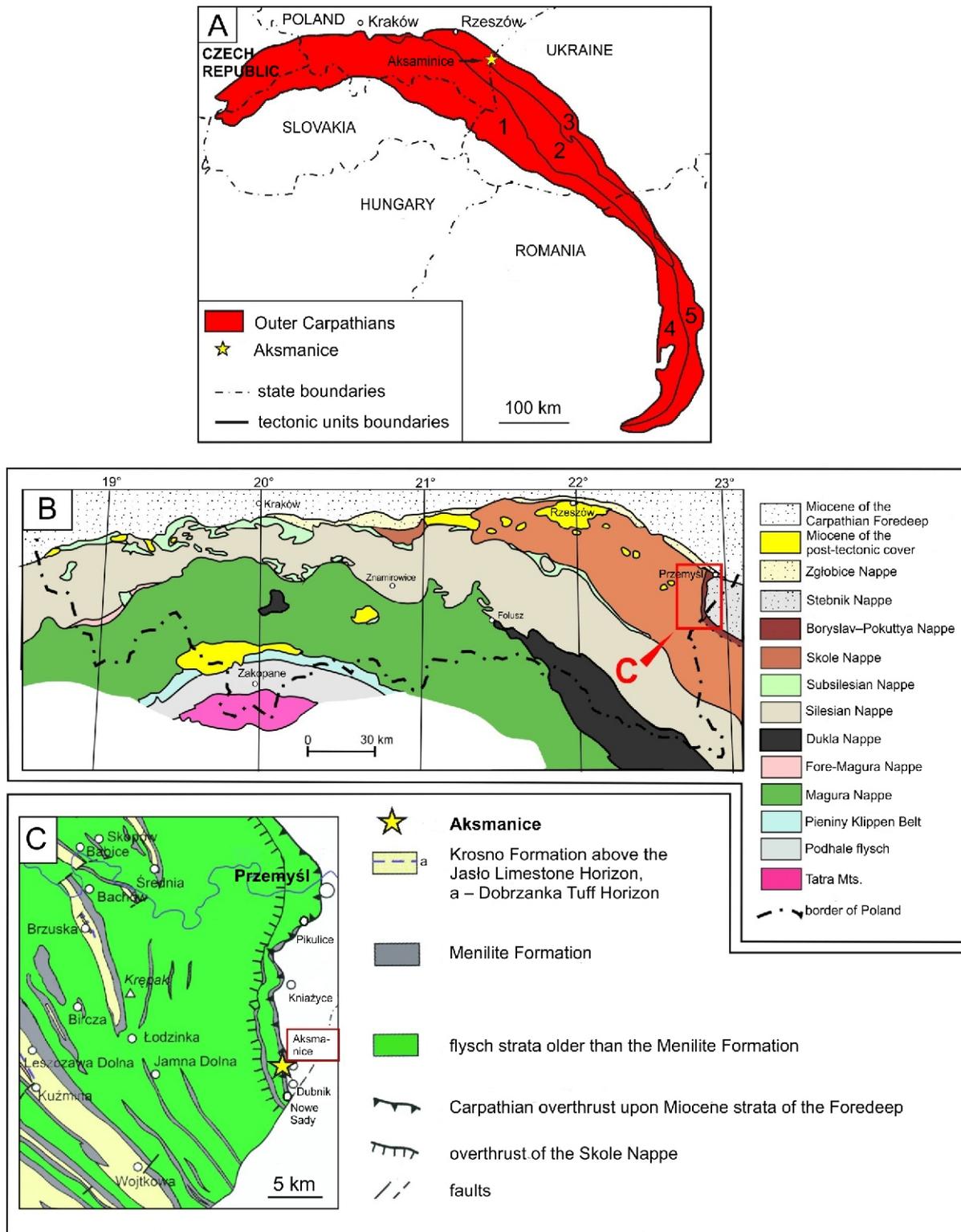
Early Miocene, e.g. the Schöneck Formation in the Austrian Mollase Basin, the Menilite Formation in the Western Carpathians, the Lower and Upper Dysodilic Shale members in the Eastern Carpathians, and the Maikop Group in Western Black Sea and Caspian Sea (Sachsenhoffer et al., 2018).

The Menilite shales and their organic-rich facies equivalents form a widespread marker of the Lower Oligocene in various nappes along the Outer Carpathians in the Slovak and Czech republics, Poland, Ukraine, Romania and the Pannonian Basin System. A specific biofacies development, connected with restricted conditions, allows distinction of a “Paratethys bioprovince”, at first restricted to the Neogene (Laskarev, 1924), then also to the Paleogene (Báldi, 1984, 1989; Rusu, 1988).

These deposits from oxygen-poor environments are difficult to analyse biostratigraphically because the Menilite Formation is generally devoid of microfossils suitable for high-resolution biostratigraphy. Furthermore, observed reworking renders age determinations problematic.

Dinoflagellate cyst assemblages from the Eocene–Oligocene boundary in the Boryslav–Pokuttya Nappe (Fig. 1) were comprehensively studied in the Koniusza section by Gedl (2013). The sections exposed in Koniusza and described here in Aksmanice are devoid of the sub-Menilite Globigerina Marl Member, which is widespread in the Carpathian area (Silesian,

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**Fig. 1. Location of the Aksmanice section**

**A** – schematic map of the Outer Carpathians: 1 – Magura, Dukla, Silesian nappes, 2 – Skole Nappe, 3 – Boryslav–Pokuttya (Marginal fold in Romania) and Sambor nappes, 4 – Tarcău and Vrancea nappes, 5 – Pericarpethian Nappe; **B** – tectonic units (nappes) of the Outer Carpathians of Poland (after *Książkiewicz, 1962, Żyto et al., 1989*, modified); **C** – schematic map of the Outer Carpathians near Przemyśl (*Kotlarczyk et al., 2006*)

Subsilesian, Skole and Boryslav–Pokuttya nappes). This unit is replaced by the Popiele Member, composed of olistolith deposits and is succeeded by organic-rich deposits of the Menilite Formation.

Dinoflagellate cysts are almost completely absent from most of the Lower Oligocene deposits in the Polish Flysch Carpathian area (Polish Outer Carpathians; [Gedl, 1999, 2005, 2013](#)). They are replaced by palynofacies rich in sporomorphs, terrestrial phytoclasts or amorphous organic matter (AOM). The biodiversity of other organisms (e.g., foraminifera) also decreases ([Olszewska, 1985](#)). Changes in the organic composition of the sedimentary units reflect palaeoenvironmental changes (sea level fall, basin isolation events, euxinic conditions) at the beginning of the Oligocene in this part of the Carpathian Basin System ([Gedl, 1999](#)).

In the present study, we investigate dinoflagellate cyst assemblages from the Aksmanice section of the Popiele Member and the lower part of the Menilite Formation from the most external part of the Polish Flysch Carpathians (Boryslav–Pokuttya Nappe; [Fig. 1](#)). We use the assemblages to assign biostratigraphic ages to the Popiele Member and the lower part of the Menilite Formation, the Rudawka Tractionite Member. Finally, a palaeoenvironmental reconstruction is provided for the area studied.

## GEOLOGICAL SETTING

### GEOLOGICAL BACKGROUND

The Boryslav–Pokuttya Nappe is observed in the Eastern Carpathians (southeastern Poland, eastern Slovakia, Ukraine and Romania), with the great majority located in Ukraine. In the south-east it extends into Romania, where it is designated as the Marginal Folds Unit ([Fig. 1](#); [Jankowski et al., 2012](#)). The northernmost part of the Boryslav–Pokuttya Nappe is located in Poland. To the north-east, it is bounded by the Stebnik Nappe, and to the south-west by the Skole Nappe ([Fig. 1B](#); [Kotlarczyk et al., 2006](#)). The Boryslav–Pokuttya Nappe consists of Upper Cretaceous to Miocene strata transported by the thrust system and stuck onto the Stebnik Nappe ([Popadyuk et al., 2006](#)). The depositional successions are generally similar to those of the Skole Nappe, as they originated in the same basin ([Ślączka et al., 2006](#)).

The Popiele Member represents a considerable portion of the Late Eocene strata in the Outer Carpathians ([Dźułyński and Kotlarczyk, 1965](#)). This lithostratigraphic unit outcrops only in the Boryslav–Pokuttya Nappe (in Poland only in the narrow belt south of Przemyśl; [Fig. 1](#)). It lies between the Eocene Hieroglyphic and Menilite formations, instead of the Globigerina Marls, and represents deposits of submarine slumps, recognized as olistostromes. It is mostly composed of massive mudstones and siltstones, with isolated blocks of other lithologies. The blocks are predominantly composed of green shales derived from the Hieroglyphic Beds ([Dźułyński and Kotlarczyk, 1965](#)). The great majority of Popiele Member outcrops are present in Ukraine ([Rajchel, 1990](#)).

The Menilite Formation (alternatively, the Menilite Beds) is widely distributed throughout the Flysch Carpathians in Poland. It occurs in most tectonic units (i.e. the Dukla, Silesian, Subsilesian, Skole and Boryslav–Pokuttya nappes; [Fig. 1](#)). It is characterized by brown to black organic matter-rich and siliceous deposits, the latter mostly formed by menilite, a dark brown or black form of opal. In terms of lithology the Menilite Formation is characterized by the alternations of dark sili-

ceous-claystone shales (menilite shales) and various sandstones. Locally, the formation includes also other siliceous (e.g., cherts, siliceous marls and diatomites), and calcareous (e.g., limestones and marls) deposits. The clastic deposits represent submarine fans, turbidites and tractional currents originating along the northern margin of the basin ([Kotlarczyk and Leśniak, 1990](#)). The limestones, diatomites and some mudrocks have a hemipelagic nature ([Kotlarczyk and Uchman, 2012](#)).

The deposits assigned to the Menilite Formation were deposited in restricted basins of the northern Central Paratethys. The isolation was caused by ongoing closure of the Neotethys Ocean. It was an effect of the collision between the European Plate and several tectonic blocks: the united microplate of Apulia and Adria, and the eastern Alpine (Austroalpine) and Inner Carpathian blocks. These detached from the northernmost fragment of Gondwana in the Late Silurian (Austroalpine, Inner Carpathian blocks) and in the Early Mesozoic (Adria–Apulia microplates) and continued their northward movement during the Cenozoic Alpine and Himalayan orogenies ([Golonka et al., 2003](#)). The shelf and continental slope sediments of the East European Platform are considered to have been the main source of sediment input for the Menilite Formation ([Kotlarczyk, 1988](#)). The topography of the eastern Carpathian Basin also included submarine ridges (Silesian Ridge, Subsilesian Ridge), which also represented significant sources of siliciclastic material and separated longitudinal troughs (the Skole, Silesian basins). The Skole Basin was the outermost (northernmost) part of the Carpathian Basin and was subdivided into an outer narrow trench, the Boryslav–Pokuttya Nappe, and an inner broad trench, the Skole Nappe. It was separated from the Silesian Basin by the Subsilesian Ridge (Węglówka Ridge; [Golonka et al., 2003](#)). Sediments of the Menilite Formation were deposited at the base of continental and intrabasinal slopes, and on the basin floor. Facies equivalents of the Menilite Formation are known from the entire extent of the Outer Carpathians, the Central-Carpathian Paleogene Basin (Podhale, Orava, Spiš and Liptov flysch) and from other regions of the Alpine belt (an orogenic belt created during the Alpine orogeny; [Roth and Hanzlikova, 1982](#)). The deposition of dark shales, which began at the Eocene/Oligocene boundary ([Ślączka et al., 2006](#)), was likely related to sea level fall, leading to basin isolation and euxinic conditions ([Kotlarczyk, 1988](#)). Those changes in the Carpathian basins as well as in other basins of the Paratethys drove significant changes in the ecosystem, which are distinct in the palynological record. The disappearance of open-water dinoflagellate cysts (e.g., *Impagidinium*) in organic-rich deposits has been noted ([Dale, 1996](#)). Correspondingly, there was a clear increase in the abundance of peridinioid cysts (*Deflandrea*, *Wetzeliella*) as a result of environmental eutrophication ([Gedl, 1999](#)). Moreover, in the Oligocene deposits a significant enrichment in terrestrial elements, such as plant cuticles or sporomorphs, has been observed.

The lower boundary of the Menilite Formation is largely synchronous across the whole Carpathian Basin (above the Globigerina Marls horizon, at the Eocene–Oligocene boundary; [Fig. 2](#)). By contrast, the end of sedimentation was diachronous: sedimentation of the Menilite Formation ceased first in the southernmost basin (Dukla Basin – Middle Oligocene), whereas deposition persisted much longer in the northern basins (Skole Basin, Boryslav–Pokuttya Basin – Early Miocene; [Fig. 2](#)). The diachronous character of the uppermost Menilite Formation is linked to the progressive onlap of the Krosno Formation (grey, calcareous and micaceous sandstones and shales) from the south.



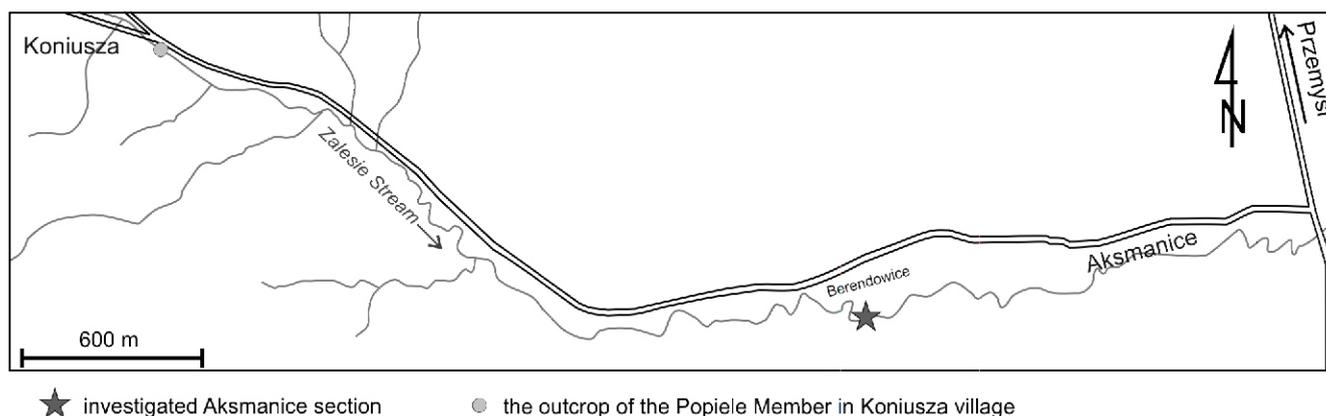


Fig. 3. Location of study area on a topographic sketch-map

lents of the Menilite Formation (Gedl, 1998, 2000; Filipek et al., 2017). Outside of Poland, palynological research in the Outer Carpathians has been conducted in Romania on the Lower Dysodilic Shale Formation and the Upper Dysodilic Shale Formation, lithostratigraphic units of black shale overlying the Lower Menilite and Bituminous Marls formations, respectively, that are exposed in the Tarcău and Vrancea nappes in the Eastern Carpathian region (Fig. 1A; the Moldavian unit; Tabără et al., 2015). In the Ukrainian Carpathians, dinoflagellate cyst assemblages were described by Andreeva-Grigorovich (1991) and Andreeva-Grigorovich and Gruzman (1994).

#### THE AKSMANICE SECTION

This study focuses on a section located near the hamlet of Berendowice of Aksmanice village, southern Poland, 15 km to the south of Przemysl (Figs. 1 and 3); this section has been previously described by Kotlarczyk and Leśniak (1990) and Kotlarczyk et al. (2006). In Aksmanice (GPS: N49°40.459', E022°43.763'), the Popiele Member and Menilite Formation are exposed in the Zalesie Stream (Fig. 3), within the Boryslav–Pokuttya Nappe of the Outer Carpathians. In a broader geographic context, the Menilite Formation is exposed along the Boryslav–Pokuttya Thrust from the Nowe Sady area in the south to the Pikulice area near Przemysl in the north (Fig. 1C).

The Aksmanice section represents the best exposure of the formation in the Polish Boryslav–Pokuttya Nappe.

The interval studied comprises a portion of the Popiele Member (6 m), followed by the lower Menilite Formation (24 m) (Fig. 4). At the Aksmanice exposure, the latter consists of successive dark brown cherts (Kotów Chert Member), grey siliceous marls (Dynów Marl Member) and black siliceous shales with thin-bedded sandstones (Rudawka Tractionites Member). The lowermost part of the section is assigned to the Popiele Member and is composed of green (or yellow-green when weathered) marly shales. The Kotów Chert Member (13 m) consists of black and brown cherts interbedded with mm-thick brown siliceous shales (known as the Menilite shales; Fig. 4). The Dynów Marl Member, (2 m) is developed as grey siliceous marls (Fig. 4) with laminated chert intercalations. It is highly reduced or absent in the Boryslav–Pokuttya Nappe, whereas in the Skole Nappe, it reaches a thickness of 20 m (Kotlarczyk and Leśniak, 1990). The uppermost portion of the section belongs

to the Rudawka Tractionites Member (9.5 m), which is dominated by black, clayey-siliceous shale (Menilite shales).

#### MATERIALS AND METHODS

Eleven samples were collected from individual lithostratigraphical levels in the section investigated (Fig. 4). Samples were taken from fine-grained rocks, marls and siliceous rocks. The material was processed using a standard palynological procedure, with hydrochloric acid (37% HCl) treatment, to remove calcium carbonate, followed by hydrofluoric acid (70% HF) to remove silica. The residue was sieved using a 15 µm nylon-mesh: organic matter was then separated using heavy liquids ( $\text{ZnCl}_2 + \text{HCl}$ ;  $\rho = 2.0 \text{ g/cm}^3$ ). Slides were made from each sample, using glycerin jelly as the mounting medium. Photographs were made in transmitted light using *Nikon Eclipse 600* and *Nikon Eclipse LV 100 POL* cameras. Two slides per sample were logged due to the low number of dinoflagellate cysts within the assemblages studied.

#### RESULTS

Species abundances and frequencies are shown in Figure 5. The highest abundances of dinocysts are recorded in samples A0 and A4. The poorest, mostly monospecific assemblages occur in samples A1 and A5a, the most siliceous deposits sampled.

**Sample A0** is characterized by a high abundance of well-preserved dinoflagellate cysts (Figs. 6 and 7). The most abundant are *Homotryblum tenuispinosum* (14%) and *Spiniferites ramosus* (13%). *Enneadocysta pectiniformis* and *Thalassiphora pelagic* are relatively frequent. Representatives of the taxa *Achomosphaera* spp., *Areosphaeridium diktyoplokum*, *Areosphaeridium michoudi*, *Charlesdowniea coleothrypta*, *Cleistosphaeridium* spp., *Cordosphaeridium fibrospinosum*, *Cribroperidinium tenuitabulatum*, *Deflandrea phosphoritica*, *Homotryblum plectilum*, *Impagidinium velorum*, *Lentinia serrata*, *Lingulodinium* spp., *Oligosphaeridium complex* and *Operculodinium centrocarpum* were also noted. *Cleistosphaeridium placacanthum*, *Cordosphaeridium cantharellus*, *Hystrichokolpoma rigaudiae* and *Nematosphaeropsis labyrinthus* are rarely present.

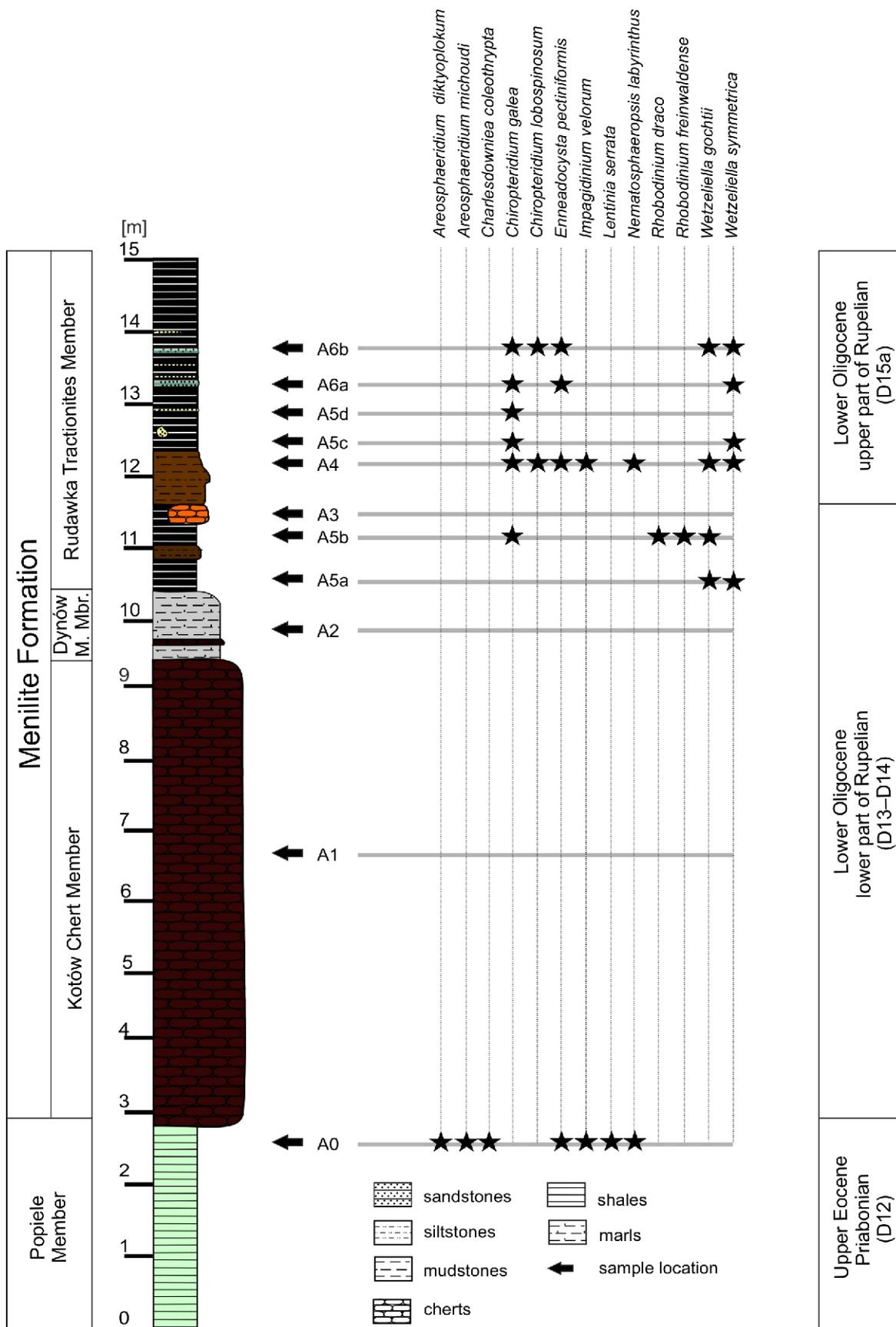


Fig. 4. Lithostratigraphic log of the Aksmanice section and age interpretations based on dinoflagellate cysts

Dynów M. Mbr. – Dynów Marl Member

Pop. Mbr.	Menilite Formation										Lithostratigraphy
	K. Ch. Mbr.	D. M. Mbr.	Rudawka Tractionites Member								
	A	C	C	B	B	C	A	B	B	A	
A0	A1	A2	A5a	A5b	A3	A4	A5c	A5d	A6a	A6b	Samples
7		4									<i>Achomosphaera</i> spp.
8											<i>Areosphaeridium diktyoplokum</i>
	9	14	6	3	15		6		5	2	<i>Caligodinium amiculum</i>
			3		9						<i>Caligodinium endoreticulatum</i>
	3	5									<i>Caligodinium</i> spp.
4											<i>Charlesdowniea coleothrypta</i>
				3		8	1	2	6	7	<i>Chiropteridium galea</i>
						12				3	<i>Chiropteridium lobospinosum</i>
3						2					<i>Cleistosphaeridium placacanthum</i>
8								1		4	<i>Cleistosphaeridium</i> spp.
3									1	2	<i>Cordosphaeridium cantharellus</i>
6						6					<i>Cordosphaeridium fibrospinosum</i>
							2			1	<i>Cordosphaeridium</i> spp.
4											<i>Cribopteridium tenuitubulatum</i>
9				22		22	6	8	5	8	<i>Deflandrea phosphoritica</i>
11						15			4	4	<i>Enneadocysta pectiniformis</i>
									2		<i>Homotryblum abbreviatum</i>
6											<i>Homotryblum plectilum</i>
						3				2	<i>Homotryblum</i> spp.
23				6		4				2	<i>Homotryblum tenuispinosum</i>
1											<i>Hystrichokolpoma rigaudiae</i>
6						7					<i>Impagidinium velorum</i>
4											<i>Lentinia serrata</i>
6		6									<i>Lingulodinium</i> spp.
			1								<i>Litosphaeridium siphonophorum</i>
						9	1		12	3	<i>Membranophoridium aspinatum</i>
3						2					<i>Nematosphaeropsis labyrinthus</i>
9											<i>Oligosphaeridium complex</i>
8											<i>Operculodinium centrocarpum</i>
						9					<i>Palaeocystodinium golzovense</i>
						3			3		<i>Pentadinium lophophorum</i>
				9							<i>Rhobodinium draco</i>
				10							<i>Rhobodinium freinwaldense</i>
									2		<i>Rottnestia borussica</i>
21		10				19	3	6		7	<i>Spiniferites ramosus</i>
12						13	2			2	<i>Thalassiphora pelagica</i>
			1	6		9				5	<i>Wetzeliella gochtii</i>
			1			11	2	1	9	12	<i>Wetzeliella symmetrica</i>
<b>166</b>	<b>12</b>	<b>39</b>	<b>12</b>	<b>59</b>	<b>24</b>	<b>154</b>	<b>23</b>	<b>18</b>	<b>49</b>	<b>64</b>	<b>Total</b>

Fig. 5. Dinoflagellate cyst distribution of the Aksmanice section

Pop. Mbr. – Popiele Member; K. Ch. Mbr. – Kotów Chert Member; D. M. Mbr. – Dynów Marl Member; A – very good preservation; B – mediocre preservation; C – absence of dinoflagellate cysts or very poor preservation

The assemblage from **sample A1** contains only a few dinocysts belonging to one genus, *Caligodinium* (Fig. 8).

The assemblage from **sample A2** (Fig. 8) is dominated by *Caligodinium amiculum* (36%) and *Spiniferites ramosus* (26%). Other taxa are nearly absent. Single specimens of *Achomosphaera*, *Caligodinium* and *Lingulodinium* were found.

The assemblage of **sample A5a** (Fig. 8) is very poor. It consists mainly of *Caligodinium amiculum*. Other taxa, such as *Wetzeliella gochtii* and *Wetzeliella symmetrica*, are subordinate. One specimen of *Litosphaeridium siphonophorum* was recovered.

**Sample A5b** (Figs. 8 and 9) contains a relatively high percentage of *Deflandrea phosphoritica* (37%). *Rhodobodium* (*R. freinwaldense* and *R. draco*) is also common (32% in total, both species in similar proportions). The remaining taxa consist of *Caligodinium amiculum*, *Chiropteridium galea*, *Homotryblium tenuispinosum* and *Wetzeliella gochtii*.

The dinocyst assemblage from **sample A3** is quite similar to that of sample A5a (only representatives of the genus *Caligodinium*), but the number of dinocysts is larger.

**Sample A4** (Figs. 9 and 10) is rich in dinoflagellate cysts. The most frequent taxa are *Deflandrea phosphoritica* (14%) and *Spiniferites ramosus* (12%). A relatively frequent occurrence of *Enneadocysta pectiniformis* (9%) was noted. *Chiropteridium* (*C. galea* and *C. lobospinosum*), *Cordosphaeridium fibrospinosum*, *Membranophoridium aspinatum*, *Palaeocystodinium golzovense*, *Thalassiphora pelagica*, *Wetzeliella* (*W. gochtii* and *W. symmetrica*) are quite common. The other taxa found in sample A4 are *Cleistosphaeridium placacanthum*, *Homotryblium* spp., *Homotryblium tenuispinosum*, *Impagidinium velorum*, *Nematosphaeropsis labyrinthus* and *Pentadinium lophophorum*.

The dinoflagellate cyst assemblage from **sample A5c** is dominated by *Caligodinium amiculum* and *Deflandrea phosphoritica* (both 26%). Other taxa – namely, *Cordosphaeridium* spp., *Spiniferites ramosus*, *Thalassiphora pelagic* and *Wetzeliella symmetrica* – are rare. Single specimens of *Chiropteridium galea* and *Membranophoridium aspinatum* were found.

**Sample A5d** (Fig. 9) contains mainly *Deflandrea phosphoritica* (44%) and *Spiniferites ramosus* (33%). Other taxa are very rare: *Chiropteridium galea*, *Cleistosphaeridium* spp., *Wetzeliella symmetrica*. **Sample A6a** (Fig. 10) is dominated by *Membranophoridium aspinatum* (24.5%). *Caligodinium amiculum*, *Chiropteridium galea*, *Deflandrea phosphoritica*, *Enneadocysta pectiniformis* and *Wetzeliella symmetrica* are relatively frequent. A few specimens of *Homotryblium abbreviatum*, *Pentadinium lophophorum* and *Rottnestia borussica* were noticed. A single specimen of *Cordosphaeridium cantharellus* was found.

**Sample A6b** (Fig. 10) is dominated by *Wetzeliella symmetrica* (19%). Other frequent taxa found in this sample are *Chiropteridium galea*, *Deflandrea phosphoritica*, *Spiniferites ramosus*, *Wetzeliella gochtii*. There were rare specimens of *Caligodinium amiculum*, *Chiropteridium lobospinosum*, *Cleistosphaeridium* spp., *Cordosphaeridium cantharellus*, *Cordosphaeridium* spp., *Enneadocysta pectiniformis*, *Homotryblium* spp., *Homotryblium tenuispinosum*, *Membranophoridium aspinatum* and *Thalassiphora pelagica*.

The distribution of dinoflagellate cysts shows an apparent relation to lithology. Samples taken from the most siliceous deposits are generally impoverished in dinocysts and show low di-

versity. The most diversified and rich dinoflagellate cyst assemblages were recovered from mudflow deposits and greenish shales. Hemipelagic species represented here by *Impagidinium velorum* and *Nematosphaeropsis labyrinthus* occur solely in greenish shales.

## AGE INTERPRETATION

Determination of the ages of the recovered assemblages is based on the co-occurring ranges of well-known taxa and by comparison to the standard dinocyst zones (Powell, 1992; Gradstein et al., 2012; Williams et al., 2004) with regard to biogeographical dispersal.

The ranges of index taxa for stratigraphic analysis are described in publications including Costa and Downie (1976), Châteauneuf (1980), Haq et al. (1987), Brinkhuis (1994), Stover et al. (1996), Wilpshaar et al. (1996), Coccioni et al. (2000) and Köthe and Piesker (2007).

With reference to the sedimentological character of Popiele Member deposits, dating refers to the period of sedimentation of the greenish shales, which is not the same as the timing of olistostrome formation.

### GREENISH SHALES – POPIELE MEMBER

Sample A0 (Fig. 4) was collected from greenish shales and contains rich and well-preserved dinoflagellate cyst assemblages, terrestrial sporomorphs, marine algae (*Tasmanites*, *Schizosporis*), and foraminiferal organic linings. Age-diagnostic dinoflagellate cysts include *Areosphaeridium diktyoplokum*, *Lentinia serrata* and *Enneadocysta pectiniformis*. The last occurrence of *A. diktyoplokum* is taken as the event marking the Eocene–Oligocene boundary. According to Köthe and Piesker (2007) and Costa and Manuum (1988), this coincides with the boundary of zones D12/D13. However, Williams et al. (2004) and Gradstein et al. (2012) suggest that *A. diktyoplokum* disappears in the Early Rupelian at higher latitudes: in this framework, the last appearance of *L. serrata* marks the end of the Eocene (Williams et al., 2004). The first occurrence of *E. pectiniformis* is noted above the Bartonian/Priabonian boundary (Williams et al., 2004), and can be correlated with the beginning of the NP18 nannoplankton zone. The part of the section with the greenish shales is in the D12 Zone (Priabonian).

### MENILITE FORMATION

**Cherts – Kotów Chert Member.** In the overlying beds of the Kotów Chert Member (sample A1: Fig. 4), dinoflagellate cysts are poorly preserved and nearly absent. The sample contains frequent gymnosperm pollen, along with fragments of leaf tissue. The monospecific dinoflagellate assemblage is composed of *Caligodinium amiculum*, a long-ranging taxon hindering age interpretation. **Siliceous marls – Dynów Marl Member.** The sample from the Dynów Marl Member (sample A2: Fig. 4) is almost entirely composed of AOM (amorphous organic matter). It is likewise dominated by *Caligodinium amiculum*, and rare representatives of *Spiniferites ramosus*, *Achomosphaera* spp. and *Lingulodinium* spp. were found. The sample is also rich in gymnosperm pollen grains. In light of the

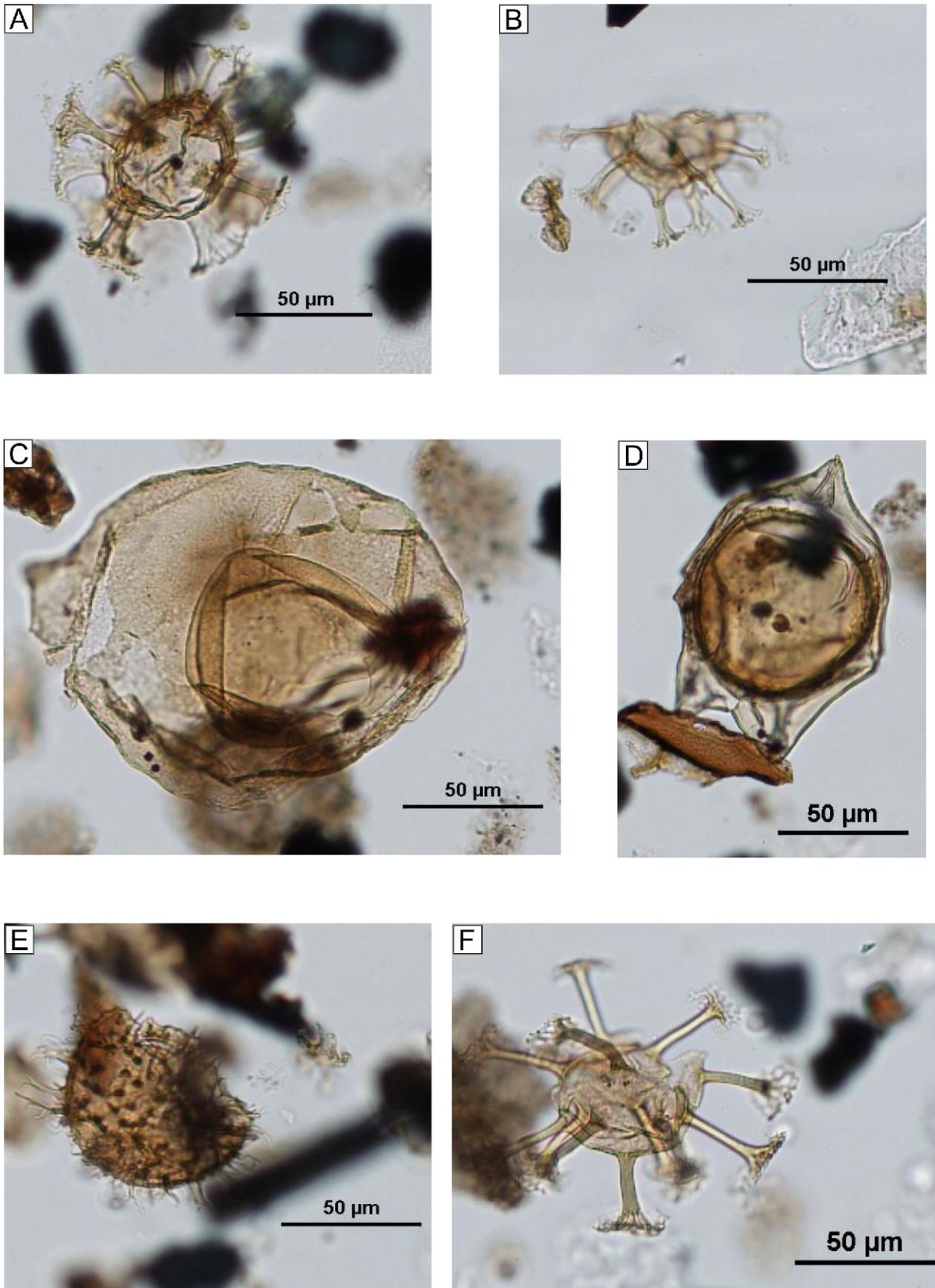
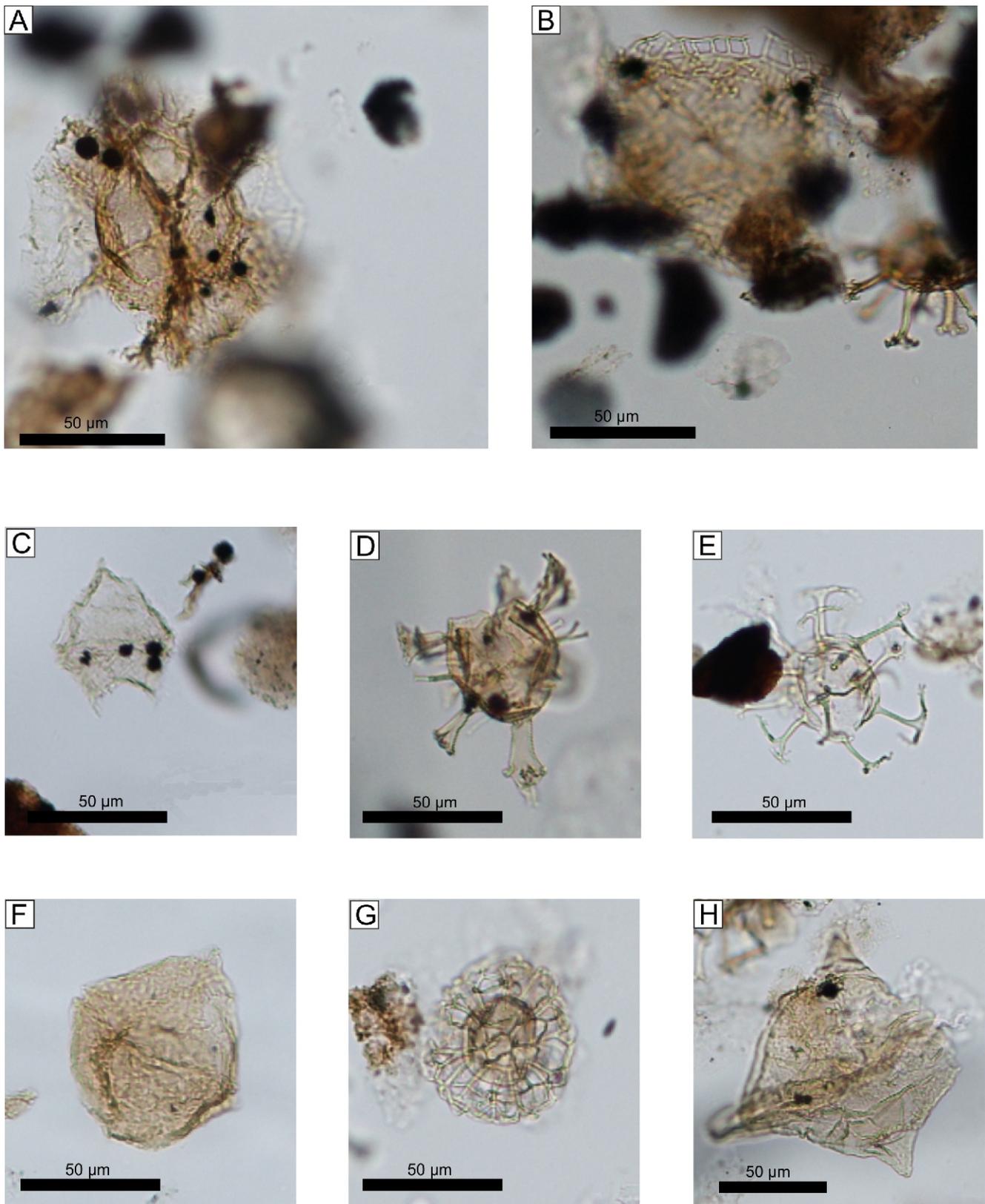


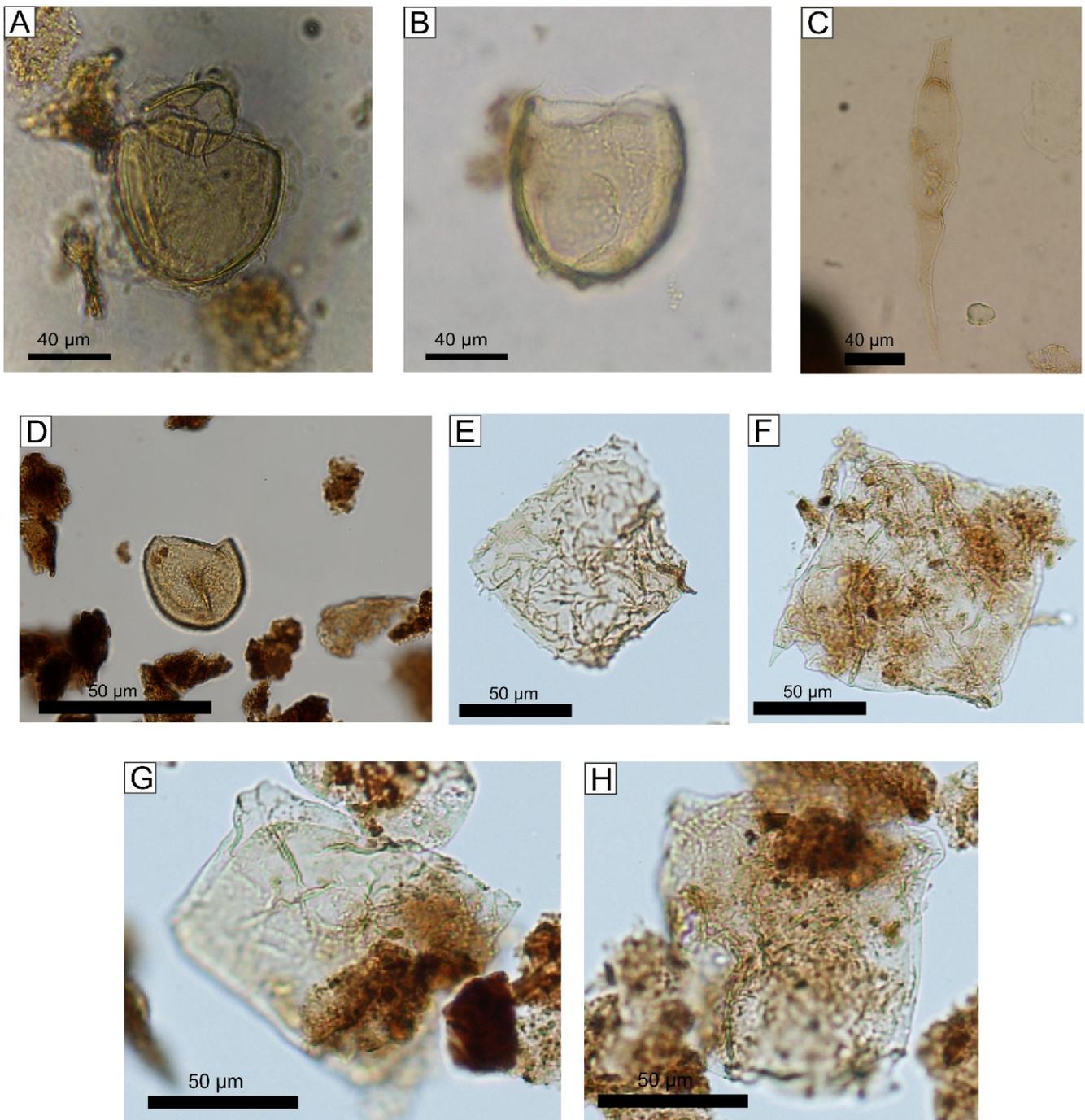
Fig. 6. Dinoflagellate cysts from the Popiele Member in the Aksmanice section (sample A0)

A – *Cordosphaeridium cantharellus*; B – *Homotryblium plectilum*; C – *Thalassiphora pelagica*; D – *Deflandrea phosphoritica*;  
E – *Cleistosphaeridium placacanthum*; F – *Areosphaeridium michoudi*



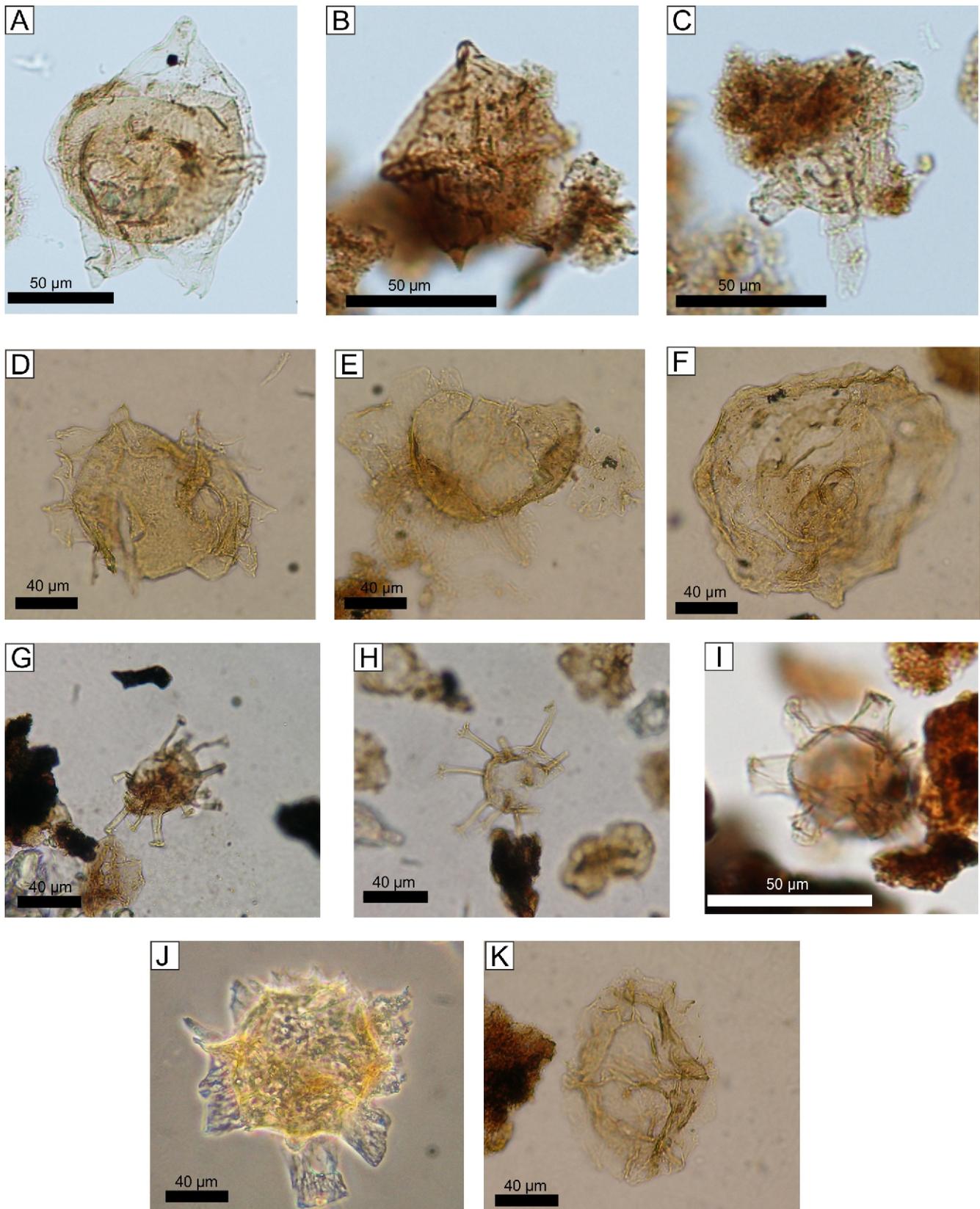
**Fig. 7. Dinoflagellate cysts from the Popiele Member in the Aksmanice section (sample A0)**

**A** – *Impagidinium velorum*; **B** – *Charlesdownia coleothrypta*; **C** – *Lentinia serrata*; **D** – *Hystrichokolpoma rigaudiae*; **E** – *Enneadocysta pectiniformis*; **F** – *Cribroperidinium tenuitabulatum*; **G** – *Nemosphaeropsis labyrinthus*; **H** – *Rhodinium draco*



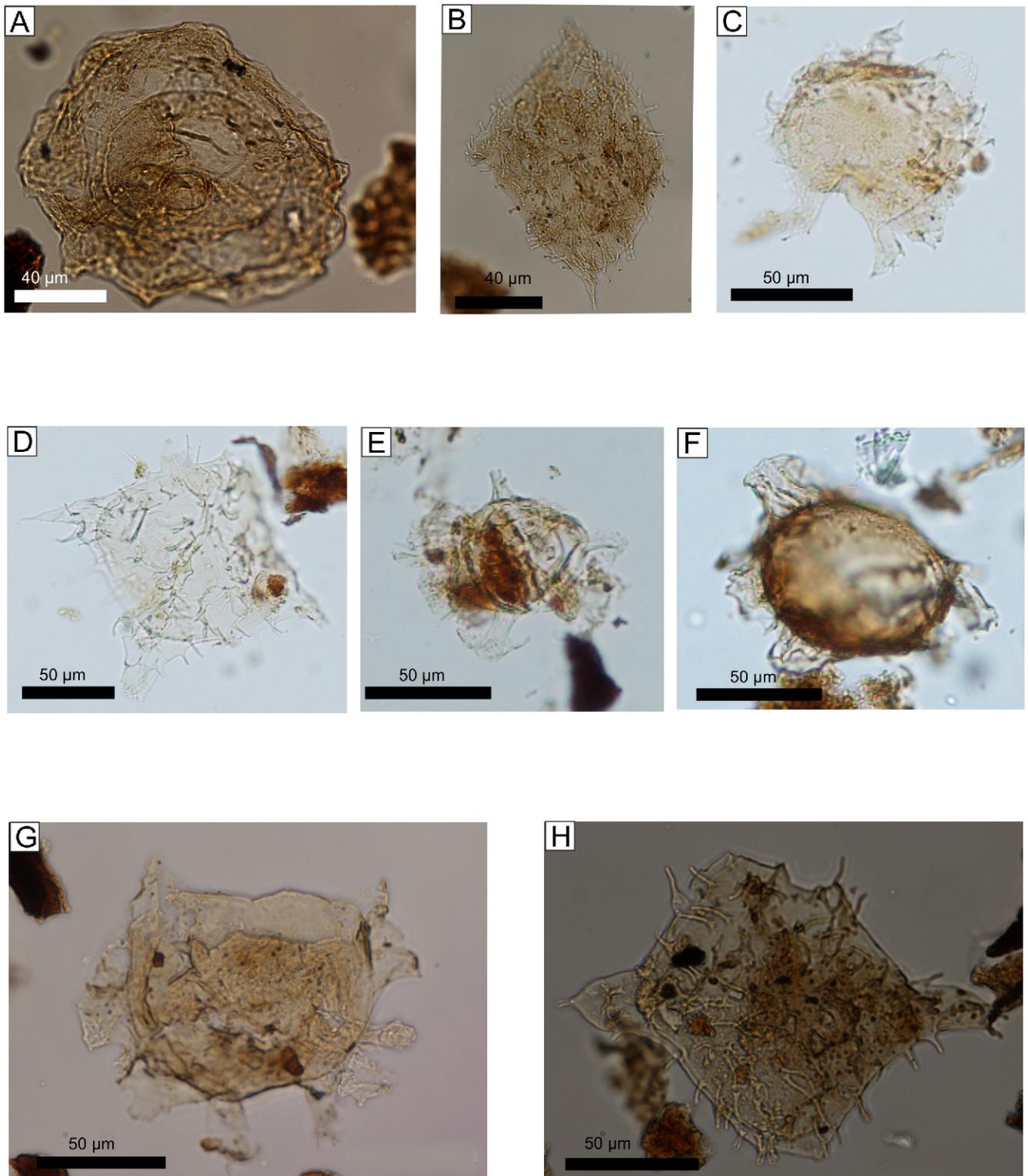
**Fig. 8. Dinoflagellate cysts from the Menilite Formation: Kotów Member (sample A1: A, C), Dynów Member (sample A2: B), Rudawka Tractionites Member (sample A5a: D), (sample A5b: E–H)**

**A** – *Caligodinium amiculum*; **B** – *Caligodinium endoreticulatum*; **C** – *Paleocystodinium golzowense*; **D** – *Caligodinium endoreticulatum*;  
**E** – *Wetzeliella* sp.; **F** – *Rhombodinium draco*; **G, H** – *Rhombodinium freinwaldense*



**Fig. 9. Dinoflagellate cysts from the Menilite Formation: Rudawka Tractionites Member (sample A5b: A–C, I; sample A5d: D–H; sample A4: J–K)**

**A** – *Deflandrea phosphoritica*; **B** – *Lentinia serrata*; **C** – *Hystrichokolpoma rigaudiae*; **D** – *Chiropteridium galea*; **E** – *Membranophoridium aspinatum*; **F** – *Thalassiphora pelagica*; **G** – *Homotryblium tenuispinosum*; **H** – *Oligosphaeridium* complex; **I** – *Litosphaeridium siphonophorum*; **J** – *Cordosphaerodium fibrospinosum*; **K** – *Impagidinium velorum*



**Fig. 10.** Dinoflagellate cysts from the Menilite Formation: Rudawka Tractionites Member (sample A4: A, B; sample A6a: C–F; sample A6b: G, H)

A – *Thalassiphora pelagica*; B – *Wetzeliella gochtii*; C – *Chiropteridium galea*; D – *Wetzeliella symmetrica*; E – *Cordosphaeridium cantharellus*; F – *Cordosphaeridium fibrospinosum*; G – *Chiropteridium galea*; H – *Wetzeliella symmetrica*

absence of age-diagnostic taxa, a biostratigraphic age based on dinoflagellate cysts cannot be determined.

**Shales and sandstones – Rudawka Tractionites Member.** Deposits of this member are lithologically and palynologically diverse. The preservation of dinoflagellate cysts varies from poor to moderate, and the taxonomic composition differs significantly from that of the Popiele Member assemblages. Black shales alternating with the light, fine-grained sandstones of the Rudawka Tractionites Member (Kotlarczyk and Leśniak, 1990; samples A5a, A5b, A5c; Fig. 4) contain impoverished dinoflagellate cyst assemblages, dominated by Peridiniaceae dinocysts. Within this family, the most common genus is *Wetzeliella* (*W. gochtii*, *W. symmetrica*); the genera *Rhombodinium* (*R. freinwaldense*, *R. draco*) and *Deflandrea* (*D. phosphoritica*) are slightly less abundant.

The age of the dinoflagellate cyst assemblage from the black shales is Lower Rupelian (zones D13–D14), as indicated by diagnostic Oligocene taxa, (namely, *Chiropteridium galea*, *Wetzeliella gochtii*, *Wetzeliella symmetrica*). *C. galea* appears at the beginning of the Rupelian, above the last occurrence of *Areosphaeridium diktyoplokum* at the base of dinocyst Zone D13. The first appearance of *W. gochtii* determines the base of dinocyst Zone D14 and correlates with the beginning of nanoplankton Zone NP22 (Williams et al., 2004; Gradstein et al., 2012). Powell (1992) reported that *Wetzeliella gochtii* appeared earlier with *W. symmetrica*, at the base of Zone D13 and in the middle of Zone NP21: on this basis he distinguished the *Wetzeliella gochtii* Zone. The last appearance of *R. draco* defines the top of Zone D14. The duration of black shale sedimentation can be constrained to within D13 and D14 (according to Köthe and Piesker, 2007).

The occurrence of *L. siphonophorum*, typically present from the end of the Albian through the Cenomanian interval, is probably a result of reworking.

Mudflow deposits noted within the Menilite Formation included brown mudstones, siltstones and siliceous deposits. Sample A3 was taken from a siliceous lens, and contains a dinocyst assemblage similar to that in the siliceous marls: only *Caligodinium amiculum* and *Caligodinium endoreticulatum* cysts were found. Conversely, dinocysts are frequent and well-preserved in the brown mudstone sample (sample A4). This assemblage includes several age-diagnostic taxa, including *Chiropteridium galea*, *C. lobospinosum*, *Wetzeliella gochtii*, *W. symmetrica*, *Deflandrea phosphoritica*, and *Enneadocysta pectiniformis*. In general, this is quite similar to the black shale assemblage; the main difference is the significantly better dinocyst preservation in the mudstones. The presence of *W. gochtii*, *W. symmetrica* and *C. lobospinosum* suggests an Oligocene age. More specifically, *C. lobospinosum* indicates a Late Rupelian age. According to Powell (1992), the first appearance of *C. lobospinosum* occurs in the Middle Rupelian, above the first appearance of *W. gochtii*. *C. lobospinosum* is the basis for defining the base of the *Phthanoperidinium cereoides* Zone (Powell, 1992), which is calibrated with nanoplankton zones NP23 (upper) and NP24 (lower). According to Gradstein et al. (2012) and Köthe and Piesker (2007), this event is within Zone D14a, which is correlated to Zone NP23. The upper age constraints of this unit are determined by the last appearance of *E. pectiniformis*, which is dated to the uppermost Rupelian (Wilpshaar et al., 1996; Williams et al., 2004).

The Rudawka Tractionites Member overlies these mudflow deposits. In sample A5d, collected from the shales above the top of the mudstones, a poor dinocyst assemblage is present, composed mainly of *Deflandrea phosphoritica*. The last appearance of this taxon occurred above the top of Zone D15 (Köthe and Piesker, 2007) below the Oligocene–Miocene boundary (Haq et al., 1987; Stover et al., 1996), or in the middle

of the Aquitanian (Williams et al., 2004). A more precise age assignment of this part of section is possible from the superposition of ages determined from overlying samples.

At the top of the succession (Fig. 4), within the Rudawka Tractionites Member, a thin bed of fine-grained glauconitic sandstone occurs (sample A6a). This shows frequent occurrences of *Wetzeliella symmetrica* and *Chiropteridium galea*; specimens of *Enneadocysta pectiniformis* were also found; the dinocyst assemblage suggests a Rupelian age.

Sample A6b was collected from the second, overlying, glauconitic sandstone (Fig. 4). The dinocyst assemblage is similar to that from sample A6a. The following dinocyst age-diagnostic taxa have been found: *Chiropteridium galea*, *C. lobospinosum*, *Wetzeliella gochtii*, *W. symmetrica*, and *Enneadocysta pectiniformis*. Based on the presence of *C. lobospinosum* and *E. pectiniformis*, the age of the upper Rudawka Tractionites Member can be constrained to the Middle–Late Rupelian, corresponding with Zone D15a.

## PALAEOENVIRONMENTAL RECONSTRUCTIONS

Significant changes in composition are observed between the Eocene and Oligocene cyst assemblages. In the Eocene Popiele Member the assemblages are diverse and abundant. By contrast, the large diversity and frequency of dinoflagellate cysts distinctly decreases in the early Oligocene. This is similar to other Eocene/Oligocene sections within the Polish Flysch Carpathians (Gedl, 1999).

### POPIELE MEMBER

The frequent occurrence of *Homotryblum*, a taxon that is tolerant of increased salinity and occurs in shallow-water settings, may suggest near-shore and lagoonal settings (Pross Brinkhuis, 2005). Other frequent taxa, such as *Cleistosphaeridium*, *Deflandrea*, *Areosphaeridium*, *Thalassiphora*, *Charlesdowniea*, *Enneadocysta* and *Cribroperidinium* are characteristic of the inner shelf (Pross, 2005). The presence of *Tasmanites* algae and foraminiferal organic linings also suggests an inner shelf setting (Gedl, 2013). Dinoflagellates from the peridinioid group (e.g., *Charlesdowniea*, *Deflandrea*) prefer brackish and nutrient-rich water, which indicates a freshwater influx from the shore; the peridinioids and numerous terrestrial sporomorphs may have been transported from estuarine settings to a more distal environment. Alternatively, the coexistence of taxa that prefer high-salinity conditions (*Homotryblum*) and brackish environments (*Charlesdowniea*) may also point to surface-water stratification (Pross, 2005). The presence of scattered offshore taxa, such as *Nematosphaeropsis* and *Impagidinium*, may have been caused by marine currents (Pross, 2005).

The presence of the typically high-latitude taxon *Impagidinium velorum* (Bujak, 1984) suggests cooling of the surface water layer, which matches with the general Late Eocene climatic cooling trend, starting in the middle Early Eocene and culminated in the earliest Oligocene (Zachos et al., 2001; Miller et al., 2009).

### MENILITE FORMATION

Dinocyst assemblage diversity decreased during the Early Oligocene. These changes are interpreted as a result of eutrophication, the appearance of dysoxic or anoxic conditions, and the isolation of the Paratethys basins (Gedl, 1999).

Samples from cherts and siliceous marls are generally poor in dinoflagellate cysts and rich in AOM. The presence of *Caligodinium*, *Spiniferistes*, and *Achomosphaera*, taxa characteristic of an inner neritic environment (Vasilyeva and Musatov, 2012), and fragments of leaf tissue, suggest a near-shore environment. The presence of *Lingulodinium* also points toward nutrient-rich waters (Tabără et al., 2015).

The most taxonomically reduced assemblages occur in the siliceous marls, in which only a monospecific assemblage of *Caligodinium* is found. The cysts are very rare and mostly covered by AOM.

More diverse assemblages were identified in black shales and glauconitic sandstones from the Rudawka Tractionites Member. These samples are dominated by peridinioids (*Deflandrea*, *Wetzeliiella*, *Rhombodinium*), taxa characteristic of the shallow waters of the inner shelf. *Chiropteridium* and *Membranophoridium* are representatives of shallow-water taxa that are found in black shales (Gedl, 2000). A lack of oceanic species, such as *Impagidinium*, in the black shales supports the interpretation of a proximal setting. The occurrence of numerous brackish taxa, such as *Deflandrea* and *Wetzeliiella*, the freshwater algae *Tasmanites*, and terrestrial elements such as cuticles, pollen grains and sporomorphs, indicates a prominent freshwater influx, e.g. the proximity of a river mouth. The prevalence of Peridinales suggests the prevalence of eutrophic conditions and oxygen deprivation. These trophic conditions can be related to the isolation of the Paratethys Sea and consequently to decreased circulation.

The richest, best-preserved dinoflagellate cyst assemblages were found in mudstones from the mudflow deposits. The superior preservation of dinocysts may have been caused by the prevalence of mud and silt sedimentation, which might have provided better protection against compaction. Increased accumulation of cysts may be associated with redeposition, as suggested by the character of mudflow deposits. The assemblages from these deposits are similar to the assemblages found in the black shale samples. The occurrence of the offshore taxon *Impagidinium velorum* is possibly the result of redeposition.

In an interpretative framework, the dinoflagellate cyst assemblages reflect a decreased circulation and a gradual eutrophication of the basins from the end of the Eocene to the Early Oligocene. Furthermore, the decline in abundance of open sea taxa and corresponding increase of their brackish counterparts suggest a progressive closure of the basin and an increased supply of fresh water.

## DISCUSSION

### POPIELE MEMBER

The Popiele Member is represented by pale-greenish shales in the Aksamnice locality. The present study indicates that this lithological unit is of Priabonian age. The Priabonian age of dinoflagellate cyst assemblages from the Popiele Member at Aksamnice is consistent with that of the mudstones from the Koniusza exposures. In Koniusza, older (Bartonian) marl clasts are also present; these are absent at Aksamnice (Gedl, 2013).

Other biostratigraphic age interpretations are congruent with those reported here. Numerous mollusc shells in these strata were examined by Wiśniowski (1908), Rogala (1925), and Krach (1985). While Wiśniowski classified the Menilite Beds as of a Lower Oligocene age, Rogala (1925) revised his classification and considered them to have a Middle to Upper Eocene age (Bartonian or Priabonian; Krach, 1985). In later

molluscan studies, Krach indicated a Priabonian to Bartonian age for the Popiele Member (Krach, 1985).

The foraminifera and nannoplankton assemblages from the Popiele Member in Ukraine were studied by Garecka et al. (2008). Based on nannoplankton, the age of this lithostratigraphic unit was determined to be Upper Eocene to lowermost Oligocene, similar to the Globigerina Marl Member. The presence of species such as *Clausiococcus subdistichus*, *Isthmolithus recurvus*, *Lanternithus minutus*, *Reticulofenestra lockeri*, *R. ornata* and *R. umbilica* indicates a Lower Oligocene age. The foraminiferal assemblages also point towards an age around the Eocene–Oligocene boundary (Garecka et al., 2008).

Other palaeontological studies of the Popiele Member are generally indicative of a nearshore shelf setting. The Popiele Member from Koniusza (Gedl, 2013) varies in terms of lithology, is similar as regards the dinoflagellate cyst assemblages. There, dark mudstones (similar to the greenish shales from Aksamnice), were deposited near to shore; in both cases, there was a notable freshwater influence. According to Krach (1985), bivalve and gastropod assemblages suggest sedimentation took place in the neritic zone, slightly below a depth of 100 m.

### MENILITE FORMATION

At the Aksamnice exposure the Menilite Formation consists of successive dark brown cherts (Kotów Chert Member), grey siliceous marls (Dynów Marl Member) and black siliceous shales with thin-bedded sandstones (Rudawka Tractionites Member). By contrast, at Koniusza the formation begins with dark brown calcareous shales and thin-bedded sandstones (Gedl, 2013), overlain by dark cherts (Kotów Chart Member; Kotłarczyk and Leśniak, 1990). This suggests that the shale layers studied by Gedl (2013) belong to the so-called 'sub-chert beds'. Siliceous marls are absent.

Most palaeontological age determinations of the Menilite Formation are based on foraminifera (Geroch et al., 1967; Olszewska, 1982, 1985, 1997) and calcareous nannoplankton (Garecka and Malata, 2001; Garecka, 2008, 2012). The Dynów Marl Member in the Paratethys region is correlated with the lower part of NP23 zone, based on a nannoplankton event: a bloom of *Reticulofenestra ornata* (Krhovský, 1981, 1998; Krhovský et al., 1992; Schulz et al., 2004; Melinte, 2005; Švábenická et al., 2007).

In the lower Menilite Formation (cherts and marls at Aksamnice and dark shales at Koniusza), dinoflagellate cysts are rare or practically absent and covered by AOM, so their taxonomic classification cannot be assessed. Rare specimens of *Wetzeliiella gochtii* were found in the lowest Menilite Formation above the Globigerina Marls at the Krosno exposure (Silesian Nappe; van Couvering et al., 1981), which indicates an Early Oligocene age. However, *W. gochtii* and *W. symmetrica* were found in Late Eocene deposits in the Magura Nappe of the Polish Carpathians (Folusz section; Gedl, 2005). This is consistent with observations from the Silesian Nappe (Znamirovice section, Fig. 1B), where *W. gochtii* was found in the Globigerina Marl Member within Zone NP19–NP20 (van Couvering et al., 1981). In the North Alpine Foreland basin in southern Germany *W. gochtii* was reported in the Late Eocene Deutenhausen Formation (turbiditic deposits; van der Boon et al., 2018). Furthermore, a Late Eocene first appearance of this taxon has also been proposed based on research in the Mediterranean region (e.g., Brinkhuis, 1994; Coccioni et al., 2000).

The results of dinoflagellate age determinations for the lower Menilite Formation support the results of foraminiferal studies (Olszewska, 1982, 1985, 1997).

Cherts from the Kotów Chert Member are devoid of foraminifera (Olszewska, 1985) and contain only severely damaged calcareous nannoplankton specimens (Garecka, 2012) which makes age determinations impossible. Black shales from layers above the chert horizon contain dinoflagellate cysts typical of the Rupelian. The foraminiferal assemblages from this part of the Menilite Formation are consistent with an the Early Oligocene age, in part because of the occurrence of the index taxon *Tenuitella liverovskae* (Olszewska, 1985). According to Garecka (2012), this lower Menilite Formation represents Zone NP23.

An equivalent of the Menilite Formation in the southern Magura Nappe is the Smereczek Shale Member, which overlies the Leluchów Marl Member – the equivalent of the Globigerina Marl Member (Malcov Formation; Fig. 2; Birkenmajer and Oszczypko, 1989). Based on the occurrence of *Wetzelialla gochtii* just below the base of this unit (Leluchów section), the age of this member was assigned by Gedl (2004) to the Early Oligocene.

Similar results were obtained for another equivalent of the lower Menilite Formation – the Lower Dysodilic Shale Formation in Romania (Tarcău Nappe; Tabăra et al., 2015). In both the Menilite and the Lower Dysodilic formations, the following taxa were reported: *Wetzelialla gochtii*, *Rhombodinium draco*, *Cordosphaeridium gracile*, *Deflandrea phosphoritica*, *Thalassiphora pelagica*, and *Palaeocystodinium golzowense*. These dinocyst assemblages indicate a Rupelian to Lower Chattian age.

Oligocene dinoflagellate cysts from the Menilite Formation may be compared with those described from the Podhale Paleogene Flysch (Fig. 1B; Central Carpathian Paleogene Basin, Central Paratethys; Gedl, 2000). In the Menilite Formation, dinocysts are less abundant than in the Podhale Flysch. Based on similar taxa, the Menilite Formation may be compared with the Zakopane and Szaflary beds. The Szaflary and Zakopane beds were assigned to the Rupelian based on the presence of the following species: *Wetzelialla symmetrica*, *W. gochtii* and *Chiropteridium lobospinosum*. These observations suggest a parallel interval of sedimentation, but with different palaeoenvironmental conditions in these two basins. Poor dinocyst assemblages in the Menilite Formation reflect unfavorable living conditions in the basins of the Outer Carpathians relative to the Central Carpathian Basin.

Palaeoenvironmental interpretations based on foraminifera (Olszewska, 1985) are similar to those from dinocyst assemblages. Foraminiferal assemblages, consisting mainly of *Globigerina* and in smaller amounts *Turborotalia*, point towards deposition in the shallow regions of the pelagic zone (water depth, 20–200 m). The dominance of one taxon (*Globigerina*) suggests high productivity, and a lack of benthic foraminifera suggests anoxic conditions at the sediment-water interface. The occurrence of easily adaptable species may imply climatic cooling.

Similar results were obtained by Bobrinskaya et al. (1998) in the Ukrainian Flysch Carpathians. In addition, the development of small, smooth-walled species of *Globigerina* and *Turborotalia* in the earliest Oligocene was noted.

Several lines of evidence suggesting shallow water depths, decreased salinity and eutrophication during the Eocene–Oligocene transition are in accordance with analyses of calcareous nannoplankton assemblages from the lower Menilite Formation (Garecka, 2012). The Dynów marls are rich in species such as *Reticulofenestra ornata* and *R. tokodensis*, which are indicative of high nutrient levels and decreased salinity. The same species are abundant in dark shales lying above the marls, coexisting with other taxa with similar environmental preferences (*Transversopontis fibula*, *Reticulofenestra lockeri*). Interpretations of a nearshore environment are supported by

the presence of *Pontosphaera latelliptica* and *P. multipora*, which are particularly abundant in dark shales. The large number of *D. bisectus* and *Dictyococcites scripsae* also point to a nearshore environment with an increased supply of nutrients. During deposition of the lower Menilite Formation, a decrease in warm water species (e.g., *Discoaster barbadiensis*) and increase in cold water taxa (e.g., *Lanternithus minutus*) was observed, which is consistent with a gradual climatic cooling.

## CONCLUSIONS

The specific composition and abundance of dinocysts in the Aksamnice section has a clear correlation with the sediment composition in the succession. Dinoflagellate cysts are frequent in the brown mudstones and glauconitic sandstones, relatively rare in the black shales and almost absent in the siliceous deposits (cherts, siliceous marls and siliceous lenses within the mudstones).

The Popiele Member is characterized by a rich dinoflagellate cyst assemblage, in contrast to the overlying Menilite Formation. A distinct reduction in abundance and diversity of dinocyst taxa is observed in the Menilite Formation. In the Kotów Chert Member, dinoflagellate cysts are nearly absent and poorly preserved. The Dynów Marl Member is composed almost entirely of AOM. However, the Rudawka Tractionites Member did yield well-preserved dinoflagellate cysts.

Dinocyst taxa indicate that the Popiele Member was deposited during the Late Eocene (Priabonian), based on the presence of *Areosphaeridium diktyoplokum*, *Enneadocysta pectiniformis* and *Lentinia serrata*. The Menilite Formation (including the Kotów Cherts, Dynów Marls and the Rudawka Tractionite) formed during the Lower Oligocene.

The lowermost Rudawka Tractionites Member coincides with dinocyst Zones D13–D14 (Lower Rupelian), based on the occurrence of *Wetzelialla gochtii*, *W. symmetrica*, *Chiropteridium galea* and *Rhombodinium draco*. The mudstones and the upper Rudawka Tractionites Member were attributed to the Upper Rupelian (Zone D15a), due to the presence of *Wetzelialla gochtii*, *Chiropteridium galea*, and *Enneadocysta pectiniformis*.

The dinocyst assemblages show that both lithostratigraphic units, the Popiele Member and the Menilite Formation, were deposited in inner shelf environments. The green shales from the Popiele Member probably accumulated in a more distal setting than the Menilite Formation, as indicated by the occurrence of more oceanic taxa (for instance, *Impagidium* and *Nematosphaeropsis*) in the Popiele Member. The Menilite Formation (Kotów Chert, Dynów Marl and the Rudawka Tractionites members) accumulated closer to the shore, as open sea taxa are absent (or nearly absent) and shallow-water taxa (peridinoids) are more abundant. The increase in abundance of peridinoids indicates the onset of eutrophication and oxygen deprivation in this basin during basal Menilite Formation sedimentation. It coincides with a sedimentary color change, from the pale green shales of the Popiele Member to the dark brown or black shales of the Menilite Formation. The environment in which the Menilite Formation was deposited was more influenced by river mouths than that of the Popiele Member, leading to elevated nutrient levels and an increased presence of terrestrial material.

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## REFERENCES

- Andreeva-Grigorovich, A.S., 1991.** Phytoplankton (dinocyst and nanoplankton) zonal stratigraphy of the Paleogene of southern USSR. Ph.D. thesis (in Russian). The Academy of Sciences of the USSR, Institute of Geological Science, Kiev.
- Andreeva-Grigorovich, A.S., (as Andreyeva-Grigorovich), Gruzman, A.D., 1994.** The biostratigraphic basis of the Paleogene–Neogene boundary in the Central (Ukrainian Carpathians) and Eastern (Black Sea depression, Northern Caucasus) Paratethys. *Geologica Carpathica*, **45**: 333–342.
- Báldi, T., 1980.** The early history of the Paratethys. *Földtani Közlöny, Bulletin of the Hungarian Geological Society*, **110**: 456–472.
- Báldi, T., 1984.** The terminal Eocene and Early Oligocene events in Hungary and the separation of an anoxic, cold Paratethys. *Eclogae Geologicae Helveticae*, **30**: 1–27.
- Báldi, T., 1989.** Tethys and Paratethys through Oligocene times. Remarks to a comment. *Geologický Zborník – Geologica Carpathica*, **40**: 85–99.
- Bujak, J.P., 1984.** Cenozoic dinoflagellate cysts and acritarchs from the Bering Sea and northern North Pacific. D. S. D. P. Leg 19. *Micropaleontology*, **30**: 180–212.
- Birkenmajer, K., Oszczypko, N., 1989.** Cretaceous and Palaeogene lithostratigraphic units of the Magura Nappe, Krynica Subunit, Carpathians. *Annales Societatis Geologorum Poloniae*, **59**: 145–181.
- Bobinskaya, O.G., Gruzman, A.D., Krasheninnikov, V.A., Serova, M.Y., Venglynskiy, I.V., 1998.** Stratigraphy of the Oligocene and Miocene deposits of the western Ukraine and Moldavia. *Ahandlungen der Senckenbergischen Naturforschenden Gesellschaft*, **549**: 34–43.
- Brinkhuis, H., 1994.** Late Eocene to Early Oligocene dinoflagellate cysts from the Priabonian type-area (Northeast Italy): biostratigraphy and palaeoenvironmental interpretation. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **107**: 121–163.
- Châteauneuf, J.-J., 1980.** Palynostratigraphie et paléoclimatologie de l'Eocene supérieur et de l'Oligocene du Bassin de Paris (France). *Bulletin du Bureau de recherches géologiques et minières*, **116**: 1–360.
- Coccioni, R., Basso, D., Brinkhuis, H., Galeotti, S., Gardin, S., Monechi, S., Spezzaferri, S., 2000.** Marine biotic signals across a late Eocene impact layer at Massignano, Italy: evidence for long-term environmental perturbations? *Terra Nova*, **12**: 258–263.
- Costa, L.I., Downie, C., 1976.** The distribution of the dinoflagellate *Wetzeliella* in the Palaeogene of north-western Europe. *Palaeontology*, **19**: 591–614.
- Costa, L.I., Manum, S.B., 1988.** The description of the interregional zonation of the Paleogene (D1–D15) and the Miocene (D16–D20). *Geologisches Jahrbuch*, **A100**: 321–342.
- Dale, B., 1996.** Dinoflagellate cyst ecology: modelling and geological applications. In: *Palynology: Principles and Applications* (eds. J. Jansonius and D.C. McGregor), **3**: 1249–1275. American Association of Stratigraphic Palynologists Foundation, Dallas, Texas.
- Dźułyński, S., Kotlarczyk, J., 1965.** Sedimentation of the Popiele beds in the Polish Carpathians. *Rocznik Polskiego Towarzystwa Geologicznego*, **35**: 103–105.
- Filipek, A., Wysocka, A., Barski, M., 2017.** Depositional setting of the Oligocene sequence of the Western Carpathians in the Polish Spisz region – a reinterpretation based on integrated palynofacies and sedimentological analyses. *Geological Quarterly*, **61** (4): 859–876.
- Garecka, M., 2008.** Oligocene/Miocene boundary in the Polish Outer Carpathians based on calcareous nanoplankton (in Polish with English summary). *Biuletyn Państwowego Instytutu Geologicznego*, **432**: 1–54.
- Garecka, M., 2012.** Record of changes in the Oligocene–Miocene sediments of the Menilite–Krosno series of the Skole Unit based on calcareous nanoplankton studies – biostratigraphy and paleogeographical implications (Polish Outer Carpathians). *Biuletyn Państwowego Instytutu Geologicznego*, **453**: 1–22.
- Garecka, M., Malata, T., 2001.** Nanoplankton wapienny serii menilitowo-krośnieńskiej jednostki skolskiej (rejon na północ od Leska) (in Polish). *Posiedzenia Naukowe Państwowego Instytutu Geologicznego*, **57**: 89–91.
- Garecka, M., Jankowski, L., Szydio, A., 2008.** Spływowe osady paleogenu wschodnich Karpat zewnętrznych w strefie przygranicznej Polski i Ukrainy (in Polish). In: *Pierwszy Polski Kongres Geologiczny, Kraków 26–28 czerwca 2008, Abstrakty* (ed. G. Haczewski): 28–29. *Polskie Towarzystwo Geologiczne, Kraków*.
- Gaździcka, E., 2001.** Stages of Skole sedimentary basin evolution in the Cretaceous and early Paleogene – nanoplankton record (in Polish with English summary). *Przegląd Geologiczny*, **49**: 449–451.
- Gedl, P., 1998.** The age of Podhale flysch based on dinocysts (in Polish with English summary). *Przegląd Geologiczny*, **46**: 45–46.
- Gedl, P., 1999.** Palynology of the Eocene–Oligocene boundary in the Polish Flysch Carpathians – preliminary results (in Polish with English summary). *Przegląd Geologiczny*, **47**: 394–398.
- Gedl, P., 2000.** Biostratigraphy and palaeoenvironment of the Podhale Palaeogene (Inner Carpathians, Poland) in the light of palynological studies. Part I (in Polish with English summary). *Studia Geologica Polonica*, **117**: 69–154.
- Gedl, P., 2004.** Dinoflagellate cyst record of the Eocene–Oligocene boundary succession in flysch deposits at Leluchów, Carpathian Mountains, Poland. *Geological Society Special Publications*, **230**: 309–324.
- Gedl, P., 2005.** Late Eocene–early Oligocene organic-walled dinoflagellate cysts from Folusz, Magura Nappe, Polish Carpathians. *Acta Palaeobotanica*, **45**: 27–83.
- Gedl, P., 2013.** Eocene dinoflagellate cysts from the Popiele beds at Koniusza (Skole Nappe, Flysch Carpathians, Poland): taxonomy, biostratigraphy, and palaeoenvironmental reconstruction of a marginal marine basin. *Studia Geologica Polonica*, **136**: 5–197.
- Gedl, P., Leszczyński, S., 2005.** Palynology of the Eocene–Oligocene transition in the marginal zone of the Magura Nappe at Folusz (Western Carpathians, Poland). *Geologica Carpathica*, **56**: 155–167.
- Geroch, S., Jednorowska, A., Książkiewicz, M., Liszkowa, J., 1967.** Stratigraphy based upon foraminifera of the western Polish Carpathians. *Instytut Geologiczny, Biuletyn*, **211**: 185–267.
- Geroch, S., Nowak, W., 1984.** Proposal of zonation for the Late Tithonian–Eocene, based upon the arenaceous foraminifera from the outer Carpathians, Poland. In: *Benthos '83; 2nd International Symposium on Benthic Foraminifera, Pau (France)* (ed. H.J. Oertli): 225–239. April 11–15, 1983. Esso REP: and Total CFP. Pau and Bordeaux.
- Golonka, J., Krobicki, M., Oszczypko, N., Słomka, T., 2003.** Early stages of the Carpathian basins development. *Mineralia Slovaca*, **35**: 4–6.
- Gradstein, F.M., Ogg, J.G., 2004.** A Geologic Time Scale 2004 – why, how, and where next! *Lethaia*, **37**: 175–181.
- Gradstein, F.M., Ogg, J.G., Smith, A.G., 2004.** A Geologic Time Scale 2004. Cambridge University Press.
- Gradstein, F.M., Ogg, J.G., Schmitz, M.D., Ogg, G.M., 2012.** A Geologic Time Scale 2012. Cambridge University Press.
- Grzybowski, J., 1894.** Mikrofauna piaskowca karpackiego z pod Dukli (in Polish). *Rozprawy Wydziału Matematyczno-przyrodniczego, Akademia Umiejętności w Krakowie*, **2**: 181–214.
- Grzybowski, J., 1898.** Otwornice pokładów naftonośnych okolicy Krosna (in Polish). *Rozprawy Wydziału Matematyczno-przyrodniczego, Akademia Umiejętności w Krakowie*, **2**: 257–305.
- Haq, B.U., Hardenbol, J., Vail, P.R., 1987.** Chronology of fluctuating sea levels since the Triassic. *Science*, **235**: 1156–1167.

- Jankowski, L., Kopciowski, R., Ryłko, W., Danysh, V., Tsarnenko, P. N., Hnylko, O., 2012. Lithostratigraphic correlation of the Outer Carpathian borderlands of Poland, Ukraine, Slovakia and Romania. *Biuletyn Państwowego Instytutu Geologicznego*, **449**: 87–98.
- Jerzmańska, A., 1958. Status of research on Tertiary fishes in Poland (in Polish with English summary). *Kwartalnik Geologiczny*, **2** (1): 177–186.
- Jerzmańska, A., 1960. Ichthyofauna from the Jasło shales at Sobniów (in Polish with English summary). *Acta Palaeontologica Polonica*, **5**: 367–425.
- Jerzmańska, A., 1968. Ichthyofaune des couches à ménilite (flysch des Karpathes). *Acta Palaeontologica Polonica*, **13**: 379–488.
- Jerzmańska, A., Kotlarczyk, J., 1976. The beginnings of the Sargasso assemblage in the Tethys? *Palaeogeography, Palaeoclimatology, Palaeoecology*, **20**: 297–306.
- Kotlarczyk, J., 1988. Problemy sedimentologii, stratygrafii i tektoniki Karpat Przemyskich oraz ich najbliższego przedpola (in Polish). In: *Karpaty Przemyskie* (eds. J. Kotlarczyk, K. Pękala and S. Gucik). *Przewodnik 59 Zjazdu Polskiego Towarzystwa Geologicznego, Przemysł*, 16–18.IX.1988, Państwowy Instytut Geologiczny, Wydawnictwo Akademii Górniczo-Hutniczej, Kraków.
- Kotlarczyk, J., Leśniak, T., 1990. Lower part of the Menilite Formation and related Futoma diatomite member in the Skole unit of the Polish Carpathians (in Polish with English summary). *AGH, Instytut Geologii i Surowców Mineralnych. Wydawnictwa własne*.
- Kotlarczyk, J., Jerzmańska, A., 1976. The beginnings of the Sargasso assemblage in the Tethys? *Palaeogeography, Palaeoclimatology, Palaeoecology*, **20**: 297–306.
- Kotlarczyk, J., Uchman, A., 2012. Integrated ichnology and ichthyology of the Oligocene Menilite Formation, Skole and Subsilesian nappes, Polish Carpathians: a proxy to oxygenation history. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **331–332**: 104–118.
- Kotlarczyk, J., Jerzmańska, A., Świdnicka, E., Wiszniowska, T., 2006. A framework of ichthyofaunal ecostratigraphy of the Oligocene–Early Miocene strata of the Polish Outer Carpathian basin. *Annales Societatis Geologorum Poloniae*, **76**: 1–111.
- Köthe, A., Piesker, B., 2007. Stratigraphic distribution of Paleogene and Miocene dinocysts in Germany. *Revue de Paléobiologie*, **26**: 1–39.
- Krach, W., 1985. The Eocene mollusk fauna from Koniusza near Przemysł (Polish Eastern Carpathians) (in Polish with English summary). *Annales Societatis Geologorum Poloniae*, **55**: 139–190.
- Krhovský, J., 1981. Microbiostratigraphic correlations in the Outer Flysch Units of the southern Moravia and influence of the eustasy on their palaeogeographical development. *Zemny Plyn a Nafta*, **26**: 665–688.
- Krhovský, J., 1998. Geology, stratigraphy and palaeoenvironment of the Southern-Moravian Flysch Belt. *Abhandlungen der Senckenbergischen Naturforschenden Gesellschaft*, **549**: 18–23.
- Krhovský, J., Adamowa J., Hladikow, J., Masłowska, H., 1992. Palaeoenvironmental changes across the Eocene–Oligocene boundary in the Ždanice Pouzdrany Units (Western Carpathians, Czechoslovakia): the long-term trend and orbitally forced changes in calcareous nannofossil assemblages. In: *Nannoplankton research* (eds. B. Harmšmid and J. Young). *Proceedings of the 4th INA Conference, Praga, 1991. Knih. ZPN*, **14b/2**: 189–221.
- Książkiewicz, M., ed., 1962. *Atlas geologiczny Polski – Zagadnienia stratygraficzno-facjalne*. 1:600 000, z. 13. Kreda i starszy trzeciorzęd w Polskich Karpatach Zewnętrznych (in Polish). Instytut Geologiczny, Warszawa.
- Laskarev, V., 1924. Sur les equivalents du Sarmatien superieur en Serbie. In: *Receuil de travaux offert à M. Jo- van Cvijic par ses amis et collaborateurs* (ed. P. Vujević): 73–85. Drzhavna Shtamparija, Beograd.
- Leszczyński, S., Malata, E., 2002. Sedimentary conditions in the Siary zone of the Magura basin (Carpathians) in the late Eocene–early Oligocene. *Annales Societatis Geologorum Poloniae*, **72**: 201–239.
- Melinte, M., 2005. Oligocene palaeoenvironmental changes in Romanian Carpathians, revealed by calcareous nannofossils. *Studia Geologica Polonica*, **124**: 341–352.
- Miller, K.G., Wright, J.D., Katz, M.E., Wade, B.S., Browning, J.V., Cramer, B.S., Rosenthal, Y., 2009. Climate threshold at the Eocene–Oligocene transition: Antarctic ice sheet influence on ocean circulation. *Geological Society of America Special Papers*, **452**: 169–178.
- Olszewska, B., 1982. Some remarks on biostratigraphy of the Menilite–Krosno Series in the Polish Outer Carpathians (in Polish with English summary). *Kwartalnik Geologiczny*, **26** (1): 137–145.
- Olszewska, B., 1985. Foraminifera of the Menilite Beds (Polish External Carpathians) (in Polish with English summary). *Rocznik Polskiego Towarzystwa Geologicznego*, **55**: 201–250.
- Olszewska, B., 1997. Foraminiferal biostratigraphy of the Polish Outer Carpathians: a record of basin geohistory. *Rocznik Polskiego Towarzystwa Geologicznego*, **67**: 325–337.
- Oszczypko-Clowes, M., Żydek, B., 2012. Paleocology of the Upper Eocene–Lower Oligocene Malcov Basin based on the calcareous nannofossils: a case study of the Leluchów section (Krynica Zone, Magura Nappe, Polish Outer Carpathians). *Geologica Carpathica*, **63**: 149–164.
- Popadyuk, I., Vul, M., Ladyzhensky, Y., Shpak, P., 2006. Petroleum geology of the Boryslav–Pokuttya zone, the Ukrainian Carpathians. *AAPG Memoir*, **84**: 455–466.
- Powell, A.J., 1992. Dinoflagellate cysts of the Tertiary System. In: *A Stratigraphic Index of Dinoflagellate Cysts* (ed. A.J. Powell). *British Micropalaeontological Society Publication Series*. Chapman & Hall, London.
- Pross, J., Brinkhuis, H., 2005. Organic-walled dinoflagellate cysts as paleoenvironmental indicators in the Paleogene: a synopsis of concepts. *Paläontologische Zeitschrift*, **79**: 53–59.
- Rajchel, J., 1990. Lithostratigraphy of the Upper Palaeocene and Eocene sediments from the Skole Unit (in Polish with English summary). *Zeszyty naukowe AGH, Geologia*, **48**: 1–112.
- Rogala, W., 1925. *Materiaux pour la géologie de Karpathes*. III. Le faune et l'âge des "couches" de Popiele (in Polish with French summary). *Kosmos*, **30**: 932–939.
- Roth, Z., Hanzlíková, E., 1982. Palaeotectonic and palaeoecological position of the Menilitic Formation in the Carpathian Mts. *Časopis pro Mineralogii a Geologii*, **27**: 113–126.
- Rusu, A., 1988. Oligocene events in Transylvania (Romania) and the first separation of Paratethys. *Dari Seama, Institute of Geology and Geophysics*: 72–73, 207–223.
- Sachsenhofer, R.F., Popov, S.V., Coric, S., Mayer, J., Misch, D., Morton, M.T., Pupp, M., Rauball, J., Tari, G., 2018. Paratethyan petroleum source rocks: an overview. *Journal of Petroleum Geology*, **41**: 219–246.
- Schulz, H.M., Bechtel, A., Rainer, T., Sachsenhofer, R.F., Struck, U., 2004. Paleooceanography of the western Central Paratethys during nannoplankton zone NP23: The Dynow Marlstone in the Austrian Molasse Basin. *Geologica Carpathica*, **55**: 311–323.
- Stover, L.E., Brinkhuis, H., Damassa, S.P., de Verteuil, L., Helby, R.J., Monteil, E., Partridge, A.D., Powell, A.J., Riding, J.B., Smelror, M., Williams, G.L., 1996. Mesozoic–Tertiary dinoflagellates, acritarchs and prasinophytes. *Palynology*, **2** (eds. J. Jansonius and D.C. McGregor): 641–750. *American Association of Stratigraphic Palynologists Foundation*, Dallas, Texas.
- Ślącza, A., Kruglow, S., Golonka, J., Oszczypko, N., Popadyuk, I., 2006. Geology and hydrocarbon resources of the Outer Carpathians, Poland, Slovakia, and Ukraine: the general geology of the Outer Carpathians, Poland, Slovakia, and Ukraine. *AAPG Memoir*, **84**: 221–258.
- Švábenická, L., Bubík, M., Stráník, Z., 2007. Biostratigraphy and paleoenvironmental changes on the transition from the Menilite to Krosno lithofacies (Western Carpathians, Czech Republic). *Geologica Carpathica*, **58**: 237–262.
- Ťabără, D., Pacton, M., Makou, M., Chirilă, G., 2015. Palynofacies and geochemical analysis of Oligo–Miocene bituminous rocks

- from the Moldavidian Domain (Eastern Carpathians, Romania): implications for petroleum exploration. *Review of Palaeobotany and Palynology*, **216**: 101–122.
- Van Couvering, J.A., Aubry, M.P., Berggren, W.A., Bujak, J.P., Naeser, C.W., Wieser, T., 1981.** The terminal Eocene event and the Polish connection. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **36**: 321–362.
- Van der Boon, A., Gaździcka, E., Ciurlej, A., Krijgsman, W., Langereis, C.G., Sachsenhofer, R.F., Grothe, A., Beniest, A., 2018.** The Eocene-Oligocene transition in the North Alpine Foreland Basin and subsequent closure of a Paratethys gateway. *Global and Planetary Change*, **162**: 101–119.
- Vasilyeva, O., Musatov, V., 2012.** The Paleogene Dinoflagellate Cyst and Nannoplankton Biostratigraphy of the Caspian Depression. *Stratigraphic Analysis of Layered Deposits* (ed. Ó. Elitok), doi: 10.5772/34019
- Williams, G.L., Brinkhuis, H., Pearce, M.A., Fensome, N.A., Weegink, J.W., 2004.** Southern Ocean and global dinoflagellate cyst events compared: index events for the late Cretaceous-Neogene. *Proceedings of the Ocean Drilling Program, Scientific Results*, **189**: 1–98.
- Wilpshaar, M., Santarelli, A., Brinkhuis, H., Visscher, H., 1996.** Dinoflagellate cysts and mid-Oligocene chronostratigraphy in the central Mediterranean region. *Journal of the Geological Society, London*, **153**: 553–561.
- Wiśniowski, T., 1908.** Atlas geologiczny Galicji (in Polish). Tekst do zeszytu XXI. Kraków.
- Zachos, J.C., Pagani, M., Sloan, L.C., Thomas, E., Billups, K., 2001.** Trends, rhythms, and aberrations in global climate 65 Ma to present. *Science*, **292**: 686–693.
- Żytko, K., Gucik, S., Oszczytko, N., Zając, R., Garlicka, I., Nemčok, J., Eliaš, M., Menčík, E., Dvorak, J., Stranik, Z., Rakuš, M., Matejovska, O., 1989.** Geological map of the Western Outer Carpathians and their foreland without Quaternary formations. In: *Geological Atlas of the Western Carpathians and their Foreland*. 1:500 000 (eds. D. Poprawa and J. Nemčok). Państwowy Instytut Geologiczny, Warszawa.