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Calcareous nannofossil biostratigraphy and paleogeographic significance in the lower Maastrichtian of the Miechów Trough (southern Poland)

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ABSTRACT:

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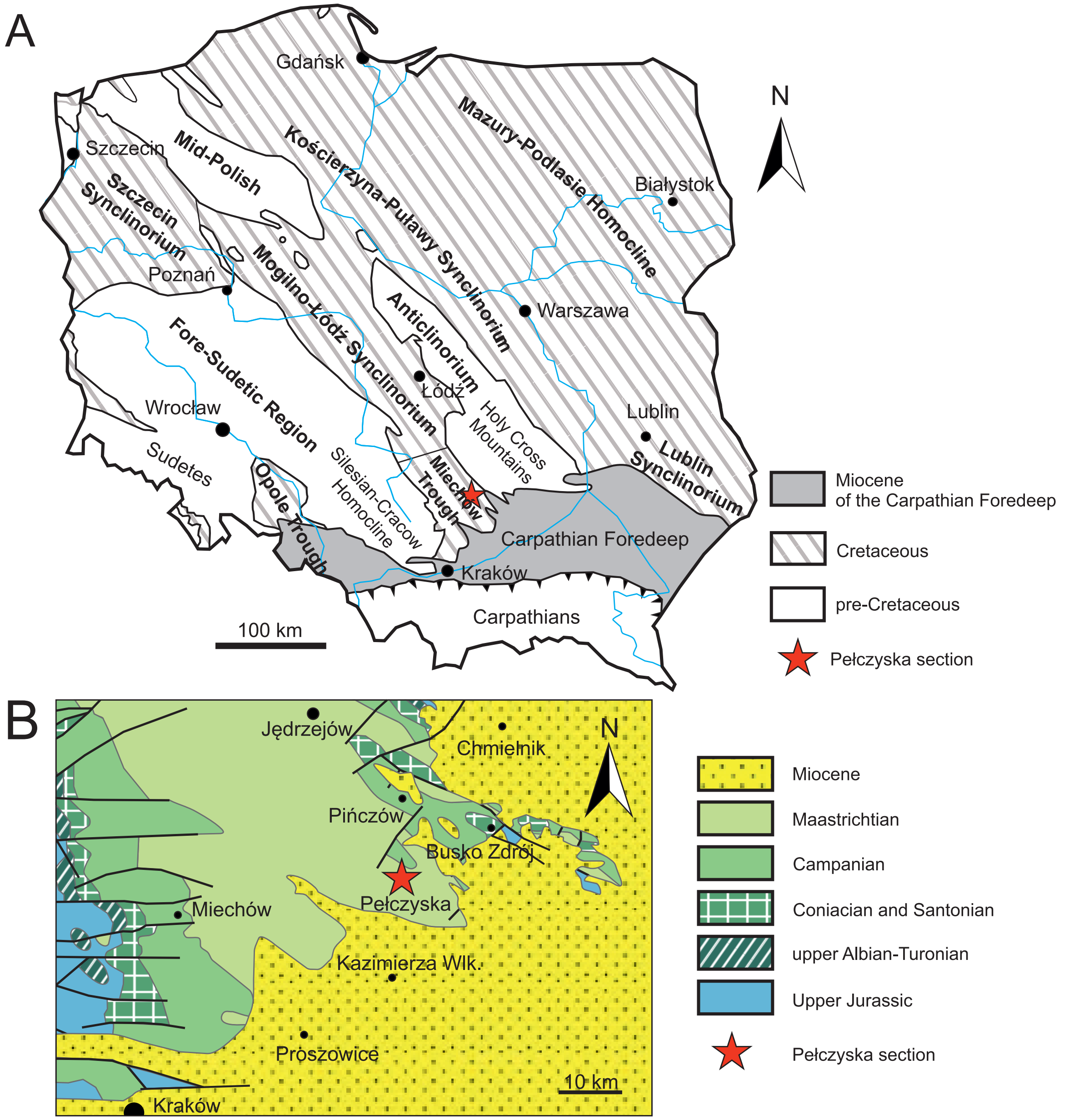
Biostratigraphic analysis of calcareous nannofossils from the Pełczyska section in the Miechów Trough (southern Poland) has revealed that the entire section covers the lowermost Maastrichtian. The UC16b^{TP} Tethyan subzone is designated based on the presence of *Broinsonia parca constricta* Hattner, Wind and Wise, 1980, reworked remains of *Uniplanarius trifidus* (Stradner) Hattner and Wise in Wind and Wise, 1983 and the simultaneous lack of *Eiffellithus eximius* (Stover) Perch-Nielsen, 1968. The studied section spans also the interval between the LO of *Zeugrhabdotus praesigmoides* Burnett, 1997 and the FO of *Prediscosphaera mgayae* Lees, 2007 (UC16 S3 Boreal subzone). Quantitative analysis of nannofossil assemblages has shown the dominance of cold water species (up to 50%), e.g., *Micula decussata* Vekshina, 1959, *Prediscosphaera* spp., *Arkhangelskiella* spp., *Calculites obscurus* (Deflandre) Prins and Sissingh in Sissingh, 1977 and *Lucianorhabdus cayeuxii* Deflandre, 1959. In the early Maastrichtian, the studied area was more influenced by cool water masses from the Boreal Province rather than by warm water from the Tethyan Province. The significant predominance of cold water taxa and the elevated presence of *Prediscosphaera cretacea* (Arkhangelsky) Gartner, 1968 also supports the hypothesis of climate cooling in the early Maastrichtian.

Key words: Lower Maastrichtian; Calcareous nannofossil biostratigraphy; Paleoecology; Cooling event; Boreal Province; Miechów Trough.

INTRODUCTION

The mid to Late Cretaceous is considered to be one of the warmest periods in the entire Phanerozoic (Frakes *et al.* 1992). The sea level at that time was one of the highest in Earth's history. Coastal areas were flooded and the rising sea level created relatively shallow epicontinental seas. However, at the end of the Cretaceous, the trend of sustained warm temperatures was disrupted. The global sea level began to decrease and the temperature dropped significantly (Hay 2008). At least two important cooling events have been recorded, near the Campanian/Maastrichtian boundary and in the late Maastrichtian (Barrera and Savin 1999). These episodes were distinguished at both high and low latitudes.

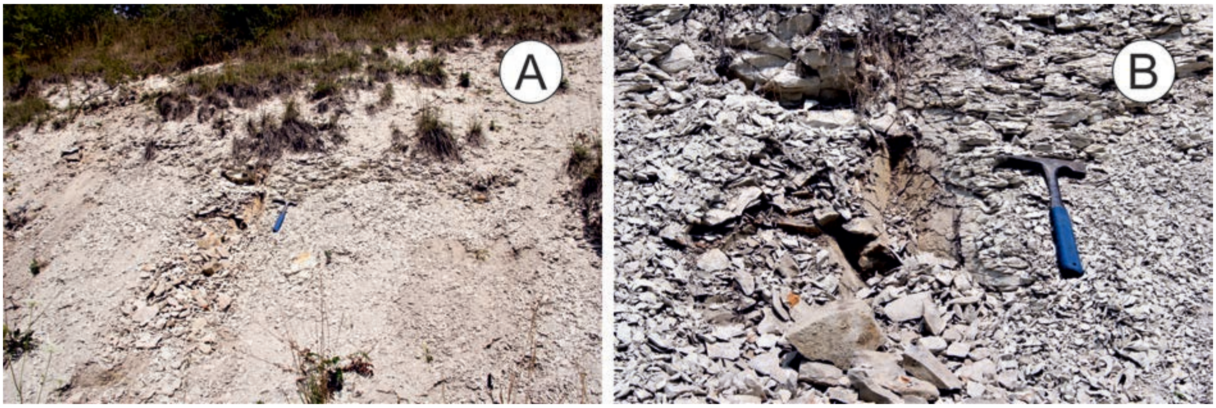
Upper Cretaceous sedimentary series of the Miechów Trough (southern Poland) have been investigated since the 1920s (e.g., Sujkowski 1926; Rutkowski 1965; Hakenberg *et al.* 1973). Stratigraphic and pale-



Text-fig. 1. Location of the study area. A – Tectonic map of Poland with the Miocene of the Carpathian Foredeep. The section studied is marked with a star (modified after: Pożaryski 1977; Żelaźniewicz *et al.* 2011; Jurkowska 2016). B – Geological map with a fragment of the Miechów Trough near the study area (modified after: Radwański 1969, 1973; Dadlez *et al.* 2000).

ontological studies covered different groups of macro- and microfossils. Important for the stratigraphy is the correlation of zonations based on cephalopods, inoceramid bivalves and benthic foraminifera (e.g., Jagt *et al.* 2004; Machalski *et al.* 2004; Remin 2010; Dubicka 2015; Walaszczyk *et al.* 2016). Sponges, ostracods and echinoids were also described from the Miechów Trough (Borszcz *et al.* 2008; Peryt *et al.* 2008; Świerczewska-Gładysz and Jurkowska 2013). These groups of fossils provided information about the paleoecological conditions in the sedimentary basin, such as water depth, turbulence and sedimentation rate. Despite numerous biostratigraphic studies, analysis of Upper Cretaceous calcareous nannofossils has not been performed so far.

In the present study we have for the first time applied the analysis of calcareous nannofossils to obtain more precise stratigraphic conclusions for the mo-



Text-fig. 2. View of the Pełczyska section. A – The section covered with weathered deposits. B – The studied slope with exposed opoka.

notonous calcareous–siliciclastic deposits of the SE part of the Miechów Trough. Another objective was to determine the paleoenvironmental conditions that prevailed during sedimentation. For this purpose, qualitative and quantitative analysis of calcareous nannofossil assemblages was performed. Our additional goal was to investigate whether cool climate events are recorded in the studied section

GEOLOGICAL SETTING

The studied section is situated in the Miechów Trough, which is currently a synclinorium, the axis of which runs from NW to SE parallel to one of the main structures of the Polish Lowlands – the Mid-Polish Anticlinorium (Text-fig. 1A). During the Permian and Mesozoic, this structure represented the deepest part of the sedimentary basin, which revealed a rift nature (Kutek and Głazek 1972; Pożaryski and Brochwicz-Lewiński 1978; Kutek 2001). This structure, known as the Mid-Polish Trough or Danish-Polish Trough, developed along the Teisseyre-Tornquist Zone, which is the border between the East-European Craton and the Paleozoic Platform. The reconstruction of its geological development on the basis of tectonic subsidence analyses indicates that the initial rift episode occurred in the late Permian–Early Triassic. It was followed by the phase of increased tectonic subsidence in the Oxfordian–Kimmeridgian and another in the Late Cretaceous, beginning in the Cenomanian (Dadlez *et al.* 1995; Stephenson *et al.* 2003). Within the Miechów Trough, the thickness of the Upper Cretaceous succession (including the lower Maastrichtian) increases eastwards, i.e., to the axial part of the sedimentary basin (Świdrowska and Hakenberg 1999). The inversion of the Mid-Polish Trough was of transpressive nature and coincided with the Laramide phase of intraplate compression in the Alpine foreland (Ziegler *et al.* 1995; Kutek 2001). It should be mentioned that there is still a controversy about the onset of inversion movements (Leszczyński and Dadlez 1999; Walaszczyk 2008).

In the Late Cretaceous, the studied area was covered by an epicontinental sea (Jurkowska *et al.* 2019) and located in the intermediate province affected by both cool waters flowing from the Boreal Realm and warm waters from the Tethyan Realm, which influenced the development of various organic assemblages (Pożaryska and Peryt 1979; Marcinowski and Gasiński 2002).

Pełczyska section

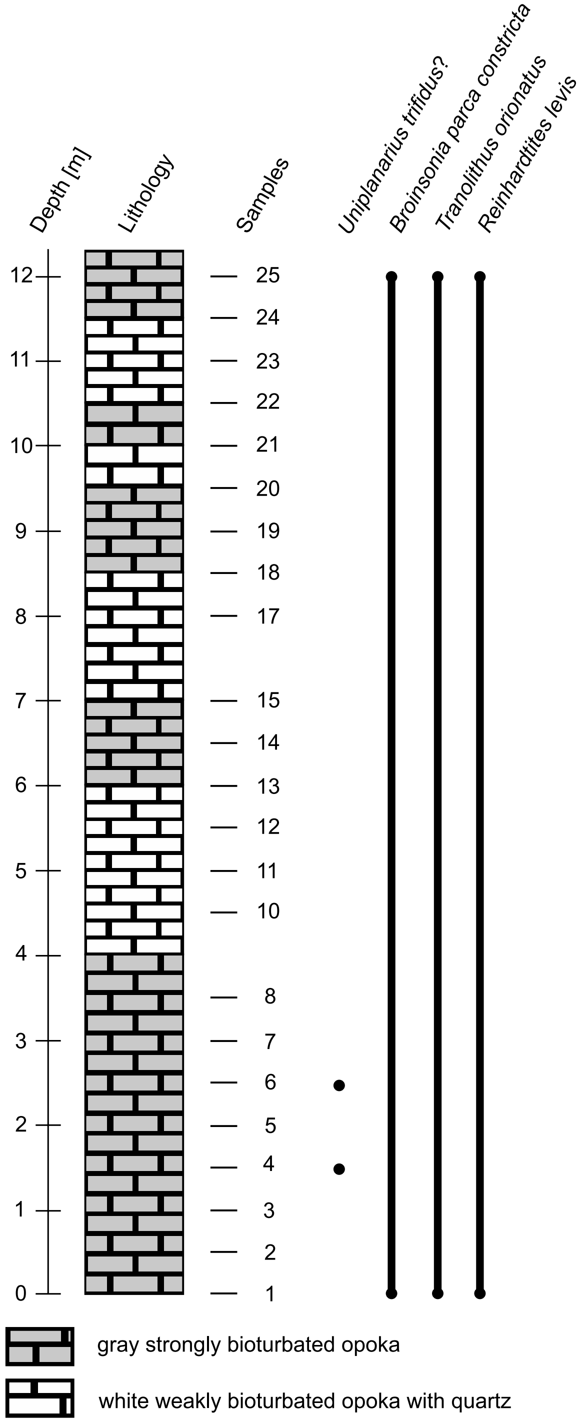
In the present study, samples for nannofossil analysis were taken from the Pełczyska natural outcrop, which is located close to Pińczów (Text-fig. 1B), in the SE limb of the Miechów Trough. The section is situated on a slope covered with weathered Cretaceous sediments (Text-fig. 2A, B). At the top of the outcrop there is a thin layer of Holocene deposits. The Pełczyska section comprises 12.3 m of two alternating types of clayey opoka: white (with quartz, weakly bioturbated) and gray (highly bioturbated), both bioclastic wackestone (Jurkowska *et al.* 2019). The silica contained in the sediments mainly comprises biogenic (opal-CT), derived from sponge spicules, but also contains terrigenous quartz grains (Świerczewska-Gładysz and Jurkowska 2013; Jurkowska *et al.* 2019).

Inoceramid biostratigraphy has been used to determine the age of the deposits, which were referred to the lower Maastrichtian *Endocostea typica* Zone by Jurkowska (2016). Jurkowska and Barski (2017) discussed the paleogeography of the Miechów Trough based on interpretations of the palynofacies. According to these authors, in the early Maastrichtian, the Pełczyska area was presumably situated close to the island that was possibly an extension of the 'Kukernitz Island'. At the Coniacian/Santonian boundary (and probably in the early Maastrichtian), this land was an obstacle partially separating the south-central European epicontinental basin from the influence of the Tethyan Realm. This observation was based on the warm water ammonites, belemnites and deep water planktonic foraminiferal assemblages that dominated in the late Coniacian and disappeared in the early Santonian in western Ukraine (Dubicka *et al.* 2014; Remin *et al.* 2016; Remin 2018). The concept of Jurkowska and Barski (2017) assumes that Pełczyska was an accumulation area for both marine deposits and fluvially derived land material. This is supported by the multiplicity of poorly preserved marine organisms, i.e., dinoflagellate cysts, sponges, small inoceramids – *E. typica* Whitfield, 1877 and *Cataceramus subcircularis* (Meek, 1876), and belemnites, organic particulate matter (dominated by terrestrial palynological elements), and the presence of freshwater prasinophyte algae (*Pterospermella* sp.), and chlorococcale algae (*Botryococcus* sp., *Palambages* sp.). It is worth noting that clinoptilolite (a rare mineral from the zeolite group) was also observed in the Pełczyska section by Jurkowska *et al.* (2019). This authigenic mineral is commonly associated with volcanism, less often with the diagenetic transformation of carbonate deposits enhanced with biogenic silica. However, in the studied succession, no volcanic sediments were identified (Jurkowska *et al.* 2019).

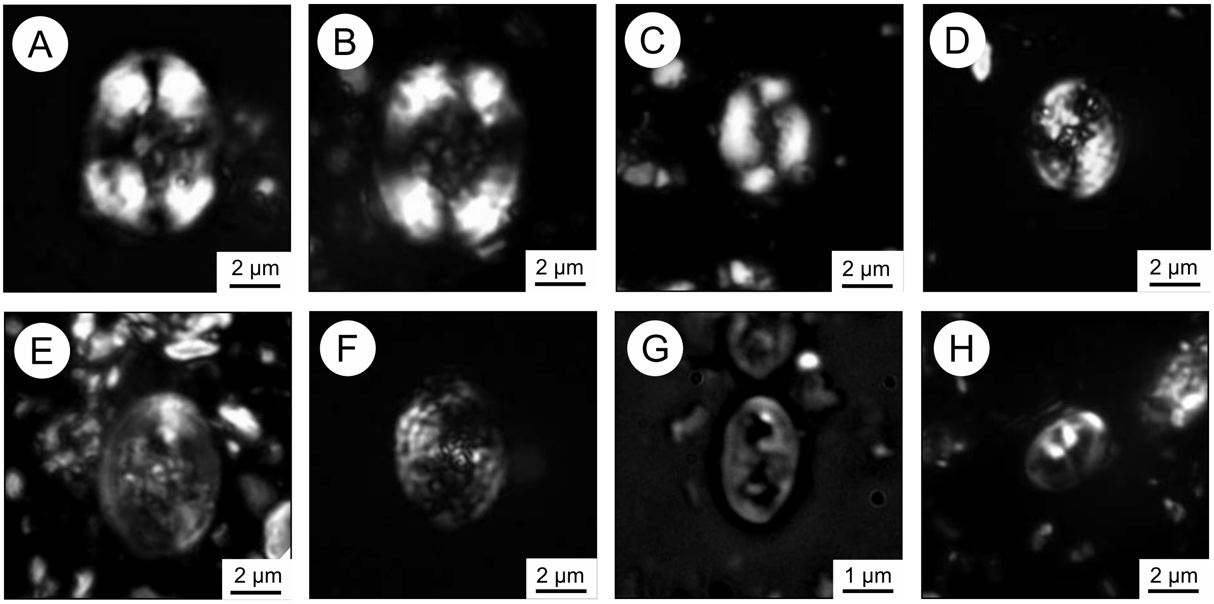
MATERIAL AND METHODS

Calcareous nannofossil analysis

For calcareous nannofossil analysis, 23 samples were collected at 0.5 m intervals (Text-fig. 3). The same samples were used in the studies of Jurkowska *et al.* (2019). Due to numerous previous analyses, there was not enough material left in two samples (nos. 9 and 16) to be used in this study. Smear-slides were prepared according to standard techniques described by Perch-Nielsen (1985) and Bown and Young (1998). The sediments were ground in a mortar and about 1 g of dried material was dispersed in 100 ml of distilled water. The solution was allowed to settle for a few seconds to eliminate particles greater than 30 µm. Then 1 ml of this suspension was



Text-fig. 3. Lithology of the Pełczyska section after Jurkowska *et al.* (2019) with ranges of selected biostratigraphically relevant nannofossil taxa (Burnett 1998) present in the studied section.

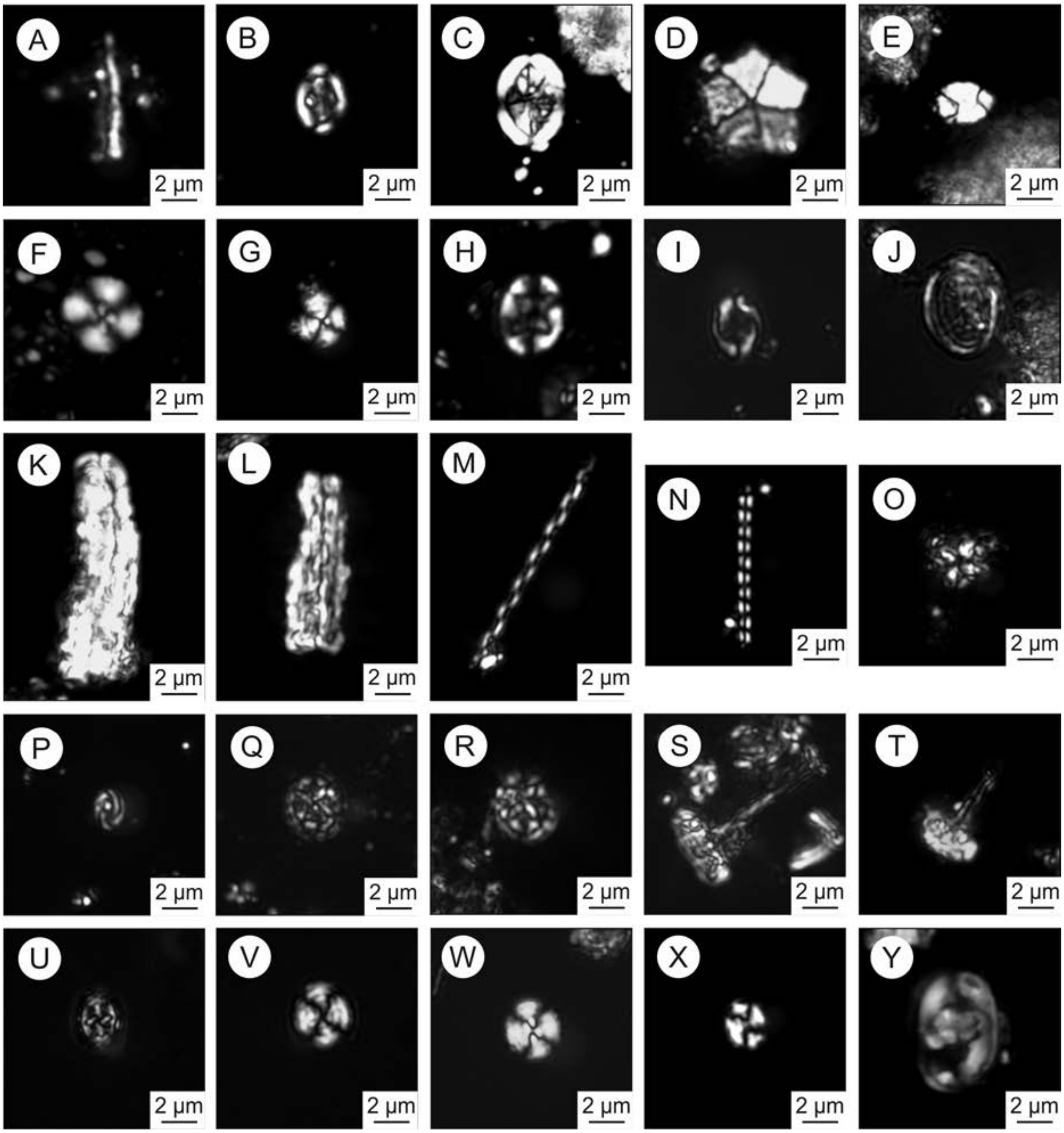


Text-fig. 4. Biostratigraphically relevant calcareous nannofossil species from the Pełczyska section (XPL images). **A–C** – *Broinsonia parca constricta* Hattner, Wind and Wise, 1980, samples nos. 2, 4; **D**–**F** – *Reinhardtites levis* Prins and Sissingh in Sissingh, 1977, samples nos. 19, 20; **G**, **H** – *Tranolithus orionatus* (Reinhardt) Reinhardt, 1966, samples nos. 2, 7.

evenly spread over the coverslip with a micropipette. The dried slides were mounted with glycerogelatin. Most slides were observed under a Nikon ECLIPSE LV100NPOL polarizing microscope at the Institute of Geological Sciences, Polish Academy of Sciences in Warsaw, Poland. Research was also conducted at the Faculty of Geology, University of Warsaw and the European Center for Geological Education in Korzecko. A Nikon ECLIPSE E100 light microscope and a ZEISS Primo Star microscope were used, respectively. Nannofossils were observed at a magnification of ×1000. Photographs of coccoliths were taken with a ZEISS Axiocam 105 color digital camera mounted on a ZEISS Axio Scope.A1 polarizing microscope (Text-figs 4 and 5).

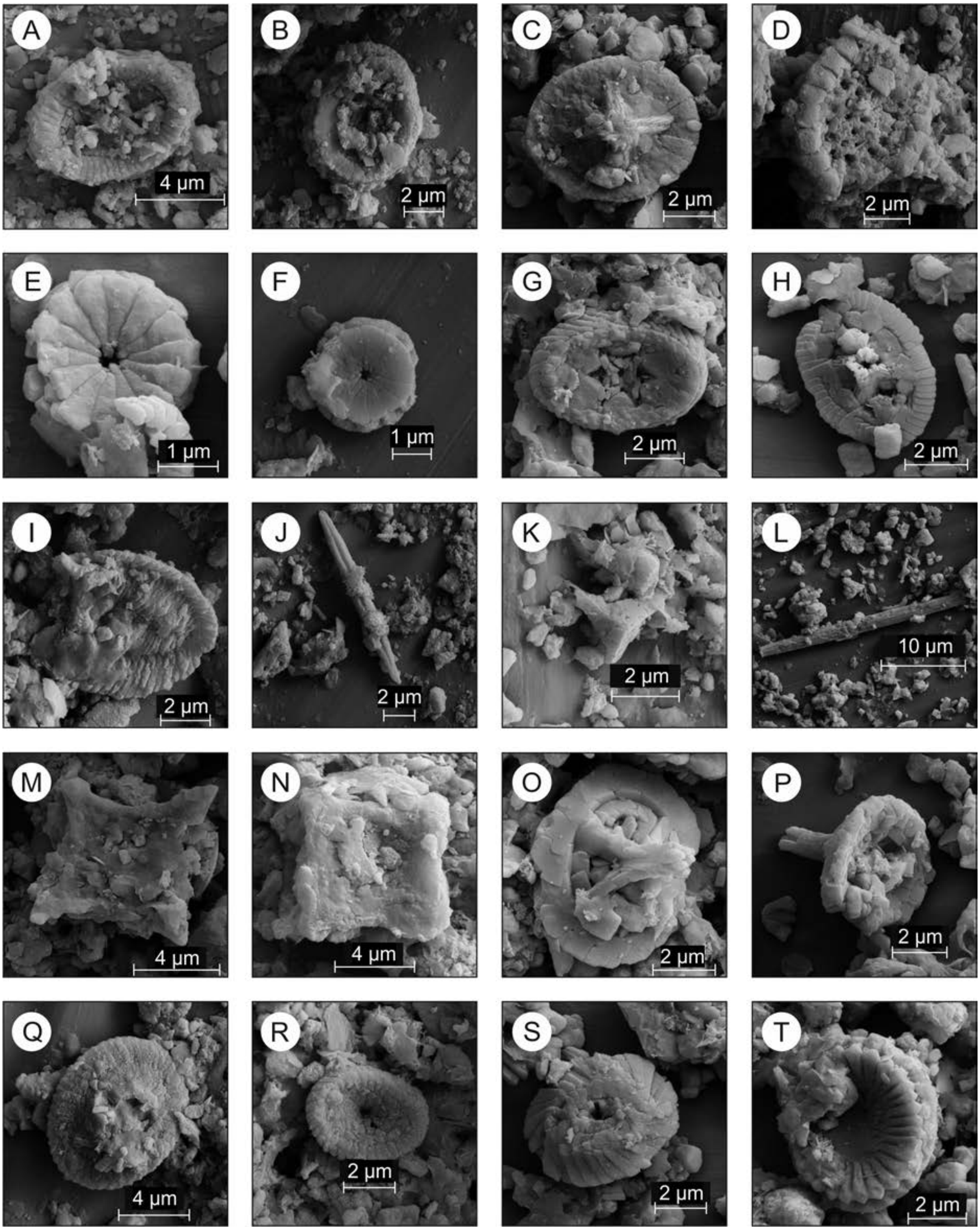
Qualitative analysis supplemented with quantitative data of nannofossil assemblages was used to reconstruct conditions during sedimentation. For the statistical analyses, at least 300 specimens per sample were counted in randomly selected fields of view. In addition, two transverses across the slide were examined in order to detect rare and biostratigraphically relevant species. The total calcareous nannofossil abundance was calculated based on the number of specimens per field of view (SPP/FOV). The relative abundance of each individual taxon was defined as follows: abundant (A) – more than 45% of the total assemblage; common (C) – 11–45% of the total assemblage; few (F) – 6–10% of the total assemblage; rare (R) – up to 5% of the total assemblage; and single (S) – if only one specimen was observed. Species richness, which can be used as an indicator of the relative stability of ecological conditions (Watkins 1989), is expressed as the total number of species recorded in each sample. The Shannon Diversity Index (heterogeneity) was calculated using MVSP 3.1. software. This indicator reflects changes in the diversity of the community. A highly diverse assemblage is expressed by a high heterogeneity index value. If the assemblage is dominated by only one or two specimens, then the Shannon Diversity Index is low (values close to 0).

Preservation was considered on the basis of the etching and overgrowth models proposed by Bown (1992): very poor (VP) – if the nannofossils are extremely etched; specimens are difficult to identify and sometimes identification is even impossible; poor (P) – if the nannofossils are etched and/or overgrown, the structures of the central area may be damaged, destroyed or obscured, fragments of crushed coccoliths are often visible; identification at species level may be difficult; moderate (M) – if the nannofossils show moderate etching and/or overgrown; primary morphological features are somewhat changed; nevertheless, most specimens can be identified to species level; good (G) – pristine samples to samples where nannofossils



Text-fig. 5. Selected calcareous nannofossils from the Pełczyska section (XPL images). **A** – *Acuturris scotus* (Risatti) Wind and Wise in Wise and Wind, 1977, sample no. 19; **B** – *Arkhangelskiella confusa* Burnett, 1997, sample no. 19; **C** – *Arkhangelskiella cymbiformis* Vekshina, 1959, sample no. 6; **D** – *Braarudosphaera bigelowii* (Gran and Braarud) Deflandre, 1947, sample no. 19; **E** – *Calculites obscurus* (Deflandre) Prins and Sissingh in Sissingh, 1977, sample no. 19; **F** – *Cyclagelosphaera margerelii* Noël, 1965, sample no. 20; **G** – *Cyclagelosphaera reinhardtii* (Perch-Nielsen) Romein, 1977, sample no. 19; **H** – *Eiffellithus turriseiffelii* (Deflandre) Reinhardt, 1965, sample no. 2; **I** – *Helicolithus trabeculatus* (Górka) Verbeek, 1977, sample no. 17; **J** – *Kamptnerius magnificus* Deflandre, 1959, sample no. 23; **K**, **L** – *Lucianorhabdus cayeuxii* Deflandre, 1959, samples nos. 10, 19; **M**, **N** – *Microrhabdulus decoratus* Deflandre, 1959, samples nos. 1, 19; **O** – *Micula decussata* Vekshina, 1959, sample no. 10; **P** – *Placozygus fibuliformis* (Reinhardt) Hoffmann, 1970, sample no. 19; **Q–T** – *Prediscosphaera cretacea* (Arkhangelsky) Gartner, 1968, samples nos. 6, 10 and 19; **U** – *Prediscosphaera spinosa* (Bramlette and Martini) Gartner, 1968, sample no. 23; **V**, **W** – *Watznaueria barnesae* (Black) Perch-Nielsen, 1968, samples nos. 19, 23; **X** – *Watznaueria biporta* Bukry, 1969, sample no. 1; **Y** – *Zeugrhabdotus embergeri* (Noël) Perch-Nielsen, 1984, sample no. 7.

Text-fig. 6. SEM micrographs of selected calcareous nannofossils from the Pełczyska section. **A**, **B** – *Arkhangelskiella* cf. *cymbiformis* Vekshina, 1959, samples nos. 19, 23; **C** – *Cretarhabdus conicus* Bramlette and Martini, 1964, sample no. 17; **D** – *Cribrosphaerella ehrenbergii* (Arkhangelsky) Deflandre in Piveteau, 1952, sample no. 23; **E**, **F** – *Discorhabdus ignotus* (Górka) Perch-Nielsen, 1968, samples nos. →



17, 23; **G** – *Eiffellithus turriseiffelii* (Deflandre) Reinhardt, 1965, sample no. 17; **H** – *Helicolithus anceps* (Górka) Noël, 1970, sample no. 17; **I** – *Kamptnerius magnificus* Deflandre, 1959, sample no. 23; **J** – *Lithraphidites carniolensis* Deflandre, 1963, sample no. 23; **K** – *Marthasterites inconspicuus* Deflandre, 1959 (reworked), sample no. 19; **L** – *Microrhabdulus decoratus* Deflandre, 1959, sample no. 17; **M** – *Micula concava* (Stradner) Verbeek, 1976, sample no. 17; **N** – *Micula decussata* Vekshina, 1959, sample no. 5; **O**, **P** – *Prediscosphaera cretacea* (Arkhangelsky) Gartner, 1968, sample no. 17; **Q** – *Reinhardtites levis* Prins and Sissingh in Sissingh, 1977, sample no. 25; **R** – *Rhagodiscus plebeius* Perch-Nielsen, 1968, sample no. 23; **S**, **T** – *Watznaueria barnesae* (Black) Perch-Nielsen, 1968, sample no. 17.

are only slightly altered by etching or overgrowing; specimens are clearly identifiable at species level.

The taxonomic identification is based on Perch-Nielsen (1985), Burnett (1998) and the online Nannotax3 database (Young *et al.* 2021). In the present study, the Upper Cretaceous zonation scheme of Burnett (1998) has been applied, supplemented with Thibault (2016) and compared with Boussaha *et al.* (2016). The biostratigraphy is based on the first occurrence (FO) or the last occurrence (LO) of nannofossil taxa.

The previously prepared solutions were also used to make samples for SEM analysis. Samples were transferred to metal plates with a radius of 0.5 cm by means of a micropipette . After the suspension was dried, the plates were plated with gold to improve conductivity. Images of calcareous nannofossils were taken with ZEISS Sigma VP (SEM), located at the Faculty of Geology, University of Warsaw (Text-fig. 6).

RESULTS

Nannofossil preservation, diversity and abundance

Most samples from the lower part of the Pełczyska section exhibit moderate coccolith preservation (up to 13). The vast majority of nannofossils show no visible traces of chemical dissolution, e.g., *Micula decussata* Vekshina, 1959, *Watznaueria barnesae* (Black) Perch-Nielsen, 1968, *Lucianorhabdus cayeuxii* Deflandre, 1959, *Arkhangelskiella cymbiformis* Vekshina, 1959, or *Broinsonia parca constricta* Hattner, Wind and Wise, 1980. However, moderate signs of mechanical disintegration are sometimes observed, e.g., *Discorhabdus ignotus* (Górka) Perch-Nielsen, 1968 and *Cribrosphaerella ehrenbergii* (Arkhangelsky) Deflandre in Piveteau, 1952. Only two samples (nos. 1 and 3) from the lowermost interval contain poorly preserved nannofossils. In the upper part of the section, the coccolith preservation deteriorates towards the top of the section. Crushed, incomplete specimens with mechanically damaged structures of the central area are more often visible, e.g., *Braarudosphaera bigelowi* (Gran and Braarud) Deflandre, 1947, *Helicolithus* spp. and *Chiastozygus* spp. Samples from the upper part of the succession (from 6 m upwards) are usually characterized by poorly preserved coccoliths (nos. 13–19 and 22–25), sometimes moderate (nos. 20 and 21) (Text-fig. 7).

In the studied material reworked species were also observed, i.e., *Broinsonia parca parca* (Stradner) Bukry, 1969, *Gartnerago obliquum* (Stradner) Noël, 1970, *Marthasterites inconspicuus* Deflandre, 1959, and *Uniplanarius trifidus* (Stradner) Hattner and Wise in Wind and Wise, 1983. They were rarely found throughout the section, and usually as single specimens in the assemblages (Appendix 1 – available only in the online version).

Sixty-nine calcareous nannofossil taxa were identified (see Appendix 2 – available only in the online version). The species richness of individual samples varies from 23 to 44 taxa resulting in a mean diversity of 35 species per sample. The total nannofossil abundance (= specimens per field of view) fluctuates from 5.8 to 14.1, with the mean value of 8.6. The Shannon Diversity Index varies from 0.88 to 1.35. A summary of the fluctuation of species richness, total nannofossil abundance, Shannon Diversity Index and the variability of the preservation is presented in Text-fig. 7.

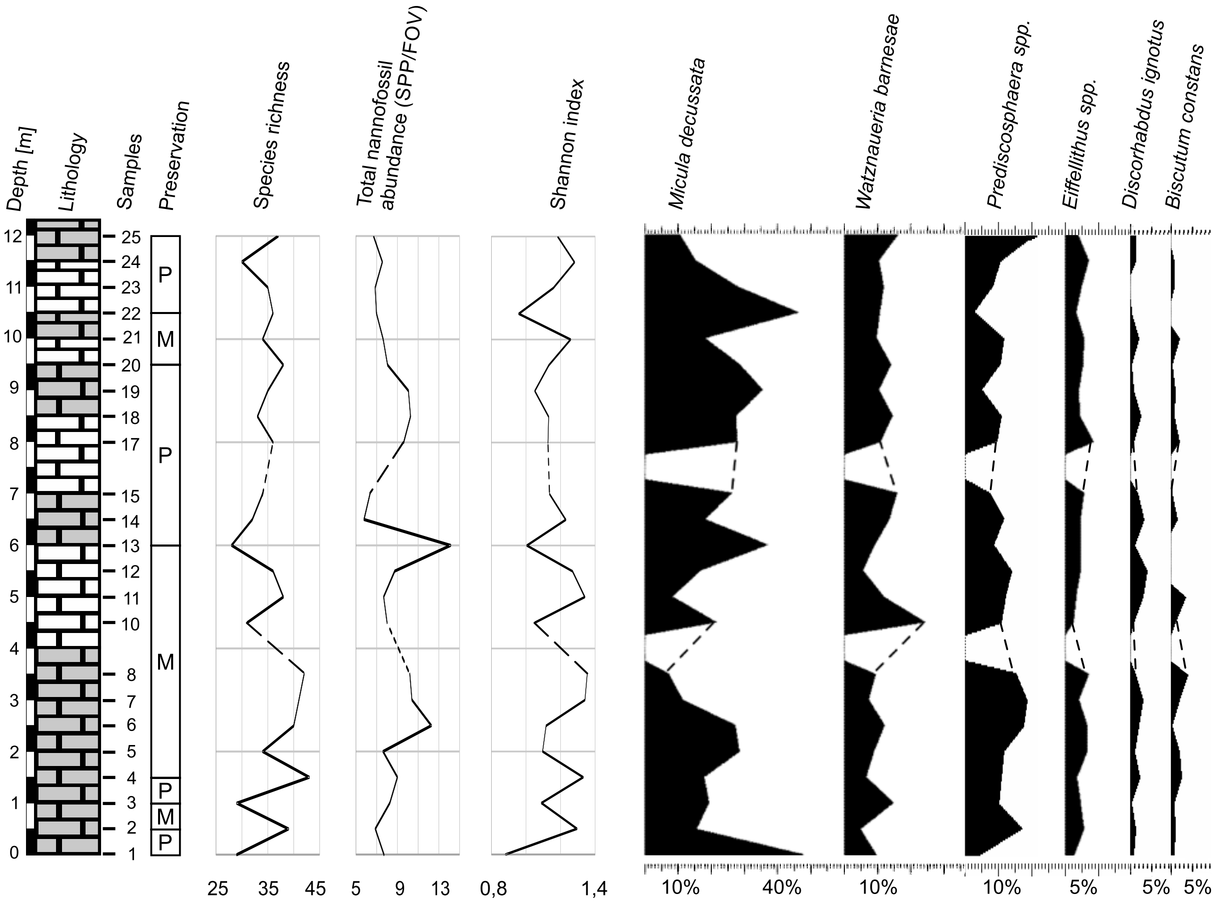
Biostratigraphy

Biostratigraphically useful species in the studied section include: *Broinsonia parca constricta*, *Reinhardtites levis* Prins and Sissingh in Sissingh, 1977 and *Tranolithus orionatus* (Reinhardt) Reinhardt, 1966 (Text-fig. 4). According to Burnett (1998), the LO of *R. levis* marks the base of nannofossil Zone UC19 and the LOs of *T. orionatus* and *B. parca constricta* define the bases of UC18 and UC17, respectively. These three species were present in each sample (Text-fig. 3). *Reinhardtites anthophorus* (Deflandre) Perch-Nielsen, 1968 and *Eiffellithus eximius* (Stover) Perch-Nielsen, 1968, the LO of which determines the base of the UC16 Zone, were not observed. Furthermore, it appears that one more crucial taxon is present in the lowest interval, although only in samples nos. 4 and 6 (Text-fig. 3), in both cases represented by the possible one- or two-armed remains of *Uniplanarius trifidus*. The LO of this taxon marks the upper Campanian/lower Maastrichtian boundary in the Tethyan Province (Thibault 2016). However, we have assumed that this species is reworked in the studied material (see below) and the entire Pełczyska section represents the subzone UC16b^{TP} (lower Maastrichtian).

Calcareous nannofossil assemblages

In the Pełczyska section, there are four nannofossil taxa which have a mean relative abundance of more than 10%. These taxa include *Micula* spp., *Watznaueria* spp., *Prediscosphaera* spp., and *Arkhangelskiella* spp.

The dominant genus is *Micula* (Text-figs 5O, 6M, N). The mean relative frequency accounts for 24%, varying from 7.2% (sample no. 8) to 47.7% (sam-



Text-fig. 7. Calcareous nannofossil data from the Pełczyska section, showing fluctuations of species richness, total nannofossil abundance, Shannon Diversity Index, vertical variation of preservation (P – poor, M – moderate), relative abundances of *Micula decussata*, *Watznaueria barnesae* and dissolution prone taxa (*Prediscosphaera* spp., *Eiffellithus* spp., *Discorhabdus ignotus*, *Biscutum constans*); lithology after Jurkowska *et al.* (2019).

ple no. 1). *Micula decussata* is the most abundant taxon (Text-fig. 7, Appendix 1), whereas *M. concava* (Stradner) Verbeek, 1976, *M. praemurus* (Bukry) Stradner and Steinmetz, 1984, and *M. premolisilvae* Lees and Bown, 2005 are less frequent.

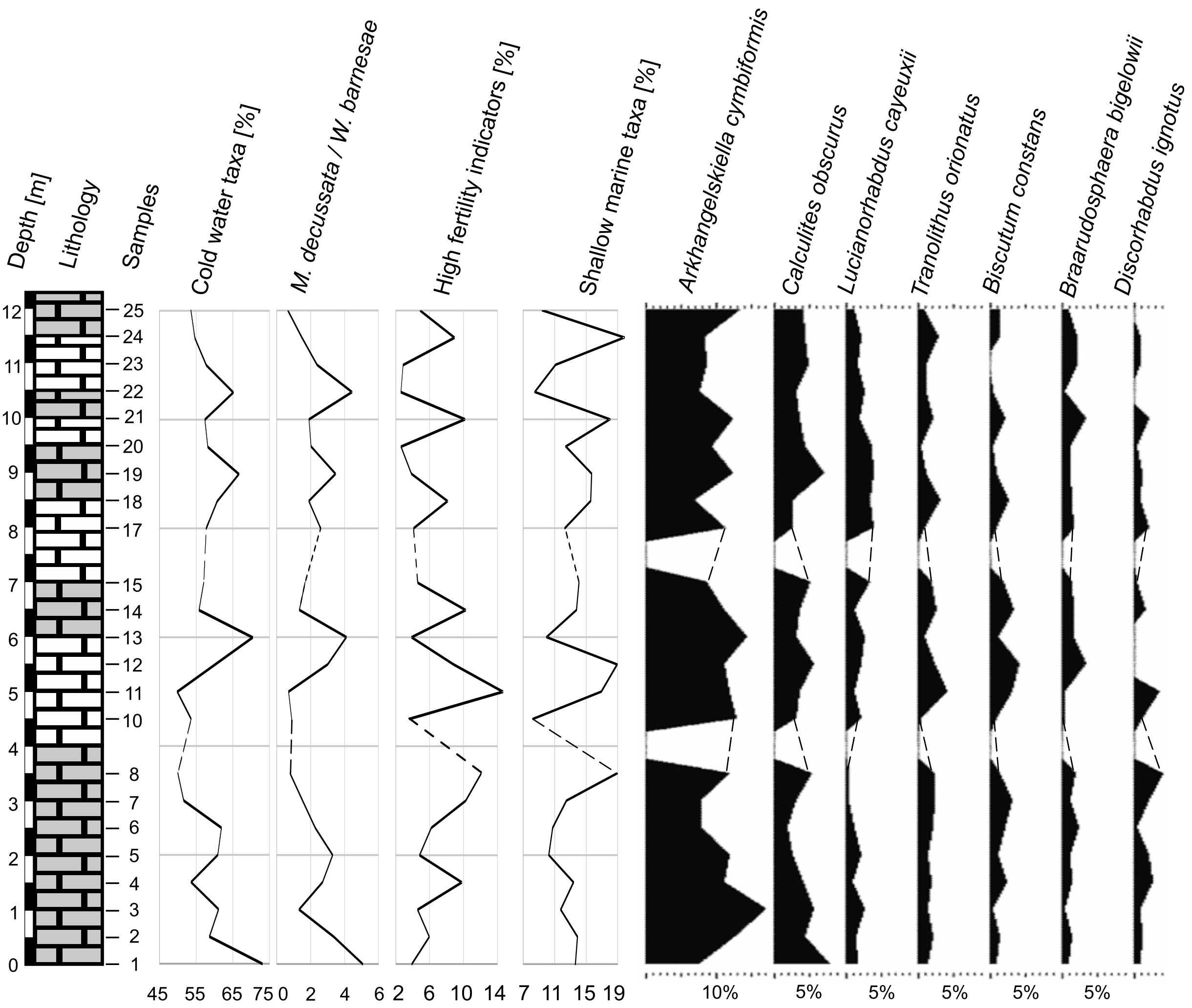
Another very common genus is *Watznaueria* (Text-figs 5V–X, 6S, T) with a mean frequency of 12%, ranging from 6% (sample no. 2) to 25% (sample no. 10). It is represented by *Watznaueria barnesae* (common), *W. biporta* Bukry, 1969 (rare) and *W. quadriradiata* Bukry, 1969 (rare).

Representatives of *Prediscosphaera* spp. (Text-figs 5Q–U, 6O, P) include *P. cretacea* (Arkhangelsky) Gartner, 1968 (common), *P. grandis* Perch-Nielsen, 1979 (few), *P. spinosa* (Bramlette and Martini) Gartner, 1968 (rare), *P. arkhangelskyi* (Reinhardt) Perch-Nielsen, 1984 (single), and *P. ponticula* (Bukry) Perch-Nielsen, 1984 (single). The abundance of *Prediscosphaera* spp. fluctuates from 2.9% (sample no. 22) to 21.8% (sample no. 25), with a mean frequency of 11.5% (Text-fig. 7).

With an average relative abundance of 11%, *Arkhangelskiella* spp. (Text-fig. 5B, C; Text-fig. 6A, B) is also common in the Pełczyska section. It is represented by *Arkhangelskiella cymbiformis* (common) and *A. confusa* Burnett, 1997 (rare). The frequency of this taxon varies from 6.8% (sample no. 18) to 17.3% (sample no. 3). The abundance of *Arkhangelskiella* spp. is relatively high throughout the section and shows no distinct trend.

Remarks on paleoecology and paleoclimatology

Calcareous nannofossil assemblages from the studied section are characterized by a large proportion of cold and cool water taxa, ranging from 50% to over



Text-fig. 8. Summary of paleoecological indices of temperature and fertility of water based on calcareous nannofossils from this study; shallow marine species (as a group, as well as *Arkhangelskiella cymbiformis*, *Calculites obscurus*, *Lucianorhabdus cayeuxii*, *Tranolithus orionatus*, *Biscutum constans*, *Braarudosphaera bigelowii*, *Discorhabdus ignotus* individually); *M. decussata*/*W. barnesae* ratio. Lithology after Jurkowska *et al.* (2019).

70% (Text-fig. 8). They include: *Ahmuellerella octoradiata* (Górka) Reinhardt, 1966, *Arkhangelskiella* spp., *Biscutum constans* (Górka) Black in Black and Barnes, 1959, *B. magnum* Wind and Wise in Wise and Wind, 1977, *Calculites obscurus* (Deflandre) Prins and Sissingh in Sissingh, 1977, *Gartnerago* spp., *Kamptnerius magnificus* Deflandre, 1959, *Lucianorhabdus cayeuxii*, *Microrhabdulus decoratus* Deflandre, 1959, *Micula decussata*, *Prediscosphaera cretacea*, *Tranolithus* spp. and *Zeugrhabdotus erectus* (Deflandre) Reinhardt, 1965 (Watkins *et al.* 1996; Lees 2002; Thibault and Gardin 2006).

The total number of warm water indicators is relatively low and varies between 9 and 31%, with a mean value of 17.2%. The thermophilic taxa include: *Ceratolithoides aculeus* (Stradner) Prins and Sissingh in Sissingh, 1977, *Cylindralithus serratus* Bramlette and Martini, 1964, *Lithraphidites carniolensis* Deflandre, 1963, *Retecapsa surirella* (Deflandre and Fert) Grün in Grün and Allemann, 1975, *Uniplanarius gothicus* (Deflandre) Hattner and Wise in Wind and Wise 1983, *U. trifidus*, and *Watznaueria* spp. (Erba *et al.* 1992; Lees 2002; Thibault and Gardin 2007).

Species adapted to higher nutrient levels, such as *Biscutum constans*, *Discorhabdus ignotus*, *Placozygus fibuliformis* (Reinhardt) Hoffmann, 1970, *Tranolithus orionatus*, and *Zeugrhabdotus erectus* (Bornemann *et al.* 2005; Sheldon *et al.* 2010; Linnert and Mutterlose 2015) are relatively low in abundance throughout the section (2.6 to 14.7%, with a mean of 6.6%; Text-fig. 8). Low fertility indicators, i.e., *Eiffellithus turriseffelii* (Deflandre) Reinhardt, 1965, *Watznaueria barnesae*, and *Prediscosphaera cretacea* are more numerous (Erba *et al.* 1992).

Shallow marine species account for 8 to 20% of the assemblages, with a mean relative abundance of 13% (Text-fig. 8). They include: *Biscutum constans*, *Braarudosphaera bigelowii*, *Calculites obscurus*, *Discorhabdus ignotus*, *Eiffellithus gorkae* Reinhardt, 1965, *Helicolithus trabeculatus* (Górka) Verbeek, 1977, *Kamptnerius magnificus*, *Lucianorhabdus cayeuxii*, *Prediscosphaera spinosa*, *Tranolithus orionatus* and *Zeugrhabdotus erectus* (Lees 2002; Linnert and Mutterlose 2015; Püttmann and Mutterlose 2019, 2021). In samples nos. 8, 11, 12, 21 and 24 we observed the declining abundance of *Micula decussata* and *Watznaueria barnesae* with a simultaneous increase of *Arkhangelskiella cymbiformis*, *Eiffellithus* spp., *Microrhabdulus decoratus*, *Placozygus fibuliformis*, *Prediscosphaera* spp., and shallow marine species (Text-figs 7 and 8). Moreover, the frequency of high fertility indicators is higher in samples nos. 8, 11, 21 and 24. This may indicate fluctuations in sea level and a change in distance from the coastline during the sedimentation.

The *M. decussata*/*W. barnesae* ratio has been used to determine paleotemperature variations and to detect cool events in the Maastrichtian (Ovechkina and Alekseev 2005; Mandur and El Ashwah 2015). The value of the *M. decussata*/*W. barnesae* ratio ranges from 0.7 to 5.1, with an average of 2.3 (Text-fig. 8). This ratio corresponds with the value of cold water taxa. However, it should be noted that *W. barnesae* and *M. decussata* are also considered to be the two species most resistant to dissolution (Thierstein 1980).

DISCUSSION

Diagenetic signal recorded in the nannofossil assemblages

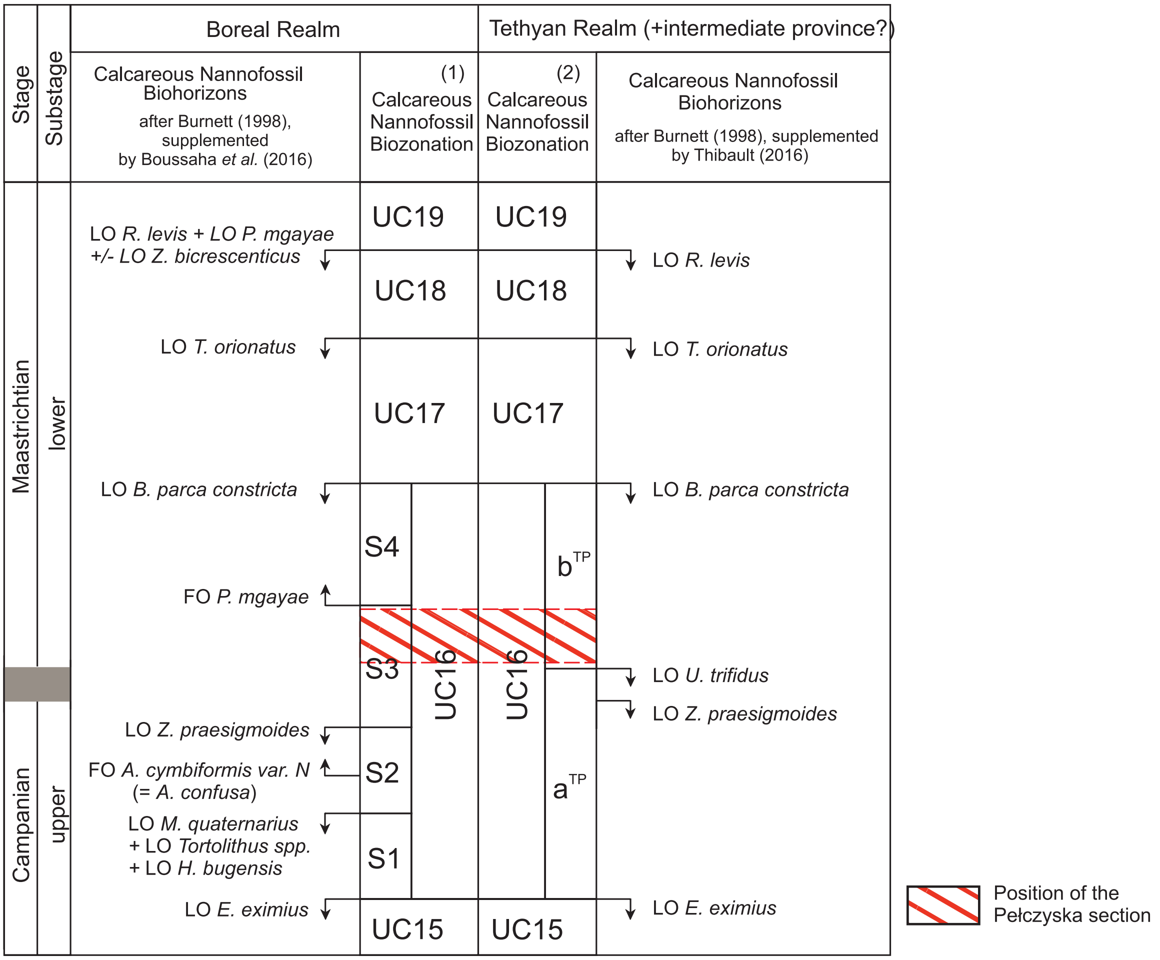
On the basis of the calcareous nannofossil community, it is possible to estimate the impact of diagenesis on the primary nannofossil assemblage. By means of experimental studies, Thierstein (1980) determined the dissolution susceptibility of selected nannofossils. A high concentration of *Micula decussata* and *Watznaueria barnesae* may indicate poor preservation of the coccolith assemblage and diagenetic enhancement (Roth 1983). Furthermore, assemblages containing over 40% of *W. barnesae*, along with a low abundance of species prone to dissolution (e.g., *Biscutum constans*, *Discorhabdus ignotus* and *Prediscosphaera* spp.) were considered to be too altered to properly reflect the original species composition (Williams and Bralower 1995). Other dissolution susceptible taxa include *Eiffellithus* spp., *Cribrosphaerella ehrenbergii* and *Zeugrhabdotus* spp. (Thierstein 1980). In the Pełczyska section, *W. barnesae* reached a maximum of 24% in the assemblages in sample no. 10. A simultaneous increase in the abundance of this species combined with a decrease in the accumulation of dissolution-sensitive taxa was observed in samples nos. 1, 3 and 10 (Text-fig. 7). In the present study, the diagenetically altered samples display a predominance of species resistant to dissolution, negligible presence of prone taxa and low values of indicators such as species richness, Shannon Diversity Index and total nannofossil abundance (Text-fig. 7).

In this study, maximum values of *M. decussata* are presented as three peaks recorded in samples nos. 1, 13 and 22 (poorly preserved) with relative abundances above 37% of the total assemblage (Text-fig. 7). The richness of this species was simultaneously associated with a low abundance of resistant prone species. The relative abundance of *W. barnesae* remains stable, at approximately 10% of the total assemblage.

The Shannon Diversity Index in all three samples is close to 1 (the minimum over the entire sequence is 0.88), indicating the dominance of one or two species. In samples nos. 1 and 13 the species richness is the lowest (around 28 species) in relation to the whole succession. In turn, in sample no. 22 the diversity increased to 36 species. The total abundance of nannofossils in samples nos. 1 and 22 amounted to c. 7 species/FOV, while in sample no. 13 it amounted to 14.1 species/FOV. All things considered, a clear diagenetic signal was only present in sample 1. It is also possible that samples nos. 13 and 22 had been diagenetically modified, but this cannot be clearly demonstrated (Text-fig. 7).

Biostratigraphic position of the Pełczyska section

Burnett (1998) defined the Upper Cretaceous (UC) nannofossil biozonation scheme for three provinces: Tethyan-intermediate, Austral and Boreal. She also compiled the main nannofossil events for all realms. Many authors still follow this zonation, but several others have noticed the diachronism of the first and last appearances of calcareous nannofossils (e.g., Nifuku *et al.* 2008; Thibault *et al.* 2010,

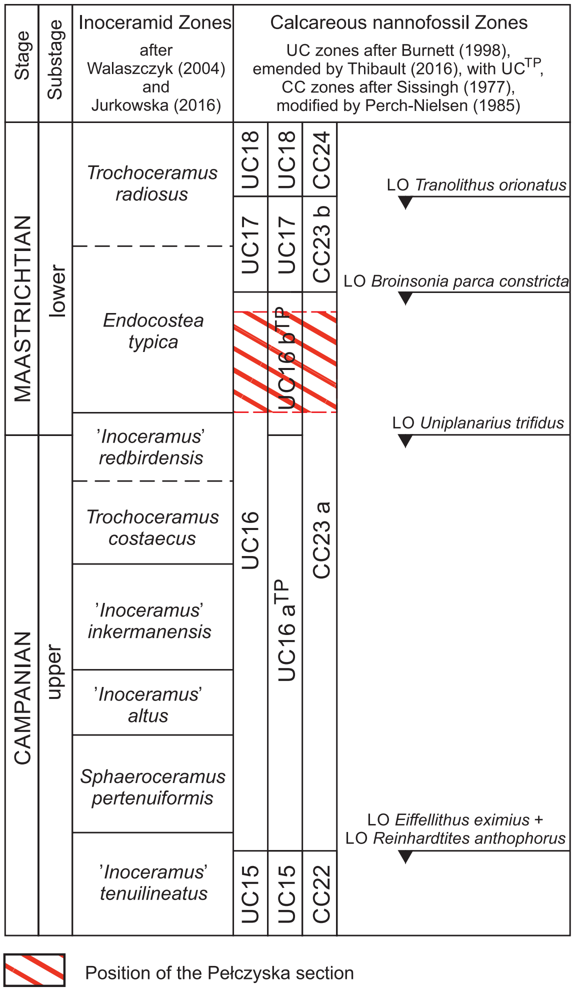


Text-fig. 9. Correlation of nannofossil biostratigraphic schemes from the Boreal Realm and the Tethyan Realm (+ intermediate province?) for the upper Campanian–lower Maastrichtian, with the position of the Pełczyska section. (1) after Burnett (1998) supplemented by Boussaha *et al.* (2016); (2) after Burnett (1998) emended by Thibault (2016).

2012b). Burnett's (1998) UC16 biozone was revised by Thibault (2016) for the Tethyan Realm and by Boussaha *et al.* (2016) for the Boreal Realm. A comparison of these two biozonations amending the zonation of Burnett (1998) is presented in Text-fig. 9. The difference between the original zonation and amended versions mainly focuses on the positioning of the LO of *Broinsonia parca constricta.* The LO of this taxon falls slightly below the Campanian/Maastrichtian boundary according to Burnett (1998), whereas Thibault (2016) and Boussaha *et al.* (2016) placed this event in the lowermost Maastrichtian. The displacement of the LO of *B. parca constricta* was also adapted e.g., by Thibault *et al.* (2012a) and Jelby *et al.* (2014) in the Danish Basin, Najafpour and Mahanipour (2015) in SW Iran, Linnert *et al.* (2016) in NW Germany, Granchovski (2019) in Bulgaria, and by Gradstein *et al.* (2020).

Therefore, it is difficult to clearly determine which biostratigraphy is suitable for the study area. In the Pełczyska section boreal subzonal marker species were not identified, i.e., *Heteromarginatus bugensis* (Górka) Crux in Crux *et al.*, 1982, *Monomarginatus quaternarius* Wind and Wise in Wise and Wind, 1977, *Prediscosphaera mgayae*, *Tortolithus caistorensis* Crux in Crux *et al.*, 1982 or *Zeugrhabdotus praesigmoides* Burnett, 1997. Only *Arkhangelskiella confusa* (= *A. cymbiformis* var. N) was present. This may suggest that a boreal influence was not relevant in this area. Nevertheless, nannofossil taxa considered to be cool water species, e.g., *Micula decussata*, *Arkhangelskiella* spp. and *Calculites obscurus*, predominate in the studied assemblage. Another possibility may be that the Pełczyska section was stratigraphically located between the LO of *Zeugrhabdotus praesigmoides* and the FO of *Praediscoshpaera mgayae* within subzone UC16 S3 (Text-fig. 9).

The nannofossil subdivision proposed by Thibault (2016) also seems to be useful for defining the stratigraphic position of the Pełczyska section. He subdivided UC16 into two subzones (UC16a^{TP} and UC16b^{TP}), separated by the LO of *Uniplanarius trifidus*, which marks the Campanian/Maastrichtian boundary. The presence of the remains of *U. trifidus* may be reworked or possibly present indicating the upper part of the UC16a^{TP} subzone (from sample no. 6 downwards; Text-fig. 3). In addition, the boreal UC16 S3 subzone correlates with both Tethyan subzones UC16a^{TP} and UC16b^{TP}. However, complete specimens have not been preserved, while the remains were sparse and occurred in only two samples (Appendix 1). To clarify this issue, we correlated the nannofossil zonation with the local inoceramid biostratigraphy (Text-fig. 10). The entire UC16a^{TP} subzone and the lower part of the UC16b^{TP} subzone correspond to the '*Inoceramus*' *redbirdensis* Zone, which was not designated by Jurkowska (in Jurkowska and Barski 2017), whereas the upper segment of the UC16b^{TP} subzone coincides with the *E. typica* Zone – the only one marked in the Pełczyska section (Jurkowska and Barski 2017). All things considered, we believe that it is more reasonable to claim that *U. trifidus* was reworked in the studied material and subzone UC16a^{TP} was not recorded in the Pełczyska section.



Text-fig. 10. Correlation of selected calcareous nannofossil zonation schemes (Sissingh 1977; Perch-Nielsen 1985; Burnett 1998; supplemented by Thibault 2016) with biozonations based on inoceramids (Walaszczyk 2004; Jurkowska 2016) for the upper Campanian–lower Maastrichtian interval with the position of the Pełczyska section. Chronostratigraphy after Gradstein *et al.* (2020).

Paleoecology

Numerous biogeographic and stratigraphic studies of calcareous nannofossils compared with other microfossils and geochemical paleoenvironmental indicators allows for the interpretation of nannofossil paleoecology (e.g., Eldrett *et al.* 2020; Nyerges *et al.* 2021; Chakraborty *et al.* 2021). Although there is agreement on the paleoenvironmental preferences of the most common Mesozoic species, the palaeoecological interpretation of many taxa is still uncertain or controversial. The main factors affecting the diversity and abundance of calcareous nannofossil assemblages were access to light and nutrients, mainly nitrates, phosphates and trace minerals (Hay and Flögel 2012), as well as fluctuations in temperature and salinity (Mutterlose *et al.* 2005).

Nannofossils as temperature indicators

Water temperature appears to be a major factor that controls the occurrence of a particular species. The geographical range for coccolithophores can be divided into three latitudinal sectors. In the Mesozoic, high species diversity was typical for low latitudes (Tethyan Realm), where the water surface temperature was warm (Brand 1994), but the standing population tended to be low (Andruleit *et al.* 2004). Common taxa in the warm Tethyan Province included: *Watznaueria* spp., *Ceratolithoides aculeus*, *Cylindralithus serratus*, *Lithraphidites carniolensis*, *Uniplanarius gothicus*, *U. trifidus* and *Retecapsa surirella* (Lees 2002; Thibault and Gardin 2007).

In the intermediate province (mid to low latitudes) the surface water was moderately warm and nutrients were usually in abundance (Street and Bown 2000). High latitudinal assemblages (Boreal Realm) were characterized by low species diversities due to more demanding conditions such as cool surface water (Mutterlose and Kessels 2000). However, in this environment there was a large input of nutrients, which allowed some taxa (*Ahmuellerella octoradiata*, *Kamptnerius magnificus* and *Gartnerago* spp. interpreted as cool water indicators) to thrive despite unstable ecological conditions (Watkins *et al.* 1996; Lees 2002; Thibault and Gardin 2006). Furthermore, *Arkhangelskiella* spp., *Lucianorhabdus cayeuxii* and *Prediscosphaera cretacea* (Thierstein 1981; Lees 2002; Mandur and El Ashwah 2015) have been found mostly in high latitudes and less frequently at mid latitudes. *Zeugrhabdotus* spp., *Biscutum constans*, *B. magnum*, *Calculites obscurus*, *Microrhabdulus decoratus* and *Tranolithus* spp. were also considered to be cool water species (Lees 2002; Thibault and Gardin 2006).

Some species, such as *Eiffellithus* spp. and *Reinhardtites levis* appear to have no latitudinal preference (Ovechkina and Alekseev 2005; Sheldon *et al.* 2010). However, they were considered as cool water taxa by Lees (2002) and Watkins and Self-Trail (2005). In this study, we included these species to cosmopolitan.

One of the main components of the Mesozoic nannofossil assemblage was *Watznaueria barnesae.* Watkins *et al.* (1996) postulated that this species was an indicator of warm surface water, because it was absent or rare at the high latitudes. In turn, other researchers (Thierstein 1981; Lees 2002; Thibault and Gardin 2007) considered it to be an eurytopic cosmopolitan species and ecologically tolerant taxon, which preferred the tropics and subtropics. *Watznaueria barnesae* has been found in abundance in both open ocean and shelfal sites (Lees 2002). In this study, we considered *W. barnesae* as a warm water indicator.

The temperature preference of *Micula decussata*, another common Mesozoic species is not entirely clear. It had a wide range of distribution. Some researchers suggested that this taxon favored cooler surface water (Watkins and Self-Trail 2005). However, others showed that *M. decussata* could also reach high values in the tropics and subtropics. Among others, Thierstein (1981) and Lees (2002) postulated that *M. decussata* was a clearly cosmopolitan species, which was dominant at high latitudes, but was also very abundant at low latitudes (see also Ovechkina and Alekseev 2005; Watkins and Self-Trail 2005). Tantawy (2003) interpreted this taxon as preferring less fertile waters and increasing in abundance in very stressful environmental conditions. In this study we consider *M. decussata* as a cool water species.

In the studied assemblage cool water species dominated over warm water taxa along the entire section (Text-fig. 8). Only *W. barnesae* was more common. Additionally, cool water indicators were less frequent. It seems that in the Pełczyska section, currents from the NW (Boreal Province) prevailed over warm currents from the Tethyan Realm.

Nannofossils as fertility indicators

Nannoplankton adapted to meso- and oligotrophic stable oceanic conditions (Brand 1994) with low nutrient concentrations (Andruleit *et al.* 2004). In habitats with higher fertility, they were not so plentiful due to competition with other groups of phytoplankton, such as diatoms and dinoflagellates (Brand 1994; Mutterlose *et al.* 2005). However, coccoliths have also been reported from almost eutrophic paleoenvironments (Erba *et al.* 1992), especially in nutrient-enriched continental shelf or upwelling areas (Linnert and Mutterlose 2015; Püttmann and Mutterlose 2019, 2021).

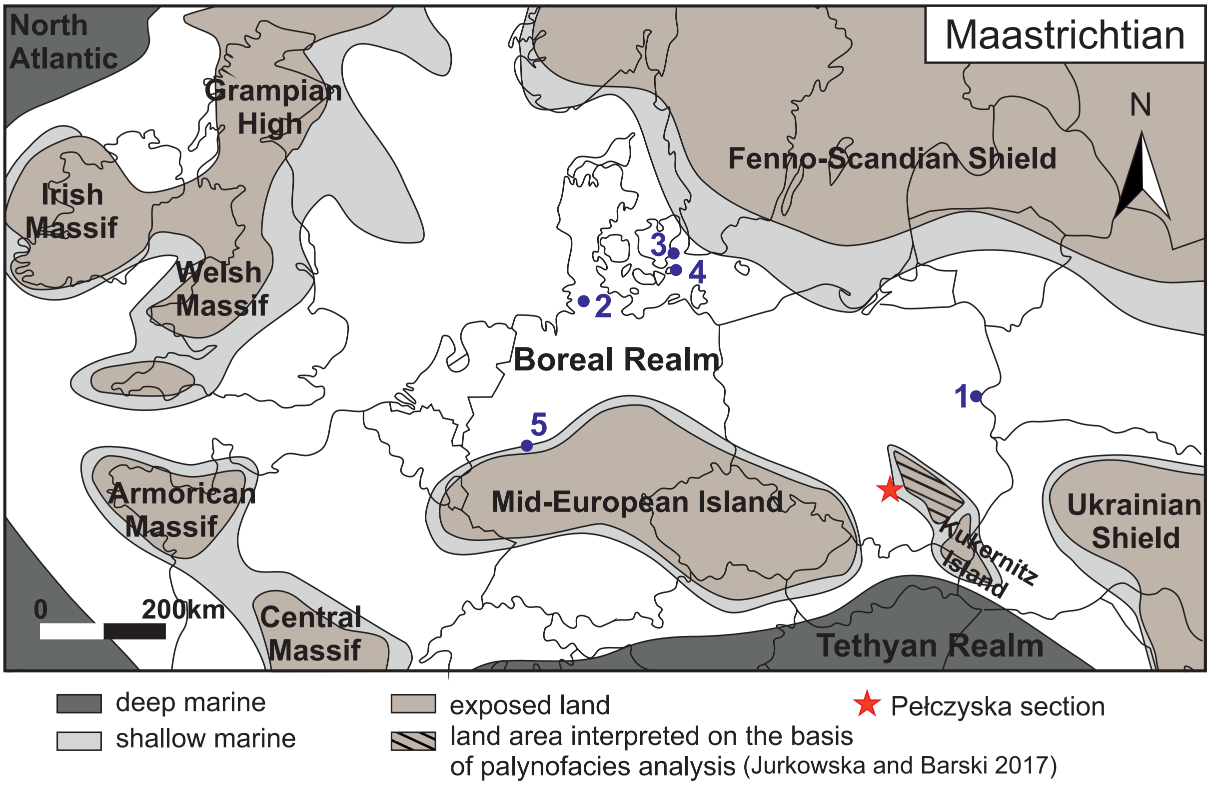
Nutrients, in particular nitrates and phosphates, could be supplied by rivers or found in upwelling areas. Some nannofossil taxa responded to the increase in nutrient content by enhancing species abundance, while a diversity of the community declined. *Biscutum constans*, *Zeugrhabdotus erectus* and *Discorhabdus ignotus* were the main Mesozoic species which bloomed under eutrophic or semi-eutrophic conditions (Erba *et al.* 1992; Bornemann *et al.* 2005). *Tranolithus orionatus* and probably *Placozygus fibuliformis* (based on the assumption that *Placozygus* is related to *Zeugrhabdotus*) also showed an affinity for high fertile waters (Sheldon *et al.* 2010; Linnert and Mutterlose 2015). On the contrary, *Watznaueria barnesae* had a preference for low water fertility conditions and is considered as an indicator of nutrient deficiency (Williams and Bralower 1995). Moreover, the population sizes of *Micula decussata*, *Prediscosphaera* spp., *Eiffellithus* spp. and *Microrhabdulus decoratus* did not respond positively to nutrient increase. This may indicate that these taxa preferred more stable oligotrophic conditions (Erba *et al.* 1992).

In the Pełczyska section high fertility indicators were low in abundance. *Biscutum constans*, *Zeugrhabdotus erectus*, *Discorhabdus ignotus*, *Tranolithus orionatus* and *Placozygus fibuliformis* were rare. The mean abundance of these individual taxa did not exceed 4% (Text-fig. 8). This indicates that the water fertility was low for almost the entire time of sedimentation.

Comparison of the Pełczyska section to shallow settings

Nannofossil species that indicate shallow sea levels have been found in the study area. *Braarudosphaera bigelowii* was rare in the open Mesozoic oceans and survived the Cretaceous/Paleogene mass extinction. It is currently found in eutrophic environments near coastal shores with low salinity, even in brackish areas, whereas in the open ocean it is rare (Konno *et al.* 2007; Bown and Young 2019). In the Mesozoic, *B. bigelowii* was considered to be an indicator of neritic environments, inhabiting the inner- to middle-shelf (Kelly *et al.* 2003). This species showed great adaptability to water salinity. *Braarudosphaera bigelowii* occurred in increased abundance in environments with low salinity (Melinte 2004), but has also been described from areas with higher salinity (Silva *et al.* 2008). *Kamptnerius magnificus* and holococcoliths such as *Calculites obscurus* and *Lucianorhabdus cayeuxii* preferred shelfal areas rather than the open sea. Moreover, relatively high abundances of *Arkhangelskiella cymbiformis* are also indicative of shallow seas (Thierstein 1981; Lees 2002).

Linnert and Mutterlose (2015), and Püttmann and Mutterlose (2019, 2021) explored Cretaceous nearshore settings from the SW part of the Münsterland Basin in northern Germany (Text-fig. 11). This allowed them to identify the species inhabiting the proximal and distal shelf. Their nearshore nannofossil assemblages were unexpectedly highly diverse and well-preserved. According to these authors, species associated with high fertility, such as *Biscutum constans*, small *Zeugrhabdotus* spp. and *Tranolithus orionatus* (Erba *et al.* 1992; Mutterlose *et al.* 2005) were abundant in cool coastal waters, rather than in the open ocean. The coastal area was most likely associated with a large supply of nutrients, because the abundance of these species declined with increasing distance from land. Other taxa associated with the proximal shelf were *Eiffellithus gorkae*, *Helicolithus trabeculatus* and *Prediscosphaera spinosa*. The authors also claim that *Watznaueria barnesae* and *Retecapsa* spp. Black, 1971, i.e., *R. angustiforata* Black, 1971; *R. crenulata* (Bramlette and Martini) Grün in Grün and Allemann, 1975; and *R. surirella*, increased in abundance in the open sea, whereas *Chiastozygus litterarius* Manivit, 1971, *Eiffellithus turriseiffelii*



Text-fig. 11. Paleogeographic map of Europe in the Maastrichtian (after: Ziegler 1990; Dadlez *et al.* 1998; Philip *et al.* 2000; Świdrowska *et al.* 2008 and Jurkowska *et al.* 2019) with localities mentioned in the text: 1 – Mielnik; 2 – Kronsmoor; 3 – Stevns Klint; 4 – Møns Klint; 5 – Bochum, Duisburg, Essen, Herne, Oberhausen (Münsterland Basin); star – studied section.

and *Prediscosphaera cretacea* showed no preference for water depth (Linnert and Mutterlose 2015).

The taxonomic data, diversity, Shannon Diversity Index and relative abundance of species that preferred fertile waters that were identified in our work, were compared with results from the coastal settings of the Münsterland Basin (Linnert and Mutterlose 2015; Püttmann and Mutterlose 2019, 2021). In Bochum and Herne the mean species richness was around 55 species per sample, whereas in Duisburg, Essen and Oberhausen the average diversity varied from 50 to even 81 species per sample. The mean abundance of individual taxa adapted to high fertility was high in all sites (*Biscutum constans* 9–28%, *Zeugrhabdotus* spp. 8–23%, *Tranolithus orionatus* over 8%). In all locations, the heterogeneity exceeded 1.5, even reaching values of up to 3. The collective data suggests that nearshore settings were characterized by a lack of clearly dominant taxa and evenly distributed species in assemblages (Linnert and Mutterlose 2015; Püttmann and Mutterlose 2019, 2021).

In the Pełczyska section, nannofossil assemblages were less diverse (23–44 taxa, 35 species per sample) and the Shannon Diversity Index was much lower (0.88–1.35) than in Germany (Linnert and Mutterlose 2015; Püttmann and Mutterlose 2019, 2021). Additionally, the percentage of high fertility indicator species from the coastal zone was low. However, shallow marine species determined by Thierstein (1981) and Lees (2002) accounted for over 20% of the total assemblages. Moreover, *Braarudosphaera bigelowii* was observed in the studied samples in a small amount and reached a maximum of 3.3% (Text-fig. 8). Therefore, it can be concluded that the Pełczyska section assemblages did not resemble the German coastal assemblages. Instead, based on the high diversity assemblages, it is more comparable to shallow epicontinental basinal settings.

The Early Maastrichtian cooling event in the Pełczyska section

Latest Campanian–earliest Maastrichtian cooling was noticeable in the Pełczyska section. It is demonstrated by the presence of a large number of cold water species (mostly *Micula decussata*, *Prediscosphaera cretacea*, *Arkhangelskiella* spp., *Calculites obscurus* and *Lucianorhabdus cayeuxii*) amounting to over 50% on almost throughout the entire section (Text-figs 7 and 8; Appendix 1). Additionally, many researchers consider the elevated presence of *Prediscosphaera cretacea* as characteristic of the latest Campanian–earliest Maastrichtian cooling (e.g., Ovechkina and Alekseev 2005; Linnert *et al.* 2016). In the Pełczyska section this species reached an average of 10% in the assemblage. On the other hand, the common abundance of *Watznaueria barnesae* and *Uniplanarius gothicus*, and the lower frequency of cool water species (*Ahmuellerella octoradiata*, *Kamptnerius magnificus* and *Gartnerago* spp.) may indicate that the intensity of this episode in the studied area was weaker rather than in the Boreal Province (Jelby *et al.* 2014; Boussaha *et al.* 2016; Thibault *et al.* 2016).

In order to investigate the presence of a cooling event in the Pełczyska section, we compared our data (composition of assemblages and frequency of individual species) with time-equivalent data from several sites in northern Europe, especially localities where the Maastrichtian cooling has been described. The nannofossil assemblages from Pełczyska are similar to those described from both the Danish (Stevns Klint and Møns Klint) and the North German basins (Text-fig. 11). Linnert *et al.* (2016) analyzed nannofossils from the Kronsmoor section (NW Germany), where species richness was high and reached 47–65 taxa, compared with 23–44 taxa from Pełczyska. The discrepancy in species richness is probably due to the relatively poor preservation of coccoliths from Pełczyska compared with those from Kronsmoor. In both sections the quantitative proportion of the dominant taxa is comparable and they include: *Prediscosphaera* spp. (*P. cretacea* was most abundant), *Micula* spp. (mainly *M. decussata*), *Arkhangelskiella cymbiformis* and *Watznaueria barnesae*. In the Kronsmoor section, *Kamptnerius magnificus* and *Retecapsa* spp. had an average relative abundance of greater than 4%, but were less frequent in the Pełczyska succession; the abundance of other taxa from the Kronsmoor section, such as *Discorhabdus ignotu*s, *Microrhabdulus* spp., *Reinhardtites levis*, *Placozygus* spp. and *Zeugrhabdotus* spp. are comparable to those from the Pełczyska section (Appendix 1). The species richness of assemblages from Stevns Klint ranged from 36 up to 80 species (Thibault *et al.* 2012a). Similarly as in our data, *Prediscosphaera* spp. [the most common species was not *P. cretacea*, but *P. stoveri* (Perch-Nielsen) Shafik and Stradner, 1971], *Arkhangelskiella cymbiformis*, *Watznaueria barnesae*, *Calculites obscurus* and *Reinhardtites levis* were frequent in assemblages from Stevns Klint and Møns Klint. In addition, *Kamptnerius magnificus* was also common (Jelby *et al.* 2014; Thibault *et al.* 2016). A feature that distinguishes the nannofossil assemblages from the Danish sections from those in the

Pełczyska section is the absence of *Braarudosphaera bigelowii* (Boussaha *et al.* 2016), indicating greater water depths for the Danish Basin sections.

More locally, our results have been compared with samples from the Campanian/Maastrichtian boundary in Poland, from the Mielnik upon Bug (Eastern Poland; Text-fig. 11). The taxonomic composition of nannofossil assemblages from Mielnik (Gaździcka 1981) is very similar to that from the Pełczyska section. No quantitative analysis has been carried out on the Mielnik samples, but based on the assemblage composition it is concluded that almost all Maastrichtian species were present in both locations. Common species include: *Micula decussata*, *Broinsonia parca*, *Kamptnerius magnificus*, *Lucianorhabdus cayeuxii*, *Eiffellithus turriseiffelii*, *Prediscosphaera cretacea*, *Calculites obscurus* and *Watznaueria barnesae* (Gaździcka 1981). The assemblages from Mielnik were defined as boreal, with a predominance of cool and cold water taxa. In addition, the species richness from Mielnik was low (20–30 taxa), which is comparable to our work.

CONCLUSIONS

The analysis of calcareous nannofossil assemblages from the Pełczyska section in the Miechów Trough has allowed for the following conclusions:

1. The succession represents the UC16b^{TP} Tethyan subzone (lower Maastrichtian), based on the continuous record of *Broinsonia parca constricta* and the reworked remains of *Uniplanarius trifidus*; additionally it is also located between the LO of *Zeugrhabdotus praesigmoides* and the FO of *Prediscosphaera mgayae* (UC16 S3 boreal subzone).

2. The UC16a^{TP} subzone was not designated due to the rarity of occurrence and abundance of incomplete remains of *Uniplanarius trifidus*, which were observed in only two samples (nos. 4 and 6). It allowed us to conclude that this species was not *in situ* in the studied material.

3. The global early Maastrichtian cooling event is marked in the Pełczyska section by an increased presence of *Prediscosphaera cretacea* and the significant dominance of cold water taxa (e.g., *Micula decussata*, *Arkhangelskiella* spp., *Calculites obscurus* and *Lucianorhabdus cayeuxii*) over warm water species (e.g., *Watznaueria barnesae*, *Uniplanarius* spp., *Lithraphidites carniolensis*). This also led us to the conclusion that during the sedimentation, cold currents from the Boreal Province prevailed over warm currents from the Tethyan Realm.

4. Shallow marine species, such as *Braarudosphaera bigelowii*, *Calculites obscurus*, *Lucianorhabdus cayeuxii* and *Kamptnerius magnificus*, which are rare in the open ocean, occur in the Pełczyska section. Their mean relative abundance exceeds 13%, and in some parts of the succession reaches almost 20%. We conclude that the southern part of the Miechów Trough in the early Maastrichtian was a shallow epicontinental basin. However, the studied calcareous nannofossil assemblages do not show significant features of coastal or nearshore areas.

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APPENDIX 1

Table with the distribution of calcareous nannofossil species from the Pełczyska section. Abundance: abundant (A) – more than 46% of the total assemblage; common (C) – 11–45% of the total assemblage; few (F) – 6–10% of the total assemblage; rare (R) – up to 5% of the total assemblage; and single (S) – only one specimen was observed. Preservation: good (G); moderate (M); poor (P); very poor (VP).

early Maastrichtian																									Age
UC16b^{TP} / UC16 S3																									Biozone
0	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7	7.5	8	8.5	9	9.5	10	10.5	11	11.5	12	Depth [m]
1	2	3	4	5	6	7	8	No data	10	11	12	13	14	15	No data	17	18	19	20	21	22	23	24	25	Sample no.
P	M	P	M	M	M	M	M		M	M	M	P	P	P		P	P	P	M	M	P	P	P	P	Preservation
		S			R		S		S	R	S			S				R			S				*Acuturris scotus*
S				S					S				R	S			S	S		R		S	R	S	*Ahmuellerella octoradiata*
	S										S		S						S						*Amphizygus brooksii*
	S	S	S			R	R		S		R	S						S							*Arkhangelskiella confusa*
F	C	C	C	C	F	F	C		C	C	C	C	C	F		C	F	C	F	C	F	F	F	C	*Arkhangelskiella cymbiformis*
R	R	R	R	R	R	R	R		R	R	R	R	R	R		R	R	R	R	R	R		R	R	*Biscutum constans*
	S																		S						*Biscutum hattneri*
S			R		S	R	R		S	R	S	S	S					S		S		S			*Biscutum magnum*
R	R	R	R	R	R	R	R		R	R	R	R	R	R		R	R	R	R	R	R	R	R	R	*Braarudosphaera bigelowii*
R	R	R	R	R	R	R	R		R	R	R	R	R	R		R	R	R	R	R	R	R	R	R	*Broinsonia parca constricta*
			S																						*Broinsonia parca parca*
F	R	F	R	R	R	R	F		R	R	F	R	R	R		R	R	F	R	R	R	R	R	R	*Calculites obscurus*
	R	S	S	S		R	R			S	S		R	R			S		R		R	S			*Ceratolithoides aculeus*
R		R	R		R	R	R		R	R	R	R	R	R			R	R	R	R	R	R	R	R	*Chiastozygus amphipons*
	R		S		S	R	R				S								R	R		S		S	*Chiastozygus litterarius*
			S	S								S				S					S			S	*Cretarhabdus conicus*
R	R	R	R	R	R	R	R		R	R	R	R	R	R		R	R		R	R	R	R	R	R	*Cribrosphaerella ehrenbergii*
	S		R	S		R	R			S	S			S		R	S	S	R		S	S		R	*Cyclagelosphaera margerelii*
	R		R	S	S	R	S		R	R				R		S	S		S		R	S		S	*Cyclagelosphaera reinhardtii*
	R		R							S	S													S	*Cylindralithus serratus*
R	R	R	R	R	R	R	R		R	R			R	R		R	R	R	R	R		R	R		*Discorhabdus ignotus*
S					S						R	R		S		R			R	R	R		R		*Eiffellithus gorkae*
R	F	R	R	F	F	R	F		R	R	R	R	R	F		F	R	R	R	F	R	F	F	R	*Eiffellithus turriseiffelii*
										S		S					S								*Gartnerago obliquum*
	R	S	S		S	S			S							S				R	S				*Gartnerago segmentatum*
	R	R	F	R	R	R	R		R	R	R		R	R		R	R	R	R	R	R	R	R	R	*Helicolithus anceps*
	R					R	R											S							*Helicolithus trabeculatus*
	R	R	R	R	R		R			R	R	R	R	R			R	R	R	R		R	R	R	*Kamptnerius magnificus*
S		S		R	S	S																S			*Lithraphidites carniolensis*
R	R	R	R	R	R	R	R		R	R	R	R	R	R		R	R	R	R	R	R	R	R	R	*Lucianorhabdus cayeuxii*
						S															S			S	*Manivitella pemmatoidea*
			S		S					R				S				S		S	S				*Markalius inversus*
	R		S				S			S		S				S									*Marthasterites inconspicuus*
R	R	R	R	R	R	R	R			R	R	R	R	R		R	R	R	R	R	R	R	R		*Microrhabdulus decoratus*
		S														S	R		S			S			*Micula concava*
A	C	C	C	C	C	C	F		C	F	C	C	C	C		C	C	C	C	C	C	C	C	C	*Micula decussata*
											R		R				R				R		R	R	*Micula praemurus*
													R								S				*Micula premolisilvae*
S		S	R			S	R						S						S						*Petrarhabdus copulatus*
R	R	R	R	R	R	R	R		R	R	R	R	R	R		R	R	R	R	R	R	R	R	R	*Placozygus fibuliformis*
S			S							S														S	*Placozygus spiralis*
			R	S			R																		*Prediscosphaera arkhangelskyi*
R	C	F	C	C	C	C	C		C	C	C	F	C	F		F	C	R	C	C	R	F	C	C	*Prediscosphaera cretacea*
	R		R		S		R							S		S		S	R	R	S			R	*Prediscosphaera grandis*
	S															S						S			*Prediscosphaera ponticula*
							R			R						S		R		R			S		*Prediscosphaera spinosa*
R	F	F	F	R	R	F	R		R	R	R	R	R	R		R	R	R	R	R	R	R	R	R	*Reinhardtites levis*
						R																			*Repagulum parvidentatum*
	R		R	S	S	R	R		S	R	S					S		R	R	S	S	S		R	*Retecapsa angustiforata*
S						S								S		S						S		R	*Retecapsa crenulata*
				S	S	R												S							*Retecapsa surirella*
	R				S	R	R							S											*Rhagodiscus angustus*
						R										S	S				S	S		S	*Rhagodiscus plebeius*
	R		R	S	S	S	R			R	R					R	R	S	S		S		S	R	*Staurolithites crux*
				S	S	R	S		S	R	R		R	R		S	R	S		R		R	R	S	*Tetrapodorhabdus decorus*
	S											S													*Tortolithus pagei*
R	R	R	R	R	R		R		R	R			R	R		R			R	R	R	R	R	R	*Tranolithus gabalus*
			R										R												*Tranolithus minimus*
R	R	R	R	R	R	R	R		R	R	R	R	R	R		R	R	R	R	R	R	R	R	R	*Tranolithus orionatus*
F	R	F	R	F	R	R	R		F	R	F	R	R	F		F	F	R	R	R	F	F	F	R	*Uniplanarius gothicus*
			R		R																				*Uniplanarius trifidus*
F	R	C	F	F	C	F	F		C	C	F	F	C	C		C	C	C	C	F	C	C	C	C	*Watznaueria barnesae*
	R		R				R			R	S	S							R	R		R			*Watznaueria biporta*
S				S	R		S		R	S	S	R	R			R	S	R	S	S			R	R	*Watznaueria quadriradiata*
					S	R			R																*Zeugrhabdotus bicrescenticus*
			S										S	S				S	S						*Zeugrhabdotus biperforatus*
S	R		S	R	S	R				R	S											S		S	*Zeugrhabdotus embergeri*
R		R	R	R	R	R	R		R		R	R		R		R	R		R	R	R	R	R		*Zeugrhabdotus erectus*
			R						S									S	R		S	S	S	S	*Zeugrhabdotus sigmoides*

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APPENDIX 2

Taxonomic index of calcareous nannofossil taxa reported in this study.

Acuturris scotus (Risatti) Wind and Wise in Wise and Wind, 1977
Ahmuellerella octoradiata (Górka) Reinhardt, 1966
Amphizygus brooksii Bukry, 1969
Arkhangelskiella confusa Burnett, 1997
Arkhangelskiella cymbiformis Vekshina, 1959
Biscutum constans (Górka) Black in Black and Barnes, 1959
Biscutum hattneri Wise, 1983
Biscutum magnum Wind and Wise in Wise and Wind, 1977
Braarudosphaera bigelowi (Gran and Braarud) Deflandre, 1947
Broinsonia parca constricta Hattner, Wind and Wise, 1980
Broinsonia parca parca (Stradner) Bukry, 1969
Calculites obscurus (Deflandre) Prins and Sissingh in Sissingh, 1977
Ceratolithoides aculeus (Stradner) Prins and Sissingh in Sissingh, 1977
Chiastozygus amphipons (Bramlette and Martini) Gartner, 1968
Chiastozygus litterarius Manivit, 1971
Cretarhabdus conicus Bramlette and Martini, 1964
Cribrosphaerella ehrenbergii (Arkhangelsky) Deflandre in Piveteau, 1952
Cyclagelosphaera margerelii Noël, 1965
Cyclagelosphaera reinhardtii (Perch-Nielsen) Romein, 1977
Cylindralithus serratus Bramlette and Martini, 1964
Discorhabdus ignotus (Górka) Perch-Nielsen, 1968
Eiffellithus gorkae Reinhardt, 1965
Eiffellithus turriseiffelii (Deflandre) Reinhardt, 1965
Gartnerago obliquum (Stradner) Noël, 1970
Gartnerago segmentatum (Stover) Thierstein, 1974
Helicolithus anceps (Górka) Noël, 1970
Helicolithus trabeculatus (Górka) Verbeek, 1977
Kamptnerius magnificus Deflandre, 1959
Lithraphidites carniolensis Deflandre, 1963
Lucianorhabdus cayeuxii Deflandre, 1959
Manivitella pemmatoidea (Deflandre) Thierstein, 1971
Markalius inversus (Deflandre) Bramlette and Martini, 1964
Marthasterites inconspicuus Deflandre, 1959
Microrhabdulus decoratus Deflandre, 1959
Micula concava (Stradner) Verbeek, 1976
Micula decussata Vekshina, 1959
Micula praemurus (Bukry) Stradner and Steinmetz, 1984
Micula premolisilvae Lees and Bown, 2005
Petrarhabdus copulatus (Deflandre) Wind and Wise in Wise, 1983
Placozygus fibuliformis (Reinhardt) Hoffmann, 1970
Placozygus spiralis (Bramlette and Martini) Hoffmann, 1970
Prediscosphaera arkhangelskyi (Reinhardt) Perch-Nielsen, 1984
Prediscosphaera cretacea (Arkhangelsky) Gartner, 1968
Prediscosphaera grandis Perch-Nielsen, 1979
Prediscosphaera ponticula (Bukry) Perch-Nielsen, 1984
Prediscosphaera spinosa (Bramlette and Martini) Gartner, 1968
Reinhardtites levis Prins and Sissingh in Sissingh, 1977
Repagulum parvidentatum (Deflandre and Fert) Forchheimer, 1972
Retecapsa angustiforata Black, 1971
Retecapsa crenulata (Bramlette and Martini) Grün in Grün and Allemann, 1975
Retecapsa surirella (Deflandre and Fert) Grün in Grün and Allemann, 1975
Rhagodiscus angustus (Stradner) Reinhardt, 1971
Rhagodiscus plebeius Perch-Nielsen, 1968
Staurolithites crux (Deflandre and Fert) Caratini, 1963
Tetrapodorhabdus decorus (Deflandre) Wind and Wise, 1983
Tortolithus pagei (Bukry) Crux in Crux *et al*., 1982
Tranolithus gabalus Stover, 1966
Tranolithus minimus (Bukry) Perch-Nielsen, 1984
Tranolithus orionatus (Reinhardt) Reinhardt, 1966
Uniplanarius gothicus (Deflandre) Hattner and Wise in Wind and Wise, 1983
Uniplanarius trifidus (Stradner) Hattner and Wise in Wind and Wise, 1983
Watznaueria barnesae (Black) Perch-Nielsen, 1968
Watznaueria biporta Bukry, 1969
Watznaueria quadriradiata Bukry, 1969
Zeugrhabdotus bicrescenticus (Stover) Burnett in Gale *et al*., 1996
Zeugrhabdotus biperforatus (Gartner) Burnett, 1997
Zeugrhabdotus embergeri (Noël) Perch-Nielsen, 1984
Zeugrhabdotus erectus (Deflandre) Reinhardt, 1965
Zeugrhabdotus sigmoides (Bramlette and Sullivan) Bown and Young, 1997