

Environmental conditions in a Carpathian deep sea basin during the period preceding Oceanic Anoxic Event 2 — a case study from the Skole Nappe

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Abstract: Hemipelagic green clayey shales and thin muddy turbidites accumulated in a deep sea environment below the CCD in the Skole Basin, a part of the Outer Carpathian realm, during the Middle Cenomanian. The hemipelagites contain numerous radiolarians, associated with deep-water agglutinated foraminifera. These sediments accumulated under mesotrophic conditions with limited oxygen concentration. Short-term periodic anoxia also occurred during that time. Muddy turbidity currents caused deposition of siliciclastic and biogenic material, including calcareous foraminifera and numerous sponge spicules. The preservation and diversity of the spicules suggests that they originate from disarticulation of moderately diversified sponge assemblages, which lived predominantly in the neritic-bathyal zone. Analyses of radiolarian ecological groups and pellets reflect the water column properties during the sedimentation of green shales. At that time, surface and also intermediate waters were oxygenated enough and sufficiently rich in nutrients to enable plankton production. Numerous, uncompacted pellets with nearly pristine radiolarian skeletons inside show that pelletization was the main factor of radiolarian flux into the deep basin floor. Partly dissolved skeletons indicate that waters in the Skole Basin were undersaturated in relation to silica content. Oxygen content might have been depleted in the deeper part of the water column causing periodic anoxic conditions which prevent rapid bacterial degradation of the pellets during their fall to the sea floor.

Key words: Cenomanian Upper Cretaceous, Polish Outer Carpathians Skole Nappe, environment, Radiolaria, Foraminifera, sponge spicules, pellets.

Introduction

The Skole Nappe is the most external nappe of the Eastern Outer Carpathians in their Polish segment (Fig. 1A,B). It comprises a 3.0–3.8 km thick series of the Lower Cretaceous–Neogene flysch sediments (Poprawa & Nemčok 1998). The Lower Cretaceous strata are represented by silty and clayey turbidites, classified to the Bełwin Mudstones (Hauterivian) and Spas Shales (Hauterivian–Albian). They contain sandy turbidite intercalations of the Kuźmina Sandstones (Fig. 2 — Koszarski & Ślęczka 1973; Kotlarczyk 1978; Gucik 1987; Gucik et al. 1991; Gedl 1999). This series is interpreted as deposits of post-rift thermal subsidence in the Skole Basin, which was a part of the external basins of the Outer Carpathian domain (Książkiewicz 1962; Oszczypko 2004), formed along the European margin in Late Jurassic–Early Cretaceous times (Oszczypko 2006).

The younger succession (Cenomanian in age) contains a series of deep-water hemipelagic non-calcareous shales with calcareous (biogenic) and siliciclastic turbidites. These have been determined as the Barnasiówka Radiolarian Shale Formation (BRSF — Bąk et al. 2001, 2007b,c — Fig. 2). Biogenic-rich-turbidites precede the laminated organic-rich shales and mudstones, which were deposited in the latest

Cenomanian in response to progressive eustatic sea-level rise and expansion of the oxygen minimum zone in the Outer Carpathian basins (Bąk K. 2006, 2007a–c). These organic-rich facies record an oceanic anoxic event (OAE-2), documented by carbon isotope data (Bąk K. 2007b). Such facies also occur in other Outer Carpathian basins in the same stratigraphic position representing a Bonarelli-equivalent horizon (cf. Bąk K. 2007d; Bąk M. 2011).

The OAE-2 sediments are replaced in the Skole Nappe by a ferro-manganese carbonate layer. This layer is a chronohorizon in the Outer Carpathian sediments corresponding to the uppermost Cenomanian–lowermost Turonian (Bąk K. 2007d). Its occurrence was related to the extremely low sedimentation rate in the basin and an increase in deep-water circulation, causing basin oxygenation. This layer forms the base of red non-calcareous shales of the Turonian age (Variegated shales — Fig. 2), which have been deposited mostly under well-oxygenated conditions and contain numerous biogenic particles (Bąk K. 2006, 2007a–c; Okoński et al. 2014).

The above-mentioned Cenomanian succession, classified as the BRSF, reflects the diverse environmental conditions in the Skole Basin, recorded by various facies. The present paper deals with the reconstruction of environmental conditions during the period preceding OAE-2, recorded as the

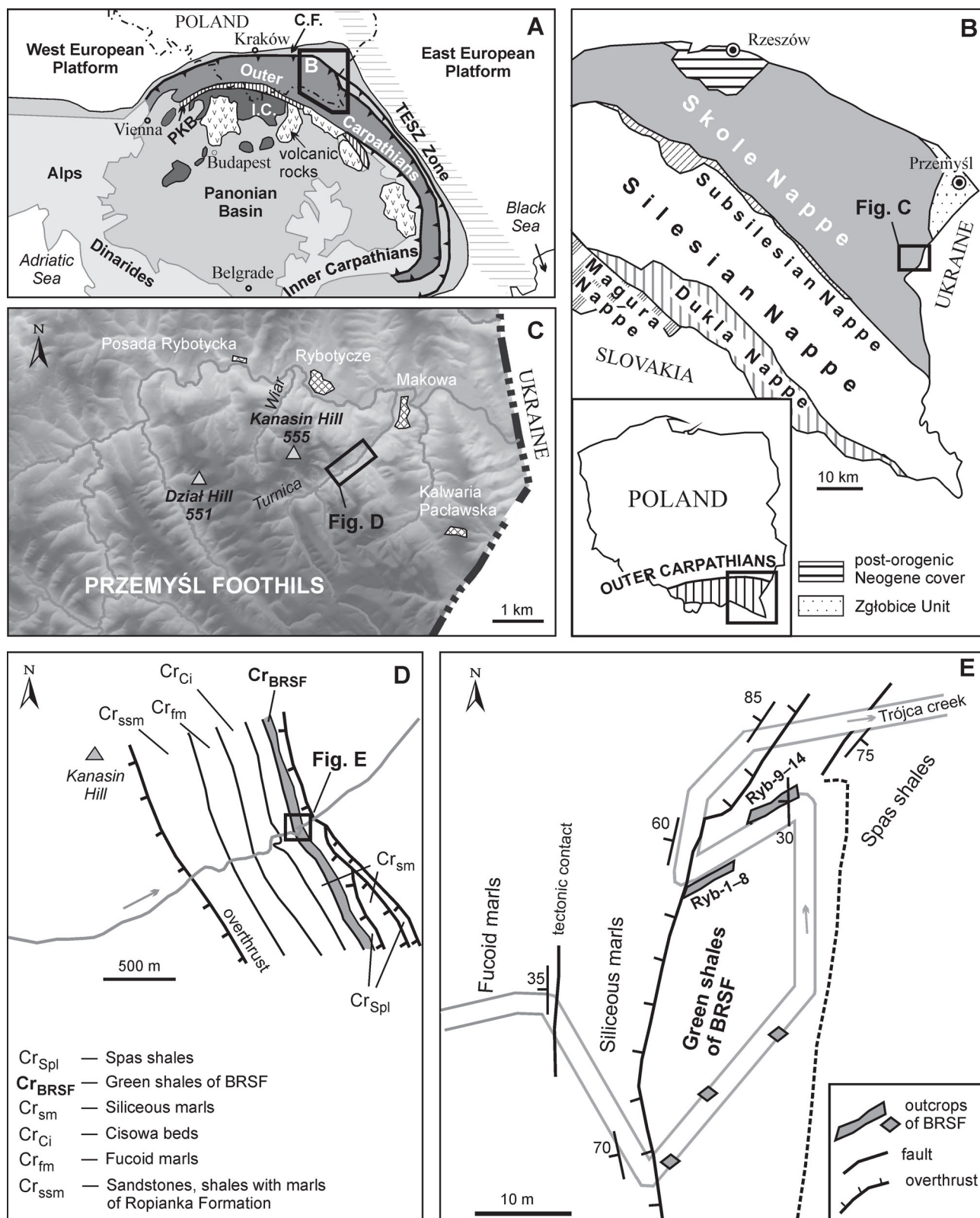


Fig. 1. Location of the study area. **A** — Outer Carpathians against the background of a simplified geological map of the Alpine orogens and their foreland: I.C. — Inner Carpathians, C.F. — Carpathian Foredeep, PKB — Pieniny Klippen Belt, TESS Zone — Trans-European Suture Zone; **B**, **C** — Location of the study area in the Polish part of the Carpathians (**B**), with sketch topographic map of the surroundings of Rybotycze village Przemyśl Foothills (**C** — after Bryndal 2011); **D**, **E** — Geological sketch map of the Trójca creek near the Kanasin Hill (**D** — after Gucik et al. 1991) with location of the studied section and outcrops (**E**).

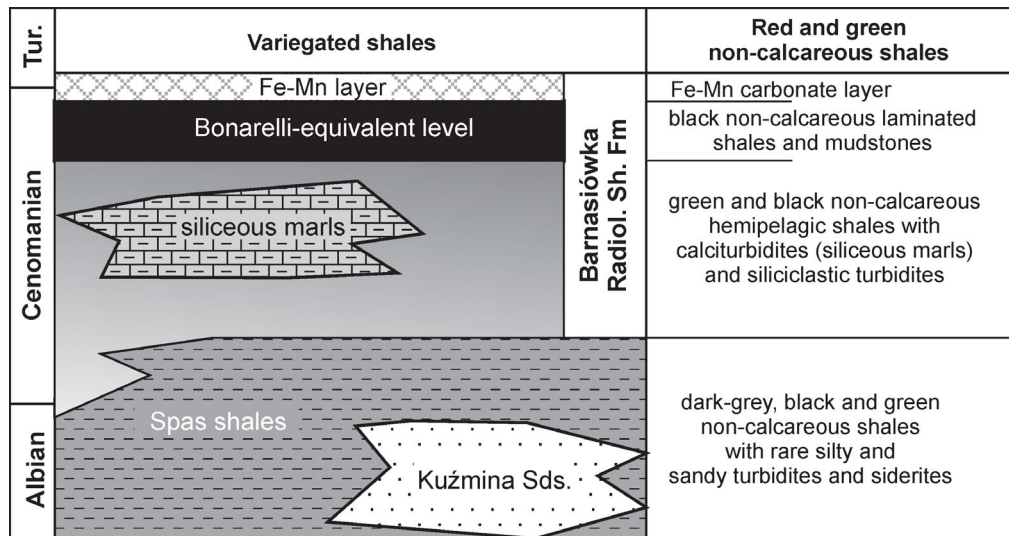


Fig. 2. Lithostratigraphy of the Lower mid-Cretaceous deposits in the Skole Nappe, Polish Outer Carpathians (after Koszarski & Ślęczka 1973; Kotlarczyk 1978; Gucik 1987; Gucik et al. 1991; Bąk 2007a,b).

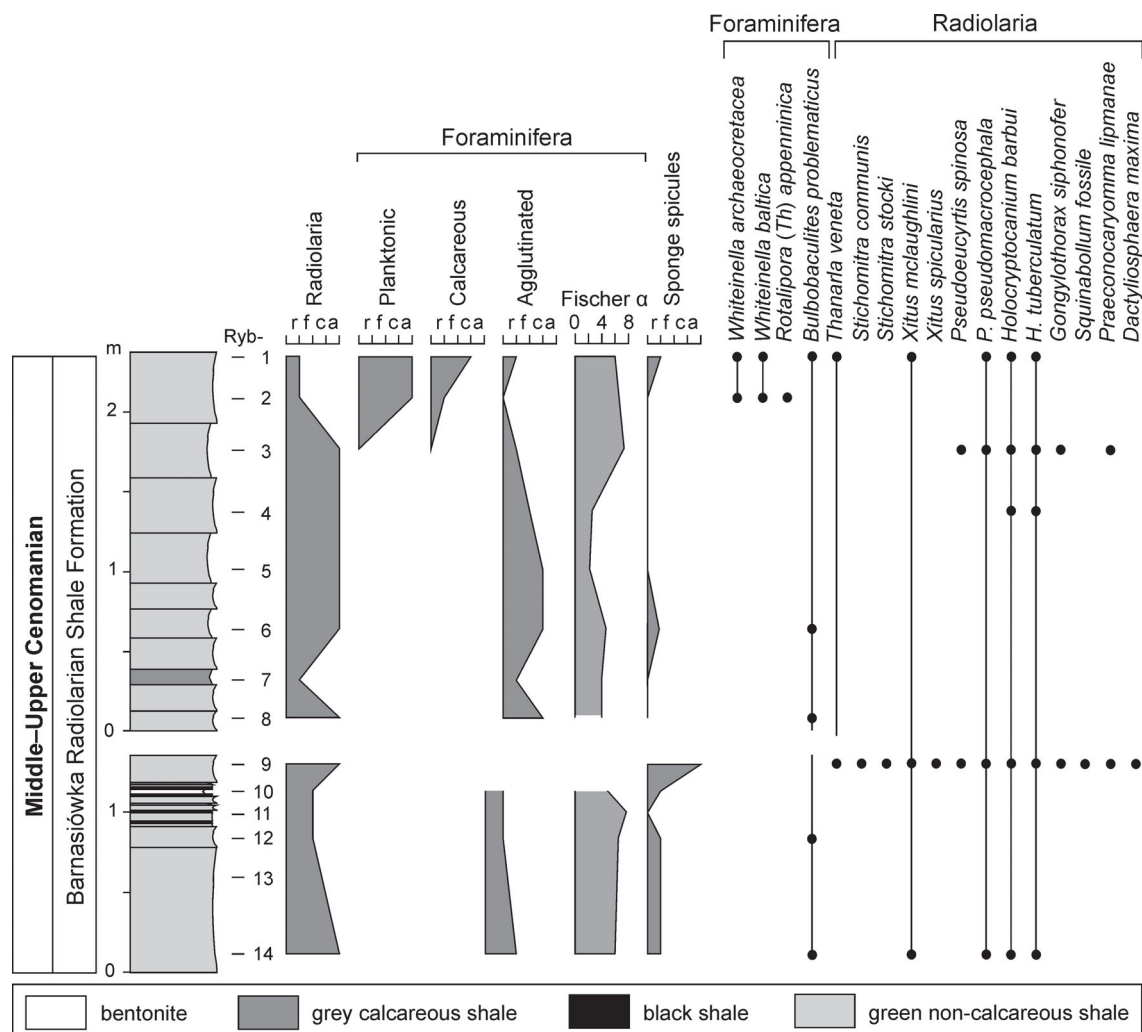


Fig. 3. Lithological log of the Trójca section (Skole Nappe, Polish Outer Carpathians) plotted against radiolarian composition foraminiferal datum events. Number of specimens: r (rare) — 1-5, f (frequent) — 6-10, c (common) — 11-20, a (abundant) — more than 20.

green radiolarian shales with muddy turbidites. Here, we document the micropaleontological record and discuss the detected paleoenvironmental features of the Skole Basin.

Geological setting

The studied section is located in the inner part of the Skole Nappe (Poland), within one of the tectonic scales, on both banks of the Trójca creek (Przemyśl Foothills), near Rybotycze village, about 30 km south of Przemyśl (Fig. 1B–E). In this area, the outcrops of the lower part of the BRSF are limited to several sections, 0.5–4.5 m thick. Two of them (Fig. 1E) have been studied and the results are presented in this paper. The contact between the BRSF and the underlying Spas Shales is tectonic at this locality. The upper and middle parts of the BRSF containing the organic-rich sediments of OAE-2 (Bonarelli-equivalent level — Fig. 2) and the Turonian red non-calcareous shales overlying the BRSF are not exposed here. The BRSF is in tectonic contact with the Turonian siliceous marls here.

Material and methods

A total of 14 samples were collected from the Trójca composite section, with an average sample interval of 30 cm (Fig. 3). Microfossils were extracted by repeated heating and drying of rock samples in a sodium carbonate solution. Residues were dried, washed through sieves with mesh in diameters of 63 µm. Foraminiferal and radiolarian specimens and sponge spicules were manually picked from the fraction 0.063–1.5 mm. Microfacies and pellet analyses were carried out in thin sections.

The microfossil slides and the residual rock samples are housed in the Department of Geology and Geotourism, Faculty of Geology, Geosciences and Environmental Protection,

AGH University of Science and Technology (collection of Marta Bąk).

Results

The studied section contains green non-calcareous clayey shales, a few black clayey shale layers (several millimeters thick) which are partly intercalated with green and grey, thin, muddy turbidites (up to 5 cm thick), which contain siliciclastic and calcareous (biogenic) particles. Among the siliciclastic material, silt-sized quartz grains dominate, and are associated with rare micas (Fig. 4J,K), glauconite (Fig. 4M,N) and Fe-Mn oxides. Redeposited in turbidity currents biogenic particles include siliceous sponge spicules, calcareous benthic and planktonic foraminifers, and fragmented otoliths (Fig. 4C,D,F,G). Biogenic material from non-calcareous hemipelagic clayey shale consists mainly of radiolarian skeletons (Fig. 3) and agglutinated foraminiferal tests. Fish teeth (Fig. 4A,B) were also found sporadically.

Radiolarian assemblages

Radiolaria occur in most of the studied samples of the Trójca section. They are frequent (Fig. 3) but poorly to moderately preserved. Most of the radiolarian skeletons are recrystallized or replaced by pyrite and Fe-oxides, resulting in destruction of external and internal wall structures. With such poor preservation, only 20 % of the skeletons were recognized and classified. Identifiable forms were found in samples Ryb-1, Ryb-3 and Ryb-9 (Fig. 5). As a general tendency, green hemipelagic shales contain higher numbers of better preserved radiolarians, while in dark-grey and black shales, the radiolarians are usually present as pyritized moulds (Fig. 4I).

Eight radiolarian families, nine genera and twelve species have been recognized in the studied material, according to

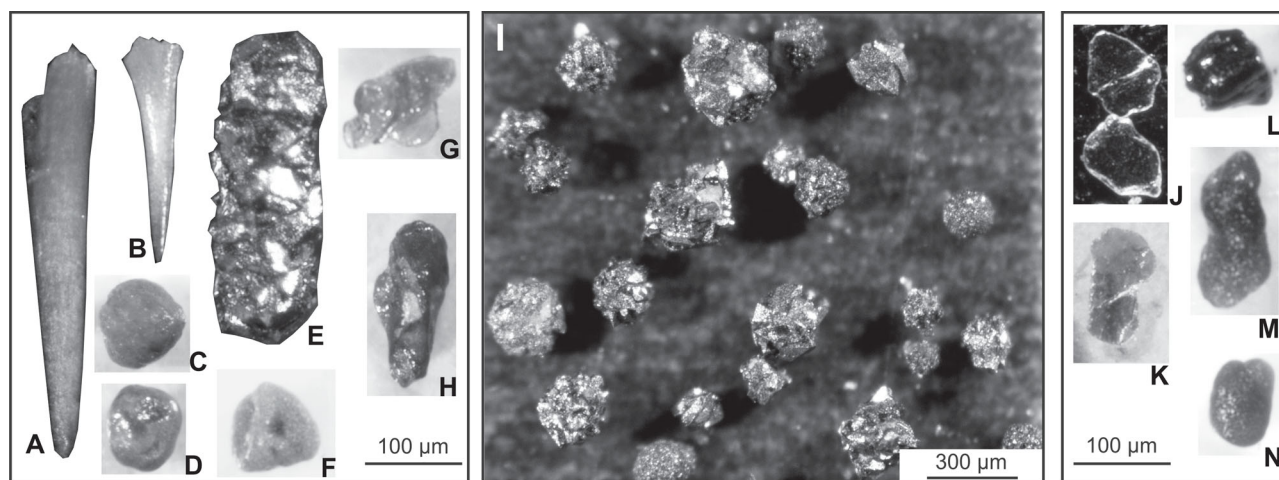


Fig. 4. Organic and mineral components from lower part of the Barnsiówka Radiolarian Shale Formation in the Trójca section (Skole Nappe, Polish Outer Carpathians). **A, B** — fish teeth (**A** — Ryb-10), **B** — Ryb-1); **C, D, F** — otoliths (Ryb-1); **E** — pyritized foraminiferal tube (Ryb-2); **G, H** — otoliths (Ryb-1); **I** — Pyritized skeletons of radiolarians; **J** — Muscovite grains (Ryb-1); **K** — Biotite grain (Ryb-2); **L** — ?Magnetite grain (Ryb-1); **M, N** — Glauconite grains (Ryb-6).

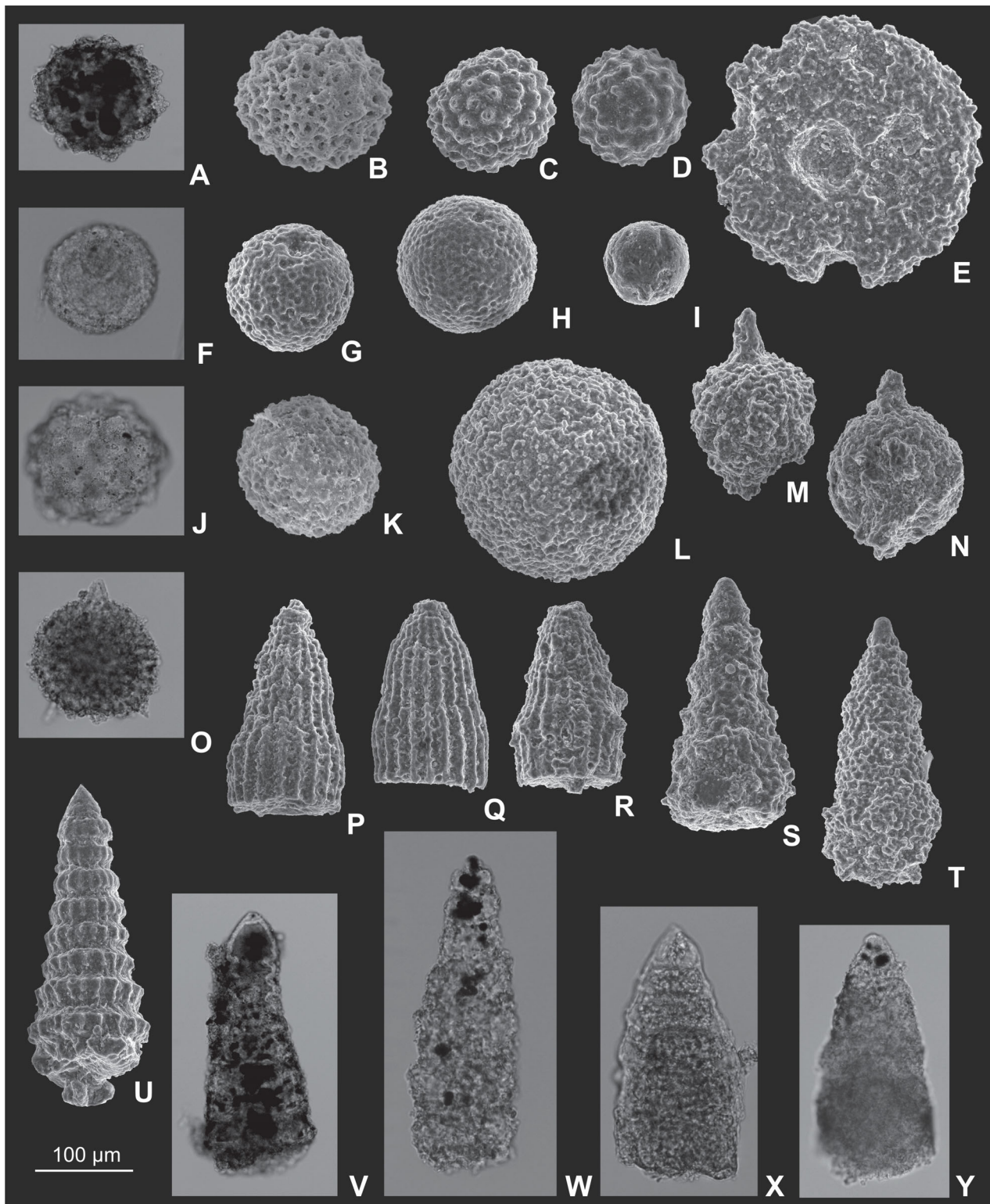


Fig. 5. Radiolarians from lower part of the Barnsiówka Radiolarian Shale Formation in the Trójca section (Skole Nappe, Polish Outer Carpathians). **A, B** — *Praeconocaryomma lipmanae* Pessagno (Ryb-3); **C, D** — *Gongylothorax siphonifer* Dumitrică (Ryb-9); **E** — *Dactyliosphaera maxima* (Pessagno) (Ryb-9); **F–H** — *Holocryptocanium barbui* Dumitrică (Ryb-9), specimens represent different stages of preservation; **I** — Secondary infield moulds after *Holocryptocanium barbui* Dumitrică (Ryb-9); **J–L** — *Holocryptocanium tuberculatum* Dumitrică (Ryb-9); **M, N** — *Pseudoeucyrtis spinosa* (Squinabol) (Ryb-9); **O** — *Squinabollum fossile* (Squinabol) (Ryb-9); **S** — *Xitus mclaughlini* Pessagno (Ryb-9); **T, X** — *Stichomitra communis* Squinabol (Ryb-9); **P–R** — *Thanarla veneta* (Squinabol) (Ryb-9); **U, V** — *Pseudodictyomitra pseudomacrocephala* (Squinabol) (Ryb-9); **W** — *Xitus spicularius* (Aliev) (Ryb-9); **Y** — *Stichomitra stocki* (Campbell & Clark) (Ryb-9).

radiolarian classification proposed by De Wever et al. (2001) and adopted to Carpathian settings by Bák M. (2011). In the whole section, cryptothoracic and cryptocephalic nassellarians are the main components of radiolarian assemblages. The species from the family Willriedellidae prevail, with most common *Holocryptocanium barbui* Dumitrică — (Fig. 5F–I), which is a dominate taxon in the mid- to late Cenomanian in Western Tethyan settings (Bák M. 2011), associated with specimens of *Holocryptocanium tuberculatum* Dumitrică — (Fig. 5J–L). These two species may consist even 70–100 % of the whole radiolarian assemblage. Other nassellarian species belong to families such as: Xitidae (*Xitus spicularius* (Aliev) — (Fig. 5W), *Xitus mclaughlini* (Pessagno) — Fig. 5S), Eucyrtidiidae (*Stichomitra stocki* (Campbell & Clark) — Fig. 5Y), *Stichomitra communis* Squinabol — (Fig. 5T,X), *Pseudoeucyrtis spinosa* (Squinabol) — Fig. 5M,N), Syringocapsidae (*Squinabollum fossile*

(Squinabol) — Fig. 5O), Pseudodictyomitridae (*Pseudodictyomitra pseudomacrocephala* (Squinabol) — Fig. 5U,V), Archaeodictyomitridae (*Thanarla veneta* (Squinabol) — Fig. 5P–R) and, Sethocapsidae (*Gongylothorax siphonifer* Dumitrică — Fig. 5C,D).

Spumellarians are less common and less diversified. Species recognized in the assemblages belong to two families: Conocaryommidae (*Praeconocaryomma lipmanae* Pessagno — Fig. 5A,B) and Dactyliosphaeridae (*Dactyliosphaera maxima* (Pessagno) — Fig. 5E).

Foraminiferal assemblages

The studied section is dominated by deep-water agglutinated foraminifera (DWAf — Table 1), moderately diversified. The Fischer alpha index ranges between 2.2 and 7.7 (calculated using the PAST software version 3.01; Hammer

Table 1: Foraminifera from the Middle Cenomanian sediments in the Trójca section, Skole Nappe, Outer Carpathians. Numbers of determined specimens are indicated.

	Ryb-14	Ryb-12	Ryb-11	Ryb-10	Ryb-8	Ryb-7	Ryb-6	Ryb-5	Ryb-4	Ryb-3	Ryb-2	Ryb-1
Agglutinated												
<i>Ammodiscus cretaceus</i> (Reuss)	6	1	3	2	.	.	.	3	.	.	.	.
<i>Ammodiscus</i> sp.	1	.	.	2	.	.	6	.	.	2	.	1
<i>Bulbobaculites problematicus</i> (Neagu)	17	1	.	.	35	.	2	17	.	.	.	2
<i>Caudammina ovula</i> (Grzybowski)	1	2	.	.	1	.	.	1	1	.	.	.
<i>Gerochammina stanislavi</i> Neagu	1	1	1	.	1	.	2	1	.	.	.	4
<i>Gerochammina lenis</i> (Grzybowski)	11	2	6	.	9	.	14	11	1	2	.	2
<i>Gerochammina obesa</i> Neagu	4	3	2	.	4	.	3	5	1	3	.	.
<i>Glomospira irregularis</i> (Grzybowski)	1	.	.	1	1	.	2	4	.	.	.	.
<i>Haplophragmoides</i> sp.	.	.	.	.	.	.	.	.	.	.	.	1
<i>Hyperammina</i> sp.	1	1	.	.	.	.	.	.	1	.	.	.
<i>Psammospaera</i> sp.	.	.	1	.	1	1	.	.	.	.	.	.
<i>Pseudonodosinella parvula</i> (Huss)	.	.	.	.	.	.	2	.	.	.	.	.
<i>Pseudonodosinella troyeri</i> (Tappan)	15	6	4	.	29	.	50	13	.	.	.	1
<i>Recurvoides contortus</i> Erland	.	.	.	.	2	.	.	.	.	.	.	.
<i>Recurvoides imperfectus</i> (Hanzlikova)	.	.	2	.	.	.	.	.	.	.	.	.
<i>Recurvoides</i> sp.	15	21	5	9	11	.	8	20	32	12	.	5
<i>Reophax</i> sp.	.	.	.	1	.	.	.	.	.	.	.	.
<i>Repmanina charoides</i> (Jones & Parker)	1	1	1	.	11	.	6	1	.	.	.	2
<i>Rhabdammina</i> sp.	.	.	.	.	.	.	.	1	1	1	.	2
<i>Rhizammina</i> sp.	2	2	1	1	4	.	3	6	.	3	.	.
<i>Rothina silesica</i>	.	1	.	.	.	.	2	.	.	.	.	.
<i>Saccammina grzybowskii</i> (Schubert)	1	.	.	1	.	.	.	.	.	.	.	.
<i>Saccammina placenta</i> (Grzybowski)	2	.	.	.	.	1	.	1	.	.	.	1
<i>Thalm. meandertornata</i> Neagu & Tocorjescu	5	4	2	4	6	.	17	9	.	.	.	.
<i>Trochammina</i> sp.	12	4	1	5	8	.	10	20	14	.	.	5
Calcareous benthic												
<i>Berthelina baltica</i> Brotzen	.	.	.	.	.	.	.	.	.	.	2	5
<i>Berthelina cenomanica</i> (Brotzen)	.	.	.	.	.	.	.	.	.	.	1	4
<i>Globulina Prisca</i> Reuss	.	.	.	.	.	.	.	.	.	.	.	1
<i>Pleurostomella</i> sp.	.	.	.	.	.	.	.	.	.	.	1	1
<i>Valvulinera lenticularia</i> (Reuss)	.	.	.	.	.	.	.	.	.	.	2	9
Planktonic												
<i>Hedbergella delrioensis</i> Casey	.	.	.	.	.	.	.	.	.	.	85	97
<i>Hedbergella planispira</i> (Tappan)	.	.	.	.	.	.	.	.	.	.	6	3
<i>Globigerinelloides ultramicro</i> Subbotina	.	.	.	.	.	.	.	.	.	.	7	12
<i>Praeglobotruncana</i> cf. <i>delrioensis</i> Plummer	.	.	.	.	.	.	.	.	.	.	.	2
<i>Rotalipora</i> (Th.) cf. <i>appenninica</i> Renz	.	.	.	.	.	.	.	.	.	.	.	2
<i>Rotalipora</i> (Th.) sp.	.	.	.	.	.	.	.	.	.	.	.	2
<i>Whiteinella archaeocretacea</i> Pessagno	.	.	.	.	.	.	.	.	.	.	3	.
<i>Whiteinella baltica</i> Douglas & Rankin	.	.	.	.	.	.	.	.	.	.	2	.

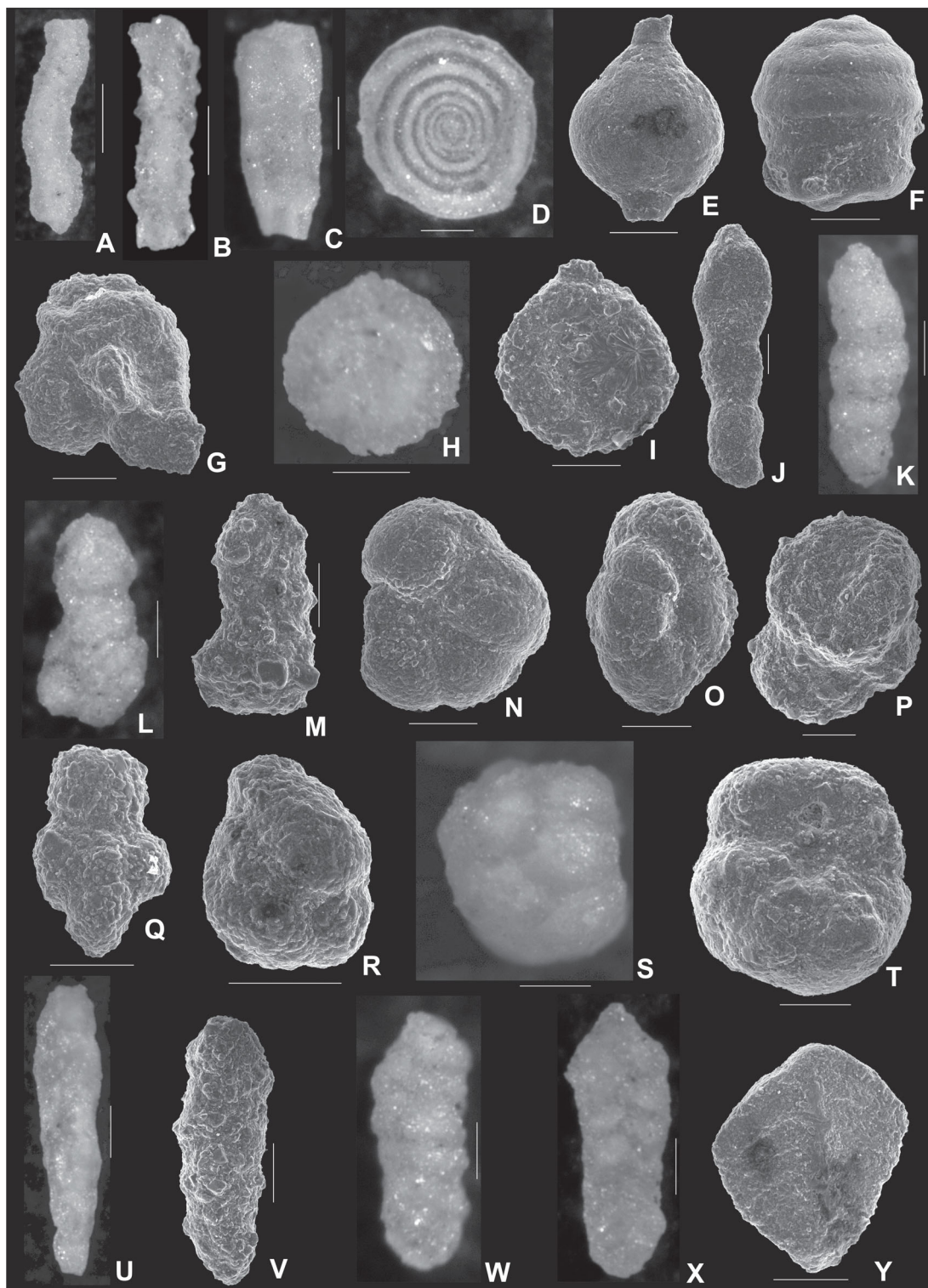


Fig. 6. Agglutinated foraminifera from lower part of the Barnasiówka Radiolarian Shale Formation in the Trójca section (Skole Nappe, Polish Outer Carpathians). **A** — *Rhizammina* sp. (Ryb-5); **B** — *Psammosiphonella discreta* (Brady) (Ryb-1); **C** — *Kalamopsis grzybowskii* (Dyląganka) (Ryb-12); **D** — *Ammodiscus cretaceous* (Reuss) (Ryb-11); **E** — *Caudammina ovula* (Grzybowski) (Ryb-1); **F** — *Repmanina charoides* (Jones & Parker) (Ryb-8); **G** — *Glomospira irregularis* (Grzybowski) (Ryb-8); **H** — *Saccamina placenta* (Grzybowski) (Ryb-1); **I** — *Saccamina grzybowskii* (Schubert) (Ryb-10); **J, K** — *Pseudonodosinella troyeri* (Tappan) (Ryb-6); **L, M** — *Bulbobaculites problematicus* (Neagu) (Ryb-6); **N, O** — *Haplophragmoides kirki* Wickenden (Ryb-6); **P** — *Trochammina* sp.: **A** — (Ryb-14); **Q** — *Trochammina* sp.: **B** — (Ryb-5); **R, S** — *Thalmannammina meandertornata* Neagu & Tocorjescu (Ryb-5); **T** — *Recurvoides* sp. (Ryb-10); **U** — *Gerochammina* cf. *stanislawi* Neagu (Ryb-12); **V–X** — *Gerochammina lenis* (Grzybowski) (**V** — Ryb-6, **W** — Ryb-8, **X** — Ryb-11); **Y** — *Spiroplectinella dentata* (Alth) (Ryb-1).

et al. 2001 — Fig. 3). Most of them represent flysch-type microfauna, known from Cretaceous and Paleogene bathyal-abysal turbiditic environments (e.g. Morgiel & Olszewska 1982; Kuhnt & Kaminski 1989; Kuhnt et al. 1990, 1992; Bak 2004; Kaminski & Gradstein 2005). Tubular specimens belonging to a few genera (*Rhizammina* — Fig. 6A), *Rhabdammina*, *Psammosiphonella* — (Fig. 6B) and *Kalamopsis* — (Fig. 6C) are rare. The most frequent among them are tiny rhizamminids (Table 1). The most abundant agglutinated foraminifera, each with frequency exceeding 20 %, belong to *Bulbobaculites problematicus* (Neagu) — (Fig. 6L,M), *Pseudonodosinella troyeri* (Tappan) — (Fig. 6J,K) and geramminids — (Fig. 6U-X). *Recurvoides* — (Fig. 6T) and *Thalmanammina* — (Fig. 6R,S) are also abundant throughout the studied sections. However, their frequency is difficult to measure, because many of them are not transparent and are partly filled with pyrite. Some samples also contain numerous completely pyritized large moulds of *Recurvoides* (*Thalmanammina*)-type shapes. Less frequent in the studied sections are *Ammodiscus* — (Fig. 6D), *Saccammina* — (Fig. 6H,I),

Caudammina — (Fig. 6E), *Repmanina* — (Fig. 6F), *Glomospira* — (Fig. 6G), *Haplophragmoides* — (Fig. 6N,O), and *Spiroplectinella* — (Fig. 6Y). The total frequency of these taxa is around 10 % in individual samples. Similarly, small trochamminids (Fig. 6P,Q) comprise nearly 10 % of the total number of specimens in the samples.

Calcareous benthic foraminifera have been recorded in only two samples occurring together with sponge spicules and planktonic foraminifera (Table 1). This suggests that they constitute redeposited assemblages, transported by turbidity currents. Only five species have been recognized that belong to *Valvulineria lenticula* (Reuss), *Berthelina cenomanica* (Brotzen), *Berthelina baltica* Brotzen, *Globulina prisca* Reuss and *Pleurostomella* sp. All these taxa are well known from the Upper Cretaceous epicontinental seas that surrounded the northern basins of the Western Tethys (e.g. Gawor-Biedowa 1972; Heller 1975; Pożaryska & Wytwicka 1983; Peryt 1983; Hradecka 1993; Dubicka & Peryt 2012).

Numerous planktonic foraminifera are found in the topmost part of the studied section (samples Ryb-1 and Ryb-2 — Fig. 3)

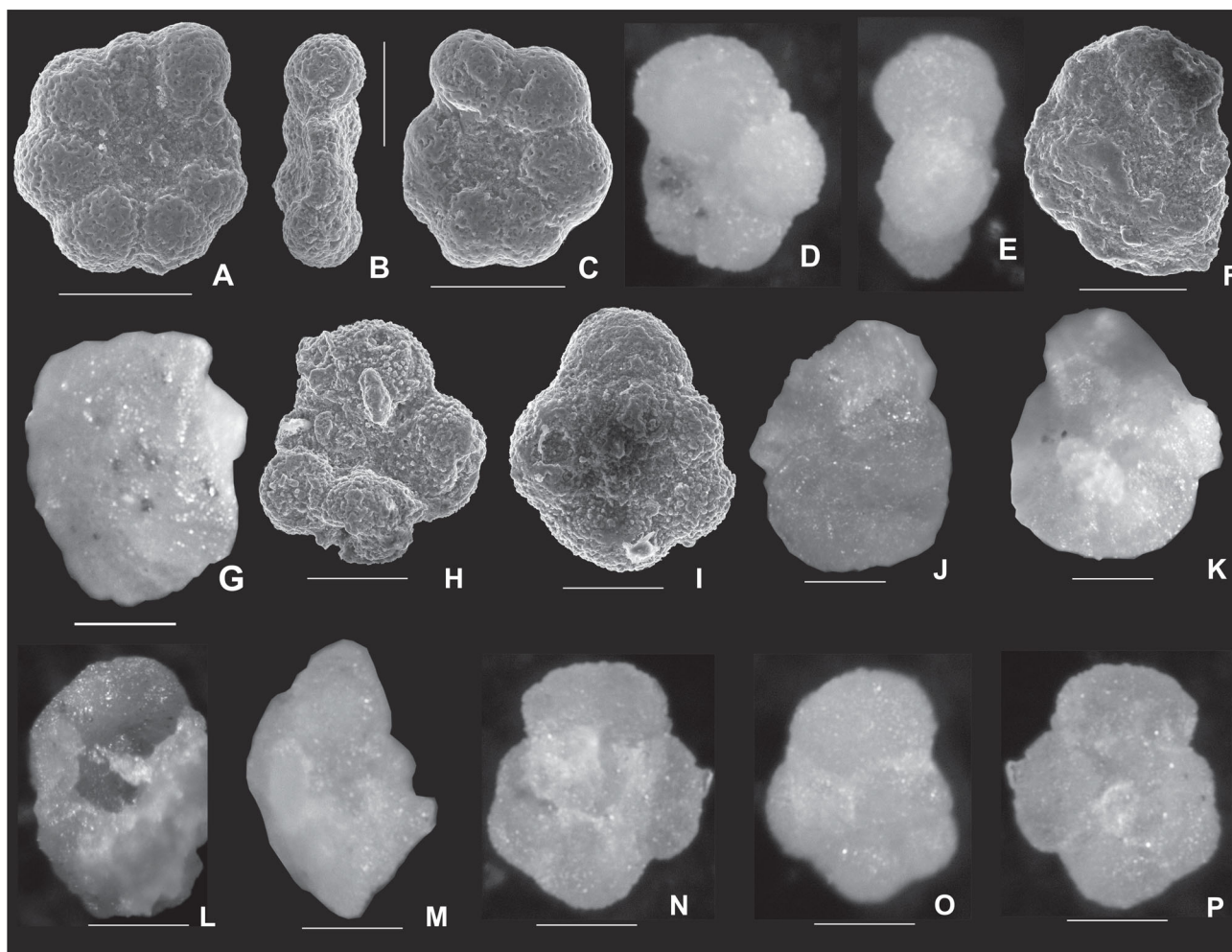


Fig. 7. Planktonic foraminifera from lower part of the Barnasiówka Radiolarian Shale Formation in the Trójca section (Skole Nappe, Polish Outer Carpathians). A–C — *Globigerinelloides ultramicra* Subbotina (Ryb-1); D, E — *Hedbergella delrioensis* Carsey (Ryb-2); F, G — *Rotalipora* sp. (Ryb-1); H, I — *Whiteinella baltica* Douglas & Rankin (Ryb-2); J, K — *Rotalipora* (Th) cf. *appenninica* Renz (Ryb-1); L, M — *Praeglobotruncana* cf. *delrioensis* (Plummer) (Ryb-1); N–P — *Whiteinella archaeocretacea* Pessagno (Ryb-2).

with numerous forms belonging to *Globigerinelloides ultra-micra* Subbotina — (Fig. 7A–C) and *Hedbergella delrioensis* Carsey — (Fig. 7D,E). Their dimensions do not exceed 150 µm — most of them are 80–120 µm in diameter. Moreover, rare and small (not longer than 200 µm) specimens of *Whiteinella baltica* Douglas & Rankin — (Fig. 7H,I), *Whiteinella archaeocretacea* Pessagno — (Fig. 7N–P), *Praeglobotruncana delrioensis* Plummer — (Fig. 7L,M) and *Rotalipora (Th.) appenninica* Renz — (Fig. 7J,K) have been recorded from these sediments.

Sponge spicules

Loose sponge spicules have been found in six samples (Fig. 3) but the most numerous and diversified spicules occur in a turbidite siltstone–claystone layer (Ryb-9). All of them belong to sponges classified as Demospongiae (Fig. 8G–Z) and Hexactinellidae (Fig. 8A–F). Practically all the spicules are broken and strongly disintegrated. The spicules represent choanosomal and dermal assemblages which derived from various sponge species (Fig. 8). Spicules of Demospongiae are the most common. They consist of 64 % of the whole assemblages and prevail over the spicules classified to Hexactinellidae (21 %). Various types of oxea, which may belong to both sponge groups, consist of 15 % of the spicule assemblages.

Hexactinellidae spicules are represented only by hexactines and pentactines (Fig. 8A–F). The hexactines are most probably choanosomal spicules. Some fused spines present in the studied material suggest that they were a part of solid skeletons of Hexactinosa (Schrammen).

Demospongiae are represented mostly as loose and usually strongly articulated tetraxial and monaxial spicules. The most common spicules belong to the Lithistida. These are a different type of desmas (Fig. 8G–O), which were a part of choanosomal skeletons, as well as different types of ectosomal phyllostriaenes (Fig. 8U–V). Tetraclone desmas and phyllostriaenes are characteristic of lithistid sponges of the family Theonellidae Lendenfeld (Pisera & Levi 2002a,b). The most common choanosomal desmas are rhizoclones (Fig. 8G–K). Fossil rhizoclones are usually assigned to the suborder Rhizomorina Zittel (Pisera 1997, 2002). The presence of various types of triaenes with long rhabdomes may indicate the presence of species from the group of Astrophorida Sollas (Fig. 8R–T).

In addition to macroscleres, the microscleres are also present in the material studied, represented by sterrasters (Fig. 8Q). They are undoubtedly derived from species of the family Geodiidae. A more precise assignment is not possible, because the shape and sculpture of singular forms have no taxonomic value (Uriz 2002). Some of the oxeas found in the material studied may also belong to geodiid sponges.

Pellets

Pellets are a common component of the green shales succession in the BRSF. Analysis of thin-sections shows that pellets are one of the main constituents of silt and clay fractions (Fig. 9). They vary in size and shape, which suggests

their production was caused by both micro- and mesozooplankton. Most common are elliptical forms with the longer axis up to 300 µm. (Fig. 9A). Semi-spherical pellets have diameters up to 500 µm. Longitudinal forms extend along the longer axis over 1 mm. Pellets contain large amounts of undigested or partially digested material, which consists of complete or crushed radiolarian skeletons (Fig. 9A–D), as well as planktonic foraminiferal tests (Fig. 9B). Some pellets contain homogenous material (Fig. 9A) which might have been several times digested by different consumers during their journeys through the water column.

Radiolarian biostratigraphy

There are no precise radiolarian age markers in the assemblage investigated, however, the radiolarian species occurring in the studied section, and the general quantitative composition of radiolarian assemblages, allow us to make some observations about the stratigraphy. The general picture of nassellarian distribution in the Western Tethys is one of high abundance in the middle and upper Cenomanian deposits below the onset of OAE-2 (Båk M. 2011). This feature of radiolarian assemblages has been recognized in the Umbria-Marche and the Carpathian basins. In the Outer Carpathian sediments, the most abundant are representatives of the family Williriedellidae (e.g. Dumitrică 1975; Båk M. 2000, 2004, 2011). The same trends have been observed here in the sediments of the Skole Nappe.

The co-occurrence of two abundant radiolarian species — *Holocryptocanium barbui* Dumitrică and *H. tuberculatum* Dumitrică with the presence of *Gongylothorax siphonifer* Dumitrică indicate a middle to late Cenomanian age (Fig. 3), based on correlation with the *H. barbui*–*H. tuberculatum* radiolarian assemblage reported by Dumitrică (1975) from the Romanian Carpathians and with comparison to previous data obtained from the Polish Outer Carpathians and the Pieniny Klippen Belt (Båk M. 1993a,b, 1996a,b, 1999, 2000, 2004; Båk M. & Båk K. 1999).

On the other side, the studied sediments do not contain radiolarian species such as *Alievium superbum* (Squinabol), *Crucella cachensis* Pessagno, *Praeconocaryomma universa* Pessagno, *Dictyomitra napaensis* Pessagno, *Cavaspongia antelopensis* Pessagno, *Patellula ecliptica* O'Dogherty and *P. andrusovi* Özvoldová, which are common in the uppermost Cenomanian of the Outer and Inner Carpathian sections (e.g. Górka 1995; Båk M. 1996a,b, 2000, 2004, 2011; Båk K. & Båk M. 2013). Fortunately, Cenomanian species as *Tanarlarla veneta* (Squinabol) and *Xitus mclaughlini* (Pessagno), which finally became extinct at the top of the uppermost Cenomanian organic-rich facies of OAE-2, are present here (Fig. 3).

To refine the age assignment, an important observation is that these sediments lack a very characteristic radiolarian zonal marker — *Hemicryptocapsa prepolymetra* Dumitrică — which commonly occurs in the Carpathians (Båk M. 1996b, 2000, 2004, 2011). The first appearance of this species defines the lower boundary of the *Hemicryptocapsa prepolymetra* Interval Radiolarian Zone in the Western Tethyan sediments (Båk M. 1999, 2011). It has been dated in the Polish



Fig. 8. Sponge spicules from lower part of the Barnasiówka Radiolarian Shale Formation in the Trójca section (Skole Nappe, Polish Outer Carpathians). **A–F** — Hexactines of *Hexactinosa* (Ryb-9); **G–K** — Rhizoclone desmas of *Lithistida* (Ryb-9); **M–O** — Tetractone desmas of *Lithistida* (Ryb-9); **P** — Strongyloxeas of “soft” demosponge (Ryb-9); **Q** — Sterrasters of geodiidid (Astrophorida) (Ryb-9); **R–T** — Plagiodichotriaenes of “soft” Demospongiae, most probably *Astrophorida*; **U–V** — Ectosomal phyllostriaenes of theonellid (Ryb-9); **W–X** — Choanosomal calthrops of *Astrophorida* (Ryb-9); **Y–Z** — Criccalthrops (Ryb-9).

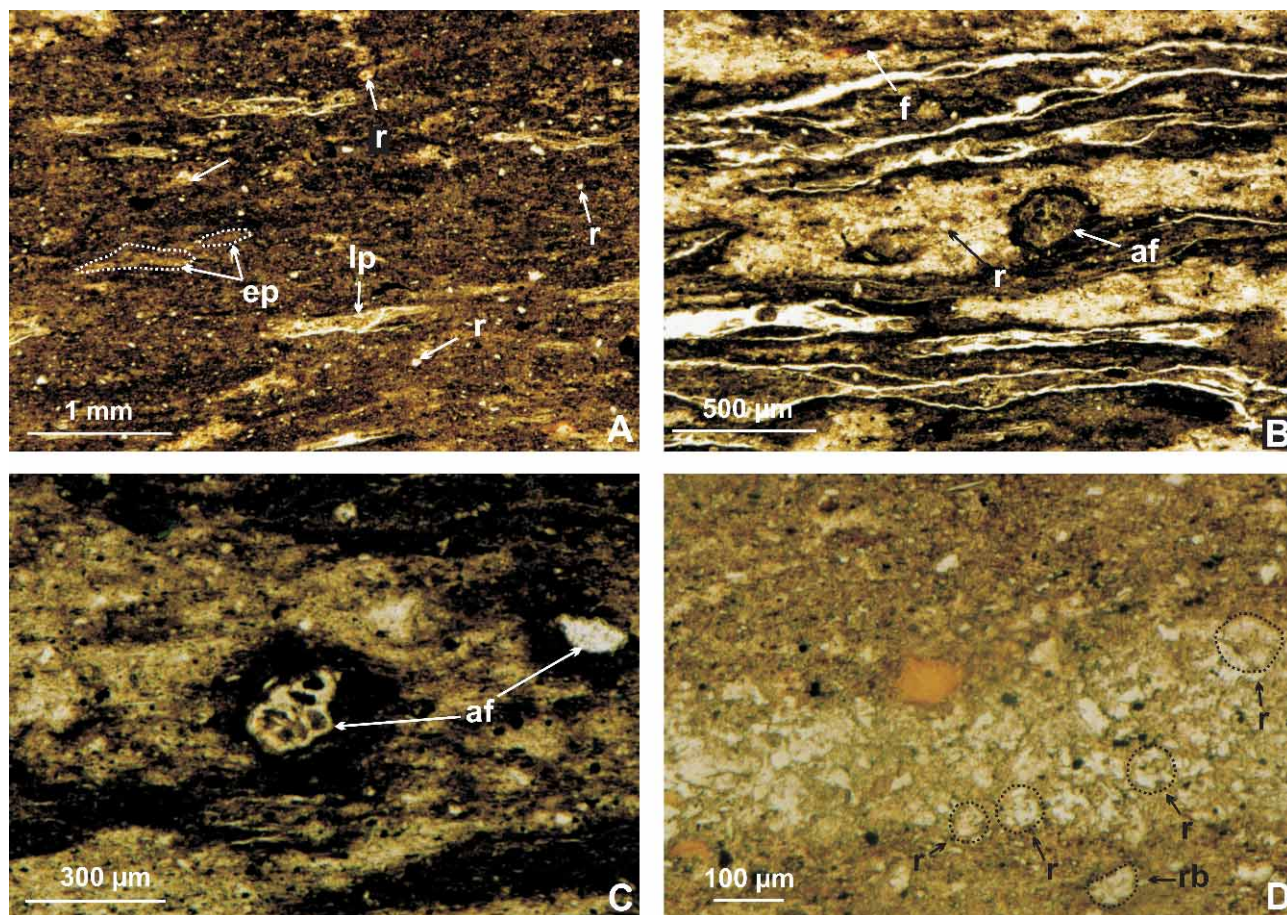


Fig. 9. Microfacies from black organic-rich mudstone layer of the Barnasiówka Radiolarian Shale Formation in the Trójca section (Skole Nappe, Polish Outer Carpathians). **A** — Bioturbated organic-rich shale with different type of pellets. Elliptical forms (ep) prevail over longitudinal (lp). Small, rounded radiolarians (r), (probably williriedellids) are incorporated into the pellets or they are attached to pellet surface; **B** — Flattened pellets with sharp boundaries in organic-rich shale. Pellets contain different organic particles such as fish bones (f), agglutinated foraminifera (af) and radiolarians (r); **C–D** — Close up of pellet with microcrystal of quartz filled in moulds after complete (r) and/or broken (rb) radiolarian skeletons. Most of the skeletons are spherical, resembling williriedellids.

Outer Carpathians to 1.0 Ma before the onset of OAE-2 (Bąk M. 2011). The Middle/Upper Cenomanian boundary lies within this radiolarian zone (Bąk M. 2011).

Another important species for stratigraphy is *Stichomitra stocki* (Campbell & Clark), the first appearance of which is known in the Carpathian basins earlier than *H. prepolihedra* but after the Mid-Cenomanian Event (MCE *sensu* Jenkyns et al. 1994; Jarvis et al. 2006 — see discussion in Bąk M. 2011).

To summarize, all the presented data indicate that sedimentation of the studied sediments began during the middle Cenomanian (after the Mid-Cenomanian Event) and finished earlier than 1.0 Ma before the onset of Oceanic Anoxic Event 2, namely near the middle–upper Cenomanian boundary taking into account the chronostratigraphy by Ogg & Hinnov (2012).

Foraminiferal biostratigraphy

Planktonic foraminiferal assemblages are present only in redeposited sediments of the topmost part of the studied sec-

tions. The Cenomanian rotaliporid index species are absent in these assemblages. Relative age interpretation can be made on the basis of sporadic forms belonging to the whiteinellids and rotaliporids (Fig. 3). The FOs of whiteinellids is noted from the Tethyan realm from the middle Cenomanian (Robaszynski & Caron 1995). On the other hand, the last appearance of rotaliporids was diachronous in the Tethys, related to the oxygen content in the water column. It took place near the base of OAE-2, corresponding to the latest Cenomanian.

The agglutinated assemblages from the whole studied succession contain numerous specimens of *Bulbobaculites problematicus* (Neagu) — (Fig. 3), an index species in benthic zonations of the Carpathian basins (e.g. Geroch & Nowak 1984; Olszewska 1997; Bąk K. & Bąk M. 2013). Its FO was precisely documented in the Pieniny Klippen Belt, where it corresponds to the *Rotalipora reicheli* Zone (middle Cenomanian) — (Bąk K. et al. 1995; Bąk K. 1998, 2000).

In conclusion, the datum events of foraminiferal species show that the studied sediments represent the interval after the first appearance of whiteinellids and *B. problematicus*

(Neagu) (Middle Cenomanian) and before the final extinction of the rotaliporids (uppermost Cenomanian). These data confirm the radiolarian stratigraphy in the sense of determining the lower boundary of the studied succession. The upper biostratigraphical limit is here less precise than that based on the radiolarian biostratigraphy.

Environmental conditions at the floor

The lack of calcareous foraminifers in the hemipelagic layers indicates that the sedimentation of the deposits studied in the Skole Basin took place below the calcium compensation depth. The green claystone layers contain numerous radiolarians with siliceous- and organic-walled benthic (agglutinated) foraminifers typical of the Cretaceous bathyal and abyssal environments. Planktonic and calcareous benthic foraminifera are redeposited and occur only in clay- and silt-sized turbidites, where they are associated with siliceous sponge spicules.

The characteristic feature of these sediments is their green colour (from pale-green in hemipelagic layers to dark-green in turbiditic layers), which dominate among the clayey and muddy shales, excluding a few very thin dark-grey and black layers. The dominance of green colouration is characteristic of the Upper Albian–Cenomanian deep-water hemipelagic sediments in all the Outer Carpathian tectonic and facies zones (e.g. Książkiewicz 1962). These sediments significantly differ in colour from the Lower Cretaceous hemipelagic strata and the latest Cenomanian OAE-2 hemipelagic sediments, which possess dark-grey and black colouration. Because of the lack of chemical studies of these sediments, the interpretation of this fact is not discussed here. However, from the general point of view, using the published micropaleontological data related to the increase in diversity of deep-water benthic foraminiferal assemblages from the Aptian to Cenomanian in the Carpathian sediments (cf. Geroch & Nowak 1984; Kuhnt et al. 1992; Olszewska & Malata 2006), the change of sediment colour from black to green would be related to the increase in the oxygen content of deep water and in the uppermost part of the sediment column in relation to the pre-Cenomanian time period.

Such a conclusion also derives from features of the studied benthic microfossils. The DWAF assemblages are low to moderately diversified. The Fisher alpha index, as a measure of species diversity ranges from 2.2 to 7.7. These values of diversity are comparable to the values of the Early Cretaceous assemblages from deep-water oxygen-depleted environments of the Tethyan realm (e.g. Geroch & Koszarski 1988; Decker & Rögl 1988; Kuhnt 1995) and significantly lower than the values in Late Cretaceous (Turonian–Maastichtian) assemblages from oxygenated deep sea basins of the same area (e.g. Kuhnt & Kaminski 1989; Bak K. 2000; Kaminski et al. 2008; Kaminski et al. 2011).

Environmental interpretation of the sea floor is also possible using paleoecological interpretation of benthic foraminifera by means of morphogroup analysis. The morphogroup concept refers to grouping of similar shapes and growth patterns of foraminiferal tests using the idea that species with the same test shape have the same preferred life habitats,

which can be related to feeding strategies, and that morphogroups distribution and abundance can reflect changes in selected environmental parameters (e.g. Jones & Charnock 1985; Nagy 1992; Nagy et al. 1995; Kaminski et al. 1995; Peryt et al. 1997; Preece et al. 1999; Van Den Akker et al. 2000; Peryt et al. 2004; Bak K. 2004; Kaminski & Gradstein 2005; Kender et al. 2008a,b; Cetean et al. 2011; Murray et al. 2011; Mancin et al. 2013).

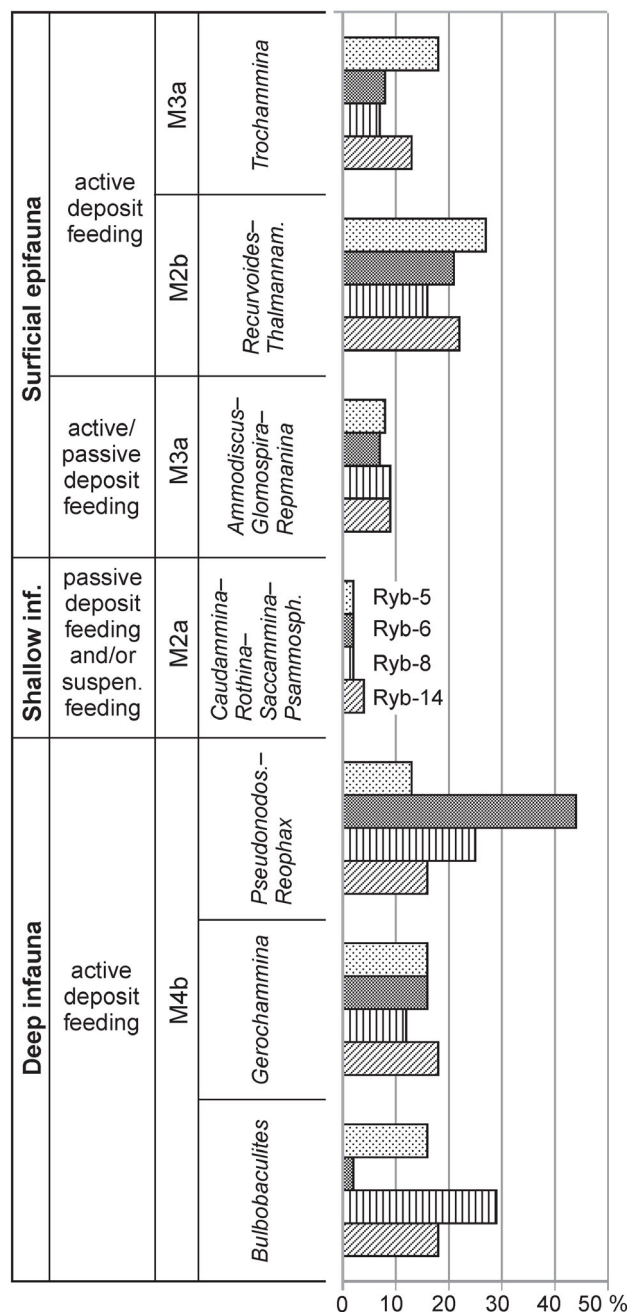


Fig. 10. Percentage content of foraminiferal genera in lower part of the Barnasiówka Radiolarian Shale Formation in the Trójca section (Skole Nappe, Polish Outer Carpathians). Tubular taxa have not been included here due to their uncertain number, related to fragmentation of the tests during fossilization and washing processes. Morphogroup numbers (M2a to M4b) after Kaminski & Gradstein (2005).

The assemblages studied are dominated by elongate subcylindrical and elongate tapered forms including *Pseudonodosinella*, *Gerochammina*, and *Bulbobaculites*. They comprise nearly 60 % of the total number of foraminiferal assemblages (Fig. 10). Using the definition of agglutinated foraminiferal morphogroups, with interpreted life habitat and feeding strategy, presented by Kaminski & Gradstein (2005), these forms, representing morphogroups M4a and M4b, are interpreted as deep infauna living as active deposit feeders. The deep infaunal forms are associated here with surficial epifaunal taxa, represented by rounded trochospiral, streptospiral, and planoconvex trochospiral forms (morphogroup M2b *sensu* Kaminski & Gradstein 2005) including *Recurvoides*, *Thalmanammina* and *Trochammina*. This morphogroup consists of nearly 30 % of the total number of foraminiferal tests (Fig. 10). The tubular taxa (mostly tiny rhizamminids) which are suspension feeders are rare in the sediments studied (Table 1), reaching a few percent in total numbers of foraminifers. Such a composition of the morphogroups points to distinct dominance of deep infaunal taxa, however, without conspicuous domination by particular species.

As observed in modern deep-water environments (e.g. Jorissen et al. 1995; Kaminski et al. 1995; Gooday & Rathburn 1999; De Rijk et al. 2000; Gooday et al. 2000; Wollenburg & Kuhnt 2000; Szarek et al. 2007; Murray et al. 2011), two main factors control the structure of benthic foraminiferal assemblages: organic carbon flux to the sea floor, and the oxygen concentration in the bottom waters and in the uppermost part of the sediment. In deep sea basins, water depth is another factor affecting the benthic foraminiferal assemblages. The depth of the basin floor influences the reduction flux of organic matter from surface plankton production, which could be several times lower if compared with marginal marine settings (cf. Szarek et al. 2007; Murray et al. 2011). On the other hand, the supply of organic matter can be occasionally enhanced in deep sea environments due to terrigenous fluxes, associated with turbidity currents. Both sources of organic matter on the deep sea floor of the Skole Basin are interpreted here, based on observation of microfacies (Fig. 9). From one side, green clayey shales contain numerous pellets, which could be one of the main sources of organic matter to the sea floor. At the same time, numerous flakes of organic matter are dispersed in muddy and silty turbiditic material (Fig. 9D).

The occurrence of relatively numerous flakes of organic matter in the green clayey shales points to another conclusion, related to the oxygen content at the sediment-water interface. The low oxygen concentration that is here suggested for the studied sediments, could favour the preservation of organic matter. From another point of view, dysoxic conditions could be the main factor which limited the number of epifaunal forms within the foraminiferal assemblages thereby providing an opportunity for exploitation of the sea floor by deep infauna, composed of low-oxygen tolerant taxa. Similar conditions occur recently in abyssal zones of the Sulu Sea, a semi-enclosed, meso-to-oligotrophic basin in the western equatorial Pacific, characterized by warm (ca. 10 °C) and oxygen-depleted (dysoxic; <1 ml/l O₂) deep-waters (Szarek et al. 2007). In such conditions, foraminiferal assemblages consisted mainly of shallow infaunal agglutinated forms, with

dominant species belonging to *Lagenammina difugiformis* (Brady), *Ammoscalaria tenuimargo* (Brady), *Ammobaculites paradoxus* Clark and various *Reophax* species. A comparison of the morphogroup composition from the sediments studied (characterized by dominance of deep infaunal forms) with the TROX ecological model by Jorissen et al. (1995) explaining benthic foraminiferal microhabitat preferences, also suggests a mesotrophic environment with limited oxygen concentration for the Skole Basin floor during the prevailing time periods of the middle Cenomanian. Nevertheless, short-term periodic anoxia also occurred during that time, as documented by the occurrence of several very thin (2–5 mm) black organic-rich layers.

Concluding, the dysaerobic bottom water conditions with a moderate rate of organic matter flux from surface plankton production and from turbidity currents with short-term anoxia characterized the deepest part of the Skole Basin during the Middle Cenomanian.

Source area of sponge spicules from turbidite layers

Turbidite layers contain a rich assemblage of siliceous sponge spicules. The assemblage indicates that the sponge fauna was dominated by lithistid demosponges represented by Theonellidae and rhizomorinids. Demosponges from family Geodiidae (Astrophorida) are also common. Hexactinellidae spicules are rare; only spicules derived from order Hexactinosa were recognized.

Bathymetric reconstructions for the studied sediments, based on sponges are imprecise because these organisms often have very wide bathymetric ranges. However, the studied assemblage is neither characteristic of very shallow nor very deep marine environments. Modern lithistid sponges prefer a deep water environment from one hundred to several hundred meters depth (Vacelet 1988; Maldonado 1992; Pisera 1997). Species from the family Geodiidae are known to have wide bathymetric ranges from intertidal to bathyal depths, however, they are more specific to the bathyal zone (Uriz 2002). In contrast, theonellids might occur mainly at shallow-water depths (Vacelet 1988). The presence of hexactinellid sponges indicate deep environments (Reid 1968) excluding the submarine caves and fjords where they could thrive at shallower depths (Vacelet 1988; Vacelet et al. 1994). Among hexactinellids, species from the order Hexactinosa, from which spicules are present in the turbiditic layers, are known to have settled environments deeper than 100 meters, preferring a stable environment with low water turbulence (Mehl 1992).

Most of the lithistids and species of the Hexactinosa group formed rigid skeletons, which could be attached to a hard substrate. However, some species from the family Geodiidae, could have been adapted to a soft substrate (Uriz 2002; Pisera 2004).

The presented data show that the spicules from the studied material came from disarticulation of moderately diversified solid sponge assemblages, which lived mainly in the deeper parts of the shelves and on the upper parts of the slopes (ner-

itic-bathyal zones), generally, below the storm wave base (100 m or more). However, some of them could have originated from shallow shelves. The poor state of preservation of spicules and well sorted spicule material may indicate that spicules were transported over a long distance, including not only transport by turbidity currents, but also by bottom currents on the shelves.

Water properties based on radiolarians and pellets analyses

The majority of radiolarians are indicators of nutrient-rich surface waters, such as in upwelling areas (Casey 1977; De Wever et al. 2001). Present day studies in the Equatorial Pacific region show that total radiolarian standing stocks increase in such regions, responding to a general increases in nutrients, chlorophyll-a, and diatom occurrence during La Niña periods (Yamashita et al. 2002). Studies of the equatorial region, Southern Ocean, and the Namibia upwelling regime show that radiolarians are most abundant in the upper 50–150 m of the water column within the mixed layer, but also occur below it (Abelmann & Gowing 1996, 1997). Intense radiolarian flux subsequently results in the accumulation of a large number of radiolarian individuals in sediments, which enhances the organic carbon flux and increases primary productivity (Wang et al. 2000; Chen et al. 2003). The lowest abundances occur in nutrient-poor subtropical regions and close to the Subtropical Front (Abelmann & Gowing 1996).

Although radiolarian assemblages in the studied deposits are strongly influenced by sedimentary and diagenetic processes, some features of the living assemblages can be recognized. The numerous radiolarians represent two ecological supergroups, “B” and “E”, distinguished for the Cenomanian–Turonian assemblages in the Tethyan realm (Bak M. 2011). Forms assembled in supergroup “B”, which are the most common, have been interpreted as living in the deeper part of the water column. Among supergroup “B”, most species belong to group “B3”, whose dominant taxon — *Holocryptocanium barbui* Dumitrică — was widely tolerant with respect to nutrient surplus in the water column, and could live in the wide vertical range below the mixed surface layer. Group “B2”, which is represented in the studied material by *Squinabolium fossile* (Squinabol), assembled specimens that lived in waters with an increasing amount of phosphorus, characteristic for the eutrophic zone. Other species (*Xitus mclaughlini* (Pessagno) and *Thanarla veneta* (Squinabol)) belong to the “B5” group, which comprises forms that lived in oxygen depleted waters and/or close above the oxic/anoxic interface. The “B6” group is represented here by *Pseudoeucyrtis spinosa* (Squinabol), which lived below the mixed layer in waters moderately rich in nutrients.

Radiolarian assemblages that belong to supergroup “E” are interpreted as an association living in surface waters, mostly in the mixed layer (Bak M. 2011). Among these radiolarian sets, *Xitus spicularius* (Aliev), *Stichomitra communis* Squinabol, and *Holocryptocanium tuberculatum* Dumitrică (“E3” group), and *Pseudodictyomitra pseudomacrocephala*

(Squinabol) (“E4” group) were surface dwellers that lived in very shallow waters, and possibly tolerated a wide range of water temperatures and salinity. Species from group “E3” (*Xitus spicularius* (Aliev), *Stichomitra communis* Squinabol, *Holocryptocanium tuberculatum* Dumitrică) have been interpreted as living also in the surface mixed layer but with increasing phosphorus content. They were more opportunistic and more widely vertically distributed. These species possess skeleton shapes predestinated to a bacterivorous type of feeding (Bak M. 2011).

The radiolarian ecological groups presented above show that the surface and intermediate waters were well enough oxygenated and sufficiently rich in nutrients to enable plankton production, however, oxygen content might have been depleted in the deeper water column or waters may have been seasonally anoxic as indicated by the occurrence of species from group “B5”.

Another indicator of water properties might be pellets, which occur in hemipelagic clayey shales. These pellets are homogenous inside or contain undigested or secondary digested radiolarian skeletons and foraminiferal tests. The radiolarian skeletons are present in various types of pellets in different positions. Usually small, rounded skeletons (most probably forms belonging to williriedellids) are located inside pellets or they are attached to the pellets periphery. This fact suggests that pellets are the main conveyor of radiolarian skeletons from the water column into sea-floor sediment. In this way, pellets could be the main source of siliceous skeleton flux from the upper water column, as previously suggested for the Carpathian deposits (Bak M. 2011). Thus sediments enriched in siliceous skeletons might be a function not only of the proliferation of silica-secreting biota, but also their consumption by larger zooplankton. Pellets came from unknown primary radiolarian consumers. Where such pellets are large (Fig. 9A,C), they might have been derived from the epipelagic zone and have sunk fast enough to avoid re-processing by other zooplankton. Crushed and strongly processed skeletons occurring inside pellets might be examples of re-ingestion by other zooplankton (Fig. 9D).

The studied pellets do not possess an organic membrane, which usually surrounds their modern counterparts. In this study, boundaries with surrounded material represent two types: sharp or with boundaries weakly visible. Sharp boundaries suggest that pellets might have retained a chitinous membrane much longer, during sinking, than pellets whose outer boundaries are difficult to determine (Fig. 9A).

Analogous pellets, most probably deriving from copepod grazing activity, are the main components of the green claystones from the younger part of the BRSF (not studied here), and green claystones from the Variegated Shale in the Silesian and Subsilesian units of the Outer Carpathians (Bak M. 2011).

One of the important factors for the contribution of pellets to transport of particles is the mineralization of pellet material during sinking. Non-mineralized pellets can be rapidly degraded by bacterial activity on the sea floor (Hansen et al. 1996) and destroyed. This process is much faster at higher water temperatures and during higher rates of biogenic pellet accumulation (Hansen et al. 1996). The degradation processes lower the particulate organic carbon value without changing

the biogenic silica flux (Dagg et al. 2003), however, released skeletons are more sensitive to dissolution in water under saturated with respect to silica. Pellets in the material investigated possess their original intact and not compacted shapes. In the case of such pellets, the degradation processes must be arrested before final bacterial decomposition. Such preservation of pellets would suggest the presence of water-column anoxia which prevented secondary digesting and rapid disintegration by microbial and faunal activity.

Water saturation with respect to silica

The radiolarian content and preservation of skeletons may approach the saturation of sea water with respect to silica. Similar processes are observed in modern counterparts, which are sensitive to dissolution during settling through the water column and within the bottom sediment (Takahashi & Honjo 1983) because modern sea water is Si-under saturated from the surface layer to the bottom. In such conditions, the pelletization process is very important for the radiolarian flux and their further preservation within the sediment.

The radiolarians in the hemipelagites of the middle Cenomanian sediments of the Skole Unit are characterized by the dominance of thick-walled, siliceous skeletons, resistant to dissolution and skeletons replaced by pyrite or ferrous oxides. Most of the radiolarian skeletons that occur in the whole studied succession are partly dissolved. Moreover, a part of the planktonic foraminifers together with radiolarians have been transported in pellets, as observed in thin sections of the sediment. Complete, undigested pellets contain better preserved skeletons, while crushed and partly dissolved radiolarian skeletons are visible in thin sections as surrounded by the remnants of disintegrated remains of the pellet. This suggests that more complete and better preserved skeletons were protected by fecal mass, while partly dissolved skeletons have been temporary exposed to aggressive waters undersaturated in respect to silica. This means that the number of radiolarian individuals is a function of production vs. resistance in the upper part of the Si-undersaturated water column.

Conclusions

Hemipelagic green clayey shales with associated thin muddy and clayey turbidites, such as the lower part of the Barnasiówka Radiolarian Shale Formation, were accumulated in a deep sea environment, below the CCD. The radiolarians and foraminifers from these sediments show that their sedimentation took place during the middle Cenomanian and continued at least until the middle-late Cenomanian boundary, namely near 1.0 Ma before the onset of OAE-2. Consequently, these sediments reflect a record of environmental conditions in the Skole Basin during the period between two oceanic anoxic events, the Mid-Cenomanian and the latest Cenomanian (OAE-2).

The taxonomic composition and low to moderate diversity of benthic foraminifers (deep-water agglutinated foraminifera) from hemipelagic shales suggests mesotrophic condi-

tions with limited oxygen concentration for the Skole Basin floor during the prevailing time periods of the middle Cenomanian. Additionally, short-term periodic anoxia also occurred during that time, as documented by the occurrence of several very thin black organic-rich layers. Comparison of the DWAF assemblages, dominated by infaunal taxa, with their modern counterparts, and using the TROX ecological model, enabled us to assess the rate of organic matter fluxes from surface plankton production as moderate, but the flux was periodically enhanced by turbidity currents.

Muddy turbidity currents transported to the seafloor siliceous and biogenic material, including calcareous foraminifers and numerous sponge spicules. The composition of the spicules, dominated by spicules of demosponges (lithistids), suggests that they originated from the disarticulation of moderately diversified solid sponge assemblages, which lived mainly in the neritic-bathyal zone, but, some of them could have come from shallower parts of the shelves. Their poor state of preservation and high rate of disintegration indicate that spicules were transported over a long distance, including transport by bottom currents on the shelves.

Analysis of radiolarian assemblages in the studied sediments, in comparison to ecological groups distinguished for the Cenomanian-Turonian taxa in the Tethyan realm (Båk M. 2011) allowed us to interpret the conditions in the water column. The investigated taxa live in a surface mixed layer with increasing phosphorus content and also in intermediate waters, well-enough oxygenated and sufficiently rich in nutrients to enable plankton production. However, the oxygen content might have been depleted in deeper parts of the water column by periodic anoxia, as indicated by the occurrence of species that lived in oxygen depleted waters and/or close above the oxic/anoxic interface.

The studied hemipelagic green shales contain numerous undigested radiolarian skeletons inside pellets. This fact suggests that pellets are the main conveyor of radiolarian skeletons from the water column into the sea-floor sediment. The occurrence of numerous uncompacted pellets with well-preserved radiolarians inside them also indicates water anoxia which impeded the rapid bacterial degradation of the pellets.

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