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# Biostratigraphic and palaeoecological significance of Badenian (Miocene) calcareous nannofossil assemblages of the western Carpathian Foredeep (Skawina Formation, southern Poland)

ANTONINA NOSOWSKA[1] and MAŁGORZATA GARECKA[2]

[1] *University of Warsaw, Faculty of Geology, Żwirki i Wigury 93, 02-089 Warszawa, Poland; e-mail: a.nosowska@uw.edu.pl*
[2] *Carpathian Branch of the Polish Geological Institute–National Research Institute, Skrzatów 1, 31-560 Kraków, Poland*

ABSTRACT:

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Calcareous microfossil investigations of the Skawina Formation were performed in the Czeczott Mine pit-shaft S-1 borehole, in the western part of the Carpathian Foredeep (near Pszczyna, southern Poland). Based on calcareous nannofossils, the section spans the uppermost NN5 Zone of the uppermost Moravian and lower Wielician substages (upper mid to lower upper Badenian Stage *sensu* Hohenegger *et al.* 2014), corresponding to the Langhian/Serravalian boundary interval (Middle Miocene). The calcareous nannofossil assemblages record the transition from relatively warm, eutrophic, outer-shelf conditions to lower nutrient availability and cooler conditions, driven by general climate cooling. This reflects a regional record of the transition from the mid Badenian Climate Transition phase to the late Badenian 'Icehouse' phase (cf. Holbourn *et al.* 2007), as globally recognised in the Middle Miocene. This biostratigraphic framework and inferred palaeoenvironmental changes are consistent with interpretations based on existing foraminifera assemblage data.

**Key words:** Miocene; Carpathian Foredeep; Calcareous nannofossils; Biostratigraphy; Palaeoecology.

## INTRODUCTION

Holbourn *et al.* (2007) distinguished three climatic phases in the Miocene: (1) the Middle Miocene Climate Optimum, characterised by rising temperatures and an ice volume minimum; (2) the Middle Miocene Climate Transition, characterised by long-term cooling, and finally (3) the 'Icehouse', i.e., the maximum cooling phase. In the regional chronostratigraphic subdivision of the Central Paratethys, the Middle Miocene Climate Optimum occurs in the early Badenian, the Middle Miocene Climate Transition in the mid Badenian, and the 'Icehouse' in the late Badenian (Hohenegger *et al.* 2014).

The world-wide extreme temperature decreases at 13.82 Ma led to the major glacio-eustatic sea level drop (Hohenegger *et al.* 2014; de Leeuw *et al.* 2010). The isolation of the Carpathian Foredeep, Transcarpathian Basin, and Transylvanian Basin in Badenian triggered to the Badenian Salinity Crisis in the Central Paratethys (Kováč *et al.* 2007), which is associated with the deposition of thick evaporitic sequences (Peryt T.M. 2006; de Leeuw *et al.* 2010, 2018; Raffi *et al.* 2020). This event is dated to the

NN5/NN6 calcareous nannofossil zones boundary, or the base of the NN6 Zone *sensu* Martini (1971) (in Wielician *sensu* Hohenegger *et al.* 2014) (e.g., Peryt D. 1997; Kováč *et al.* 2007).

In Poland, the evaporitic unit that records the Badenian Salinity Crisis is represented by remarkably thick halite and gypsum deposits of the Wieliczka and Krzyżanowice formations, respectively, that are deposited widely in the Carpathian Foredeep (Oszczypko *et al.* 2006).

In the topmost pre-evaporitic portion of this succession, the foraminiferal record supports this general environmental pattern (Pilarz and Łuczkowska 2001). Based on calcareous nannofossil analyses from the Czeczott Mine pit-shaft S-1 borehole section in the western part of the Polish Carpathian Foredeep, we seek to demonstrate how analogous patterns of environmental and climatic changes preceding the Badenian Salinity Crisis can be recorded in calcareous nannofossils, a group with remarkable environmental sensitivity (see Schueth and Bralower 2015 and references therein).

## HISTORY OF RESEARCH

Biostratigraphic research on the Neogene of the western Polish Carpathian Foredeep began in the early 19$^{th}$ century (see Roemer 1870). These initial studies relied primarily on macrofaunal assemblages, particularly scallops, and dated these deposits to the Helvetian, Tortonian and Sarmatian stages (e.g., Friedberg 1906, 1908, 1912, 1914, 1928; Krach 1939, 1954a, b, 1955, 1956a, b, 1957a, b, 1958a, b, 1974). The Tortonian succession was subdivided into sub-gypsum (sub-evaporitic) and supra-gypsum (post-evaporitic) intervals. Subsequently, Alexandrowicz (1958) proved the limited stratigraphic value of scallops due to their strong facies dependence. The advent of regional foraminiferal biostratigraphy marked a major advancement (see Łuczkowska 1955, 1958; Alexandrowicz 1956, 1958, 1963a; Kirchner 1956). Alexandrowicz (1963b) subdivided and correlated numerous Miocene sections in the Silesia-Cracow area, and established several biohorizons in the western foredeep that correlated well with the eastern foredeep horizons defined by Łuczkowska (1964). Subsequent foraminiferal studies in the western foredeep, including locations both near and beneath the Carpathian thrust, were conducted by Alexandrowicz (1967, 1969), Krach (1973), Kuciński *et al.* (1975), Porębska-Szotowa (in Nowak 1976), Odrzywolska-Bieńkowa (1977), Strzępka (1981), Łuczkowska (1986), Garecka *et al.* (1996), Gonera (1997, 2001, 2013, 2018), Garecka and Olszewska (1998), Olszewska (1999, 2014), Pilarz and Łuczkowska (2001), Zapałowicz-Bilan *et al.* (2009), Bukowski *et al.* (2018), Garecka and Pilarz (2019), and Ziarek and Pilarz (2024, 2025).

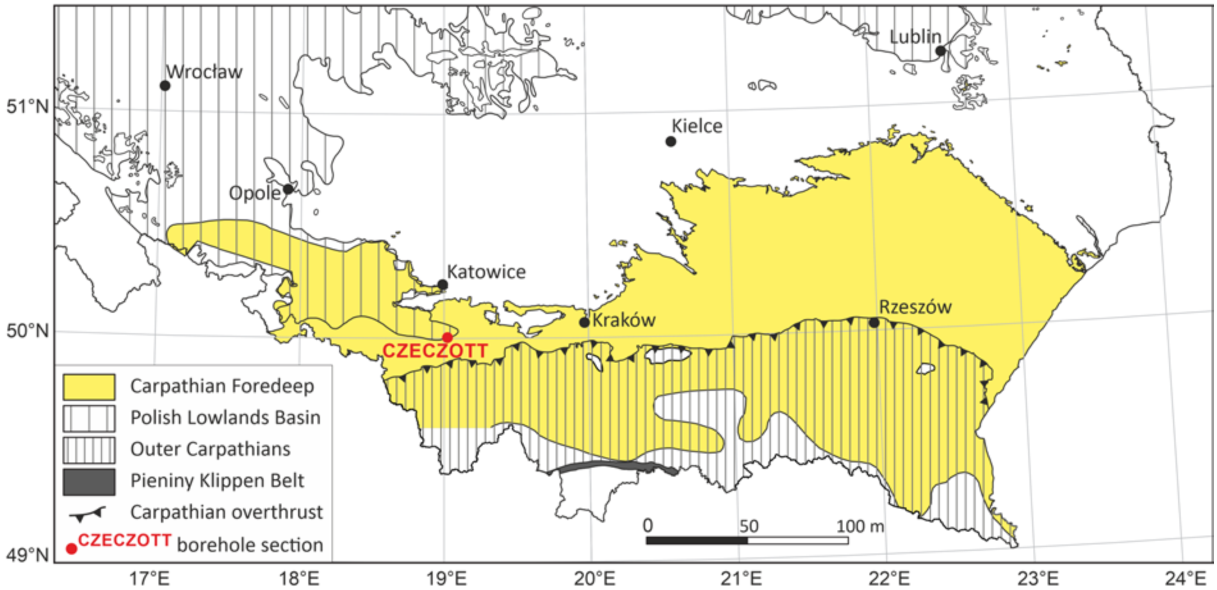
Calcareous nannofossils provide complementary biostratigraphic data to refine the subdivision of the Skawina Formation (Dudziak and Łuczkowska 1991; Garecka and Olszewska 1995; Garecka *et al.* 1996; Peryt D. 1997; Andreyeva-Grigorovich *et al.* 1999, 2003; Garecka and Jugowiec 1999; Gaździcka and Czapowski 2000; Oszczypko and Oszczypko-Clowes 2012; Garecka 2014; Gaździcka 2015; Bukowski *et al.* 2018; Garecka and Pilarz 2019), and generally support existing foraminiferal evidence.

From a geochronologic perspective, $^{40}Ar/^{39}Ar$ radiometric dating of the Wiatowice Tuffite from the upper part of the Skawina Formation yields an age of 13.76 ± 0.08 Ma (Bukowski *et al.* 2010) (Text-fig. 6).

## GEOLOGICAL SETTING AND SECTION DESCRIPTION

The Polish Carpathian Foredeep is a part of a large sedimentary basin which stretches from Austria to Romania. It developed as part of the peripheral foreland basin related to the migrating Carpathian front (Oszczypko 1997). The Polish segment of the Carpathian Foredeep is subdivided into the inner foredeep – located under the Carpathian nappes – and the outer foredeep, which is located north of the Carpathian margin (Ney *et al.* 1974; Oszczypko 1997). It can further be subdivided into western and eastern parts that are separated by the Kraków Ridge, an elevated structure composed of Palaeozoic and Mesozoic rocks (Ney 1968). This uplifted element was a significant palaeogeographic barrier during the Miocene, markedly impacting sedimentation patterns. The Polish Carpathian Foredeep is filled with predominantly marine Miocene siliciclastic sediments (Wysocka *et al.* 2016), up to 3 km thick (Oszczypko *et al.* 2006). The sedimentary succession is characteristically three-fold: in stratigraphic order, it is composed of informal sub-evaporitic, evaporitic, and supra-evaporitic units (Oszczypko 1996).

The present study is based on the topmost sub-evaporitic unit of the western Carpathian Foredeep, as recovered from the Czeczott Mine pit-shaft S-1 borehole (Text-fig. 1).




Text-fig. 1. Location of the studied Czeczott Mine pit-shaft S-1 borehole section. Map simplified and modified after Narkiewicz *et al.* (2023) and Jasionowski and Peryt (2026).

**Czeczott Mine pit-shaft S-1 borehole**

The borehole is located in the vicinity of Pszczyna, in the western part of the foredeep basin. From bottom to top, the represented stratigraphic interval spans the brackish Kłodnica Formation (probably) and the marine Skawina Formation (Pilarz and Łuczkowska 2001). The latter, originally referred to as the Skawina Beds by Alexandrowicz (1963a), is about 200 m thick (Alexandrowicz 1957, 1963b). The Skawina Formation directly underlies the evaporitic succession, and is the thickest and most widely distributed lithostratigraphic unit in the western Carpathian Foredeep (Jasionowski 1995).

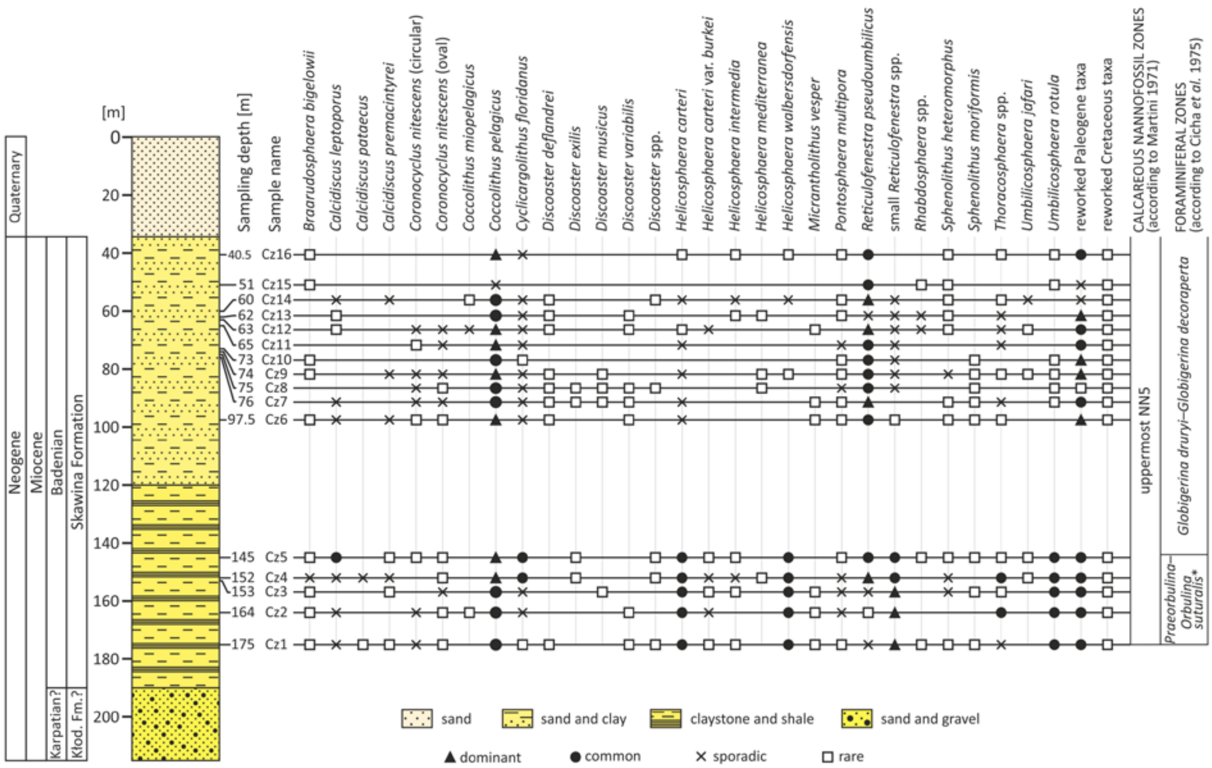
The Skawina Formation consists of clays and mudstones with intercalations of sand, gravel, conglomerates and limestones (Alexandrowicz *et al.* 1982), and contains rich microfossils (see Alexandrowicz *et al.* 1982; Peryt D. 1997; Olszewska 1999; Gonera 2001; Bukowski *et al.* 2018).

As presented by Pilarz and Łuczkowska (2001), the generalised lithological section of the Czeczott Mine pit-shaft S-1 borehole is comprised of the following lithological intervals:

– 0.0–34.4 m: Quaternary, grey, fine-grained silty sands with clay intercalations or clays with sand interbeds; at depth 14.0–16.7 m: coarse-grained gravels associated with grey-green sands;
– 34.4–120.0 m: grey, fine-grained sands with grey clay and silt intercalations, with lamellar fissility and light- and dark-coloured up to 1-cm thick laminae;
– 120.0–190.0 m: clay slates and grey-green laminated caystones plitting into plates up to 10-cm thick, plastic, tectonically disturbed at a depth of 171–155 m;
– 190.0–208.0 m: grey-green, fine-grained fragile, silty loose sands with gravel interbeds.

## MATERIAL AND METHODS

The Skawina Formation in the Czeczott section is 155.6 m thick (Pilarz and Łuczkowska 2001). Sixteen samples were collected to analyse the composition and distribution of calcareous nannofossils from the following depths: 175 m (Cz1); 164 m (Cz2); 153 m (Cz3), 152 m (Cz4), 145 m (Cz5), 97.5 m (Cz6); 76 m (Cz7); 75 m (Cz8); 74 m (Cz9); 73 m (Cz10); 65 m (Cz11); 63 m (Cz12); 62 m (Cz13); 60 m (Cz14); 51 m (Cz15); and 40.5 m (Cz16) (Text-fig. 2). Smear slides and samples for scanning electron microscopy (SEM) were prepared following standard procedures (Perch-Nielsen 1985a). Light microscopy was performed using a Nikon Eclipse E400POL microscope equipped with an oil-immersion objective at 1000× magnification, and photos of selected taxa were obtained using a 12 MP SONY digital camera. Taxon abundance was assessed semi-quantitatively using four categories: dominant (taxon markedly prevailing over others), common (>15 specimens per slide, excluding dominant taxa, if pres-




Text-fig. 2. Distribution of Miocene calcareous nannofossil taxa in the Czeczott Mine pit-shaft S-1 borehole section. Lithology after Pilarz and Łuczkowska (2001). Foraminiferal zones determined by Nosowska *et al.* (2019). Explanation: * – The *Praeorbulina glomerosa–Orbulina suturalis* Zone in Nosowska *et al.* (2019). Abbreviation: Kłod. Fm. – Kłodnica Formation.

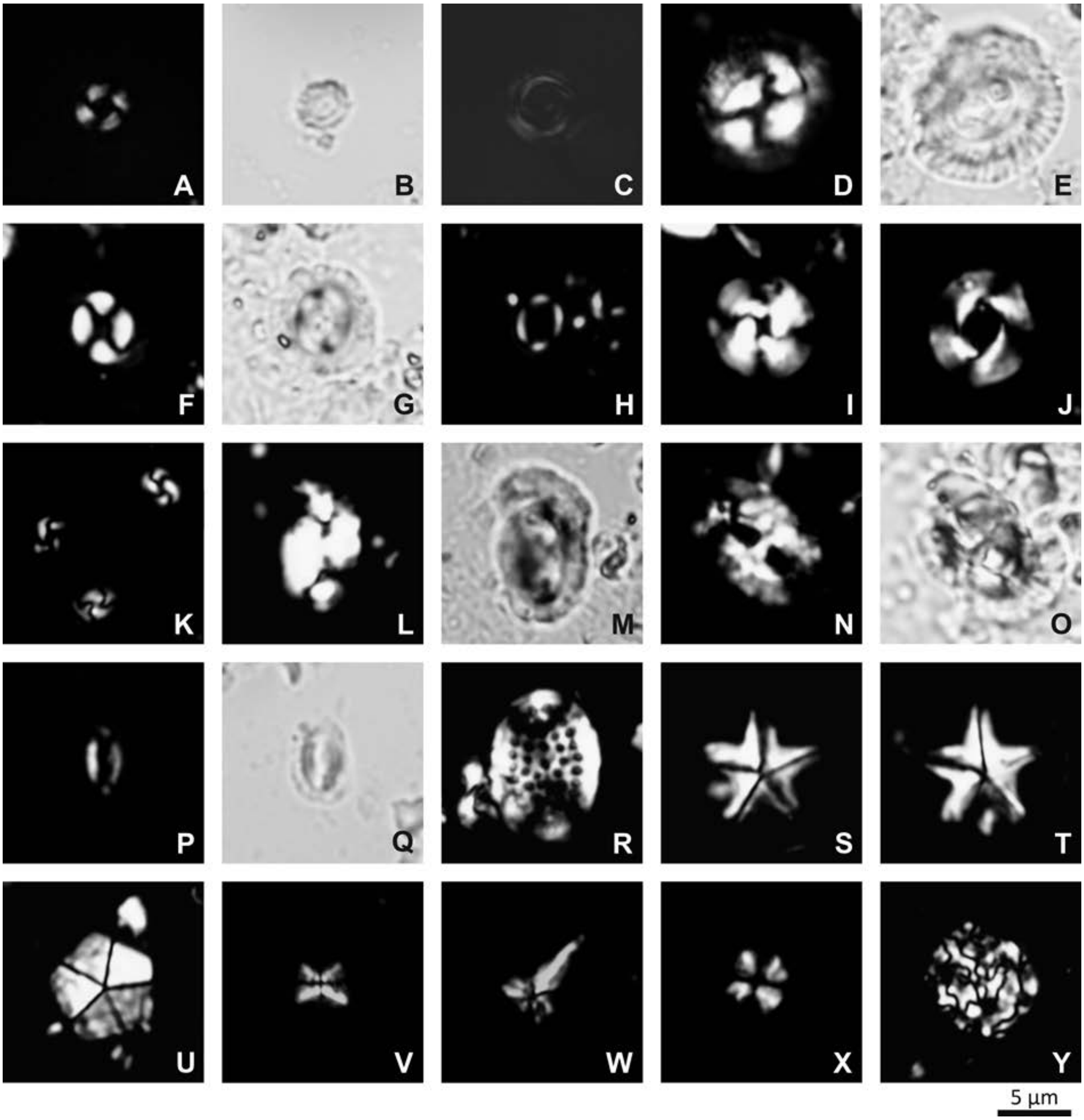
ent), sporadic (4–15 specimens) and rare (1–3 specimens) (Text-fig. 2). Approximately 150 fields of view were examined per slide (cover glass 24×32 mm). SEM observations and micrographs were conducted using Zeiss Auriga 60 and Zeiss Sigma VP scanning electron microscopes at the Faculty of Geology, University of Warsaw. Biostratigraphic determinations followed the calcareous nannofossil zonation schemes of Martini (1971) and Švábenická (2002).

## RESULTS

### Calcareous nannofossil record

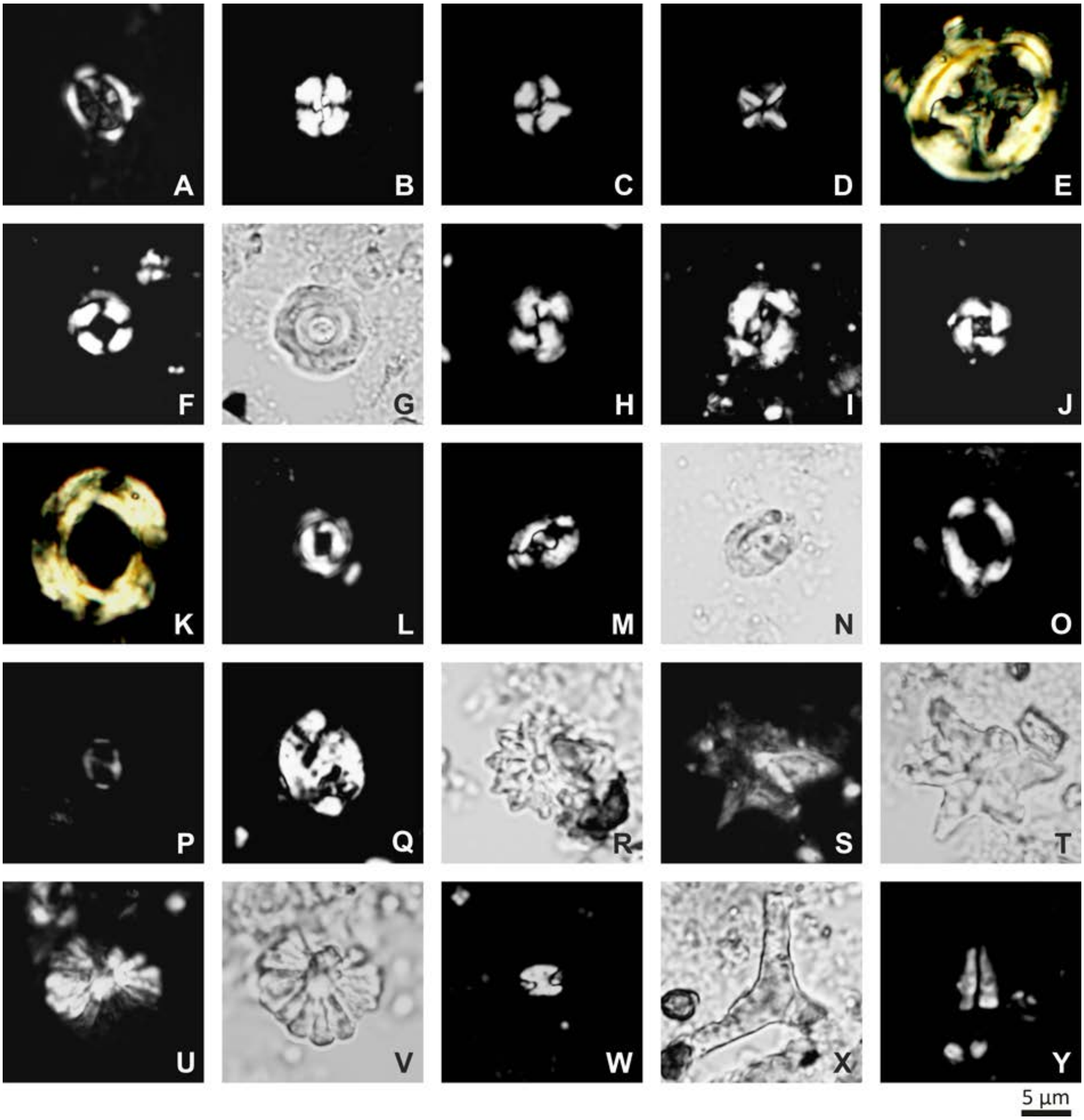
Twenty-three calcareous nannofossil species and one variant are recognised in the Skawina Formation at the Czeczott section (Text-fig. 2; Appendix), representing twelve genera: *Braarudosphaera* Deflandre, 1947; *Calcidiscus* Kamptner, 1950; *Coccolithus* Schwarz, 1894; *Coronocyclus* Hay, Mohler & Wade, 1966; *Cyclicargolithus* Bukry, 1971b; *Discoaster* Tan, 1927; *Helicosphaera* Kamptner, 1954; *Micrantholithus* Deflandre in Deflandre & Fert, 1954; *Pontosphaera* Lohmann, 1902; *Reticulofenestra* Hay, Mohler & Wade, 1966; *Sphenolithus* Deflandre, 1952; and *Umbilicosphaera* Lohmann, 1902. Some specimens of *Discoaster*, *Reticulofenestra*, *Rhabdosphaera* Haeckel, 1894 and *Thoracosphaera* Kamptner, 1927 are left in open nomenclature. Additionally, 61 redeposited taxa mainly from the Paleogene – predominantly Eocene – and fewer from the Cretaceous are recognised. Selected autochthonous and redeposited taxa are shown in Text-figs 3–5.

Two distinct assemblages can be distinguished: the lower from depth interval 175.0–145.0 m, and the upper from depth interval 97.5–40.5 m (Text-fig. 2). *Coccolithus pelagicus* (Wallich, 1877) Schiller, 1930 is the dominant taxon in both assemblages. The lower assemblage is characterised by moderately higher taxonomic richness and abundance than the upper assemblage, and is dominated by placoliths and helicoliths (placolith-like Helicosphaeraceae coccoliths that have a helical shield called a flange). It is characterised by frequent *Helicosphaera carteri* (Wallich, 1877) Kamptner, 1954; *Helicosphaera wal-*

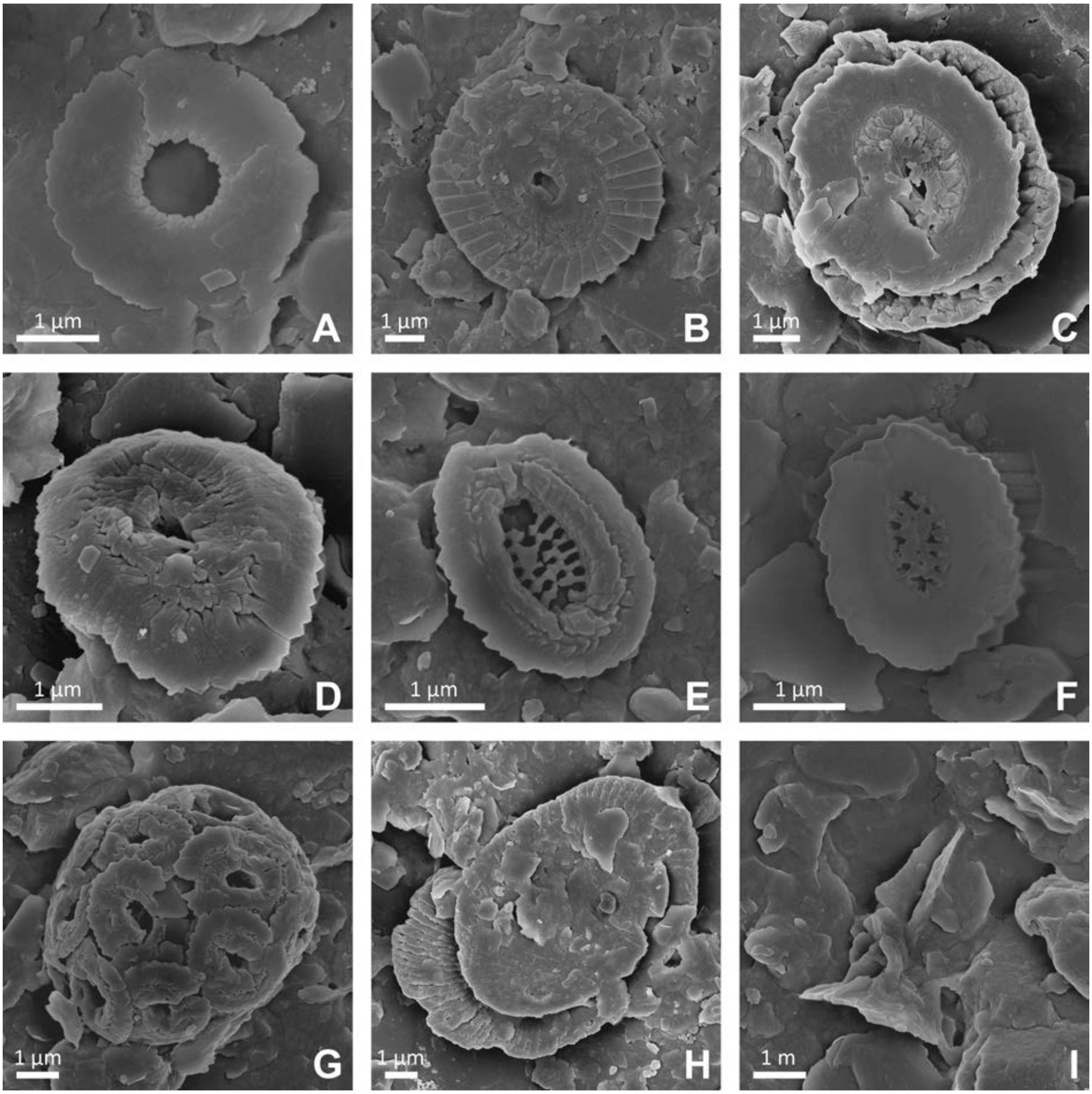



Text-fig. 3. Miocene calcareous nannofossils from the Czeczott Mine pit-shaft S-1 borehole section in polarized light microscopy. A, B – *Umbilicosphaera jafari* Müller, 1974; specimen from Cz14 (60 m) in two views; C – *Umbilicosphaera rotula* (Kamptner, 1956) Varol, 1982; Cz8 (75 m); D, E, F, G – *Coccolithus pelagicus* (Wallich, 1877) Schiller, 1930; D, E – specimen from Cz14 (60 m) in two views; F, G – specimen from Cz9 (74 m) in two views; H – *Coronocyclus nitescens* (Kamptner, 1963) Bramlette & Wilcoxon, 1967; oval form, Cz1 (175 m); I – *Cyclicargolithus floridanus* (Roth & Hay in Hay *et al.*, 1967) Bukry, 1971b; Cz9 (74 m); J – *Reticulofenestra pseudoumbilicus* (Gartner, 1967) Gartner, 1969; Cz9 (74 m); K – Small *Reticulofenestra* spp.; Cz1 (175 m); L, M – *Helicosphaera carteri* (Wallich, 1877) Kamptner, 1954; specimen from Cz3 (153 m) in two views; N, O – *Helicosphaera mediterranea* Müller, 1981; specimen from Cz9 (74 m) in two views; P, Q – *Helicosphaera walbersdorfensis* Müller, 1974; specimen from Cz9 (74 m) in two views; R – *Pontosphaera multipora* (Kamptner, 1948 ex Deflandre in Deflandre & Fert, 1954) Roth, 1970; Cz3 (153 m); S, T – *Micrantholithus vesper* Deflandre, 1950; specimen from Cz3 (153 m) in two views; U – *Braarudosphaera bigelowii* (Gran & Braarud, 1935) Deflandre, 1947; Cz3 (153 m); V, W – *Sphenolithus heteromorphus* Deflandre, 1953, specimen from Cz14 (60 m) in two views; X – *Sphenolithus* cf. *moriformis* (Brönnimann & Stradner, 1960) Bramlette & Wilcoxon, 1967, Cz9 (74 m); Y – *Thoracosphaera saxea* Stradner, 1961, Cz12 (63 m).

*bersdorfensis* Müller, 1974; *Umbilicosphaera rotula* (Kamptner, 1956) Varol, 1982; *Reticulofenestra* spp. and, less abundantly, *Cyclicargolithus floridanus* (Roth & Hay in Hay *et al.*, 1967) Bukry, 1971b and




Text-fig. 4. Redeposited calcareous nannofossils from the Czeczott Mine pit-shaft S-1 borehole section in polarized light microscopy. Cretaceous species: A – *Arkhangelskiella cymbiformis* Vekshina, 1959; Cz14 (60 m); B, C – *Watznaueria barnesiae* (Black in Black & Barnes, 1959) Perch-Nielsen, 1968; B – Cz16 (40.5 m); C – Cz13 (62 m); D – *Micula staurophora* (Gardet, 1955) Stradner, 1963; Cz5 (145 m); Paleogene species: E – *Chiasmolithus grandis* (Bramlette & Riedel, 1954) Radomski, 1968; Cz9 (74 m); colour photograph; F, G – *Coccolithus formosus* (Kamptner, 1963) Wise, 1973; specimen from Cz3 (153 m) in two views; H – *Reticulofenestra bisecta* (Hay, Mohler & Wade, 1966) Roth, 1970; Cz9 (74 m); I – *Reticulofenestra lockeri* Müller, 1970; Cz16 (40.5 m); J – *Reticulofenestra reticulata* (Gartner & Smith, 1967) Roth & Thierstein, 1972, Cz3 (153 m); K – *Reticulofenestra umbilicus* (Levin, 1965) Martini & Ritzkowski, 1968; Cz9 (74 m); colour photograph; L – *Toweius callosus* Perch-Nielsen, 1971; Cz14 (60 m); M, N – *Helicosphaera seminulum* Bramlette & Sullivan, 1961; specimen from Cz9 (74 m) in two views; O – *Pontosphaera latoculata* (Bukry & Percival, 1971) Perch-Nielsen, 1984; Cz9 (74 m); P – *Pontosphaera obliquipons* (Deflandre in Deflandre & Fert, 1954) Romein, 1979; Cz1 (175); Q – *Pontosphaera pulcheroides* (Sullivan, 1964) Romein, 1979; Cz12 (63 m); R – *Discoaster barbadiensis* Tan, 1927, Cz12 (63 m); S, T – *Discoaster* sp.; specimen from Cz13 (62 m) in two views; U, V – *Discoaster* sp., specimen from Cz14 (60 m) in two views; W – *Lanternithus minutus* Stradner, 1962, Cz1 (175 m); X – *Tribrachiatus orthostylus* Shamrai, 1963, specimen from Cz12 (63 m) in two views; Y – *Zygrhablithus bijugatus* Deflandre, 1959; Cz9 (74 m).




Text-fig. 5. Miocene calcareous nannofossils from the Czeczott Mine pit-shaft S-1 borehole section, from SEM. A – *Umbilicosphaera jafari* Müller, 1974, isolated shield; Cz4 (152 m); B, C – *Coccolithus pelagicus* (Wallich, 1877) Schiller, 1930; B – Cz4 (152 m), distal side; C – Cz9 (74 m), proximal side; D – *Reticulofenestra pseudoumbilicus* (Gartner, 1967) Gartner, 1969; Cz9 (74 m), distal side; E–G – Small *Reticulofenestra* spp.; E – Cz3 (153 m), distal side; F – Cz4 (152 m), proximal side; G – coccosphere, Cz3 (153 m); H – *Helicosphaera* sp.; Cz9 (74 m), proximal side; I – *Sphenolithus* cf. *heteromorphus* Deflandre, 1953; Cz3 (153 m).

*Thoracosphaera* spp. Other species of these genera, as well as representatives of *Braarudosphaera*, *Calcidiscus*, *Coronocyclus*, *Discoaster*, *Micrantholithus*, *Pontosphaera*, *Rhabdosphaera*, and *Sphenolithus*, rarely occur.

The upper assemblage yields most of the taxa already noted in the lower assemblage, but it is impoverished, showing a significant reduction in specimen abundance with the exception of *C. pelagicus* and *Reticulofenestra pseudoumbilicus* (Gartner, 1967) Gartner, 1969.

The difference in the abundance of *R. pseudoumbilicus*, small *Reticulofenestra* spp., *H. carteri* and *H. walbersdorfensis* between the lower and upper parts of the Czeczott section is noteworthy (Text-fig. 2). In the lowest part of the section, small *Reticulofenestra* spp. are dominant, while *R. pseudoumbilicus* occurs in small numbers. In the upper part of the section, *R. pseudoumbilicus* and *C. pelagicus* significantly outnumber small *Reticulofenestra* forms. *Helicosphaera carteri* and *H. walbersdorfensis* are much more numerous and present in all samples in the lower part of the section, in contrast to their sporadic and rare occurrence in the upper part of the section.

**Calcareous nannofossil preservation state**

While preservational states vary between groups, they are similar in all samples. Placoliths, which dominate the samples, are the best preserved. Helicoliths are generally complete. However, most *H. walbersdorfensis* representatives have their characteristic broad wing damaged. Sphenoliths and pentaliths are quite well preserved; the sphenoliths have distinct small or big apical spines, while most pentaliths have complete segments. Many specimens of *Pontosphaera multipora* (Kamptner, 1948 *ex* Deflandre in Deflandre & Fert, 1954) Roth, 1970 are damaged. Discoasters are very poorly preserved, and their rays are generally broken, which makes their correct identification very difficult or even – in many circumstances – impossible.

## DISCUSSION

**Biostratigraphy**

The primary Miocene calcareous nannofossil zonations were established on the first (FO) or last (LO) occurrences of the genus *Discoaster* (e.g., Martini and Worsley 1970; Martini 1971; Bukry 1973, 1975; Okada and Bukry 1980). However, the distribution of this genus is strongly controlled by ecological factors, and is strongly dependent on palaeogeographic conditions (e.g., Aubry 1984; Švábenická 2002). Discoasters are more diverse and abundant in open, warm, oligotrophic low latitude environments, whereas they are very rare and/or absent at higher latitudes and/or in marginal shallower settings (Perch-Nielsen 1985b). Consequently, the biostratigraphic application of this group may be problematic.

Discoasters are very rare in the studied material. Moreover, the recorded specimens are usually poorly preserved; their rays are broken, making species-level identification difficult.

Perch-Nielsen (1985b) proposed alternative markers, including representatives of the genus *Helicosphaera*. In the studied section, *H. walbersdorfensis* is particularly useful for Middle Miocene biostratigraphy. Although it ranges through the NN4 to NN6 zones (Bartol 2009), in the Mediterranean region it is characteristic of the upper NN5 Zone, as such, it is used as an index taxon for the Mediterranean Subzone MNN5b (stratigraphically equivalent to the upper NN5 Zone), defined as the co-occurrence interval of *Sphenolithus heteromorphus* Deflandre, 1953 and *H. walbersdorfensis* (Fornaciari *et al.* 1996). The latter authors determined the lower boundary of the MNN5b Zone based on the first common and continuous occurrence of *H. walbersdorfensis*.

*Sphenolithus* and *Cyclicargolithus* are also biostratigraphically useful (see Peryt D. 1995). In particular, *S. heteromorphus* is an important species for Middle Miocene biostratigraphy. Its LO marks the boundary between the NN5 and NN6 zones (Martini and Worsley 1970, 1971; Martini 1971; Bukry 1975; Theodoridis 1984; Perch-Nielsen 1985b). In contrast, *Cy. floridanus*, the only species of this genus recorded in the autochthonous assemblages, is a long-ranging taxon. This species appeared in the Paleogene and its LO was considered a marker of the NN6/NN7 boundary (Perch-Nielsen 1985b). It is particularly important in samples where the indicator of the NN7 Zone, *Discoaster kugleri* Martini and Bramlette, 1963, is not present. In Poland, *D. kugleri* is a very rare species (Galović and Young 2012; cf. Gaździcka 1994). However, the last common occurrence (LCO) of *Cy. floridanus* is in the middle NN7 Zone (Oszczypko and Oszczypko-Clowes 2012).

Other biostratigraphically important calcareous nannofossils in the studied samples include oval forms of *Coronocyclus nitescens* (Kamptner, 1963) Bramlette & Wilcoxon, 1967, which are of particular stratigraphic importance because they characterise the upper part of the horizon with *Sphenolithus heteromorphus*, where they first appear according to Švábenická (2002). She distinguished this horizon in Moravia (Czech Republic), where it corresponds to the uppermost NN5 Zone *sensu* Martini (1971). According to Young (1998), oval *Cor. nitescens* forms stratigraphically range from the NN5 to the NN6 zones. Based on calcareous nannofossil studies from the northeast Atlantic (west of the Iberian Peninsula), de Kaenel and Villa (1996) found that the LO of this morphotype is in the lower NN6 Zone.

In the Badenian (Middle Miocene), three calcareous nannofossil zones *sensu* Martini (1971) are distinguished – the upper NN4, NN5, and the lower NN6 zones (see Hohenegger *et al.* 2014). The NN4/NN5 boundary and the NN5/NN6 boundary are defined by the LO of *Helicosphaera ampliaperta* Bramlette and Wilcoxon, 1967 and the LO of *S. heteromor-*

*phus*, respectively (Martini 1971; see also Raffi *et al.* 2020). While *S. heteromorphus* was found in most samples in the studied section, *H. ampliaperta* was not recorded, thereby fingerprinting the NN5 Zone.

Among species commonly occurring in the NN5 Zone as identified by Martini (1971), the studied samples include: numerous (only in the lower assemblage) *H. carteri*, less numerous *S. heteromorphus*, and individual *Discoaster exilis* Martini & Bramlette, 1963 and *Discoaster variabilis* Martini & Bramlette, 1963 (Text-fig. 2). It should be noted, however, that Martini's (1971) samples were taken from Gabon, Italy, Malta, the USA, and the Pacific Ocean – which represent substantially different depositional environments than the Carpathian Foredeep.

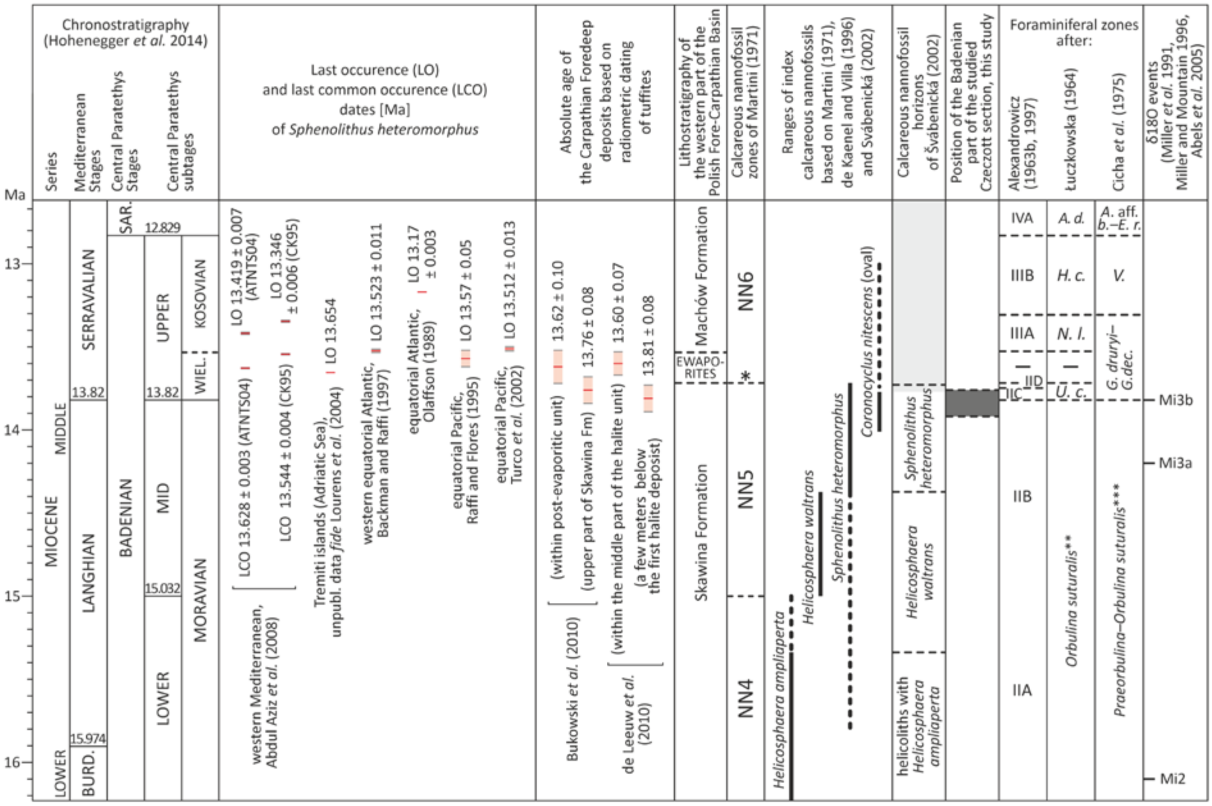
Švábenická (2002) distinguished three nannofossil horizons in Moravia: a 'helicolith' horizon with *Helicosphaera ampliaperta*, a horizon with *Helicosphaera waltrans* Theodoridis, 1984, and a horizon with *Sphenolithus heteromorphus*. The calcareous nannofossil assemblages in the Czeczott section correspond to the upper part of the *Sphenolithus heteromorphus* horizon, which is assigned to the uppermost NN5 Zone *sensu* Martini (1971). According to Švábenická (2002), this horizon yields: *S. heteromorphus*, *H. walbersdorfensis*, *H. carteri*, *P. multipora*, *U. rotula*, *Calcidiscus premacintyrei* Theodoridis, 1984, *Calcidiscus macintyrei* (Bukry and Bramlette, 1969) Loeblich and Tappan, 1978, *Calcidiscus leptoporus* (Murray & Blackman, 1898) Loeblich & Tappan, 1978, *Discoaster exilis*, *D. variabilis*, numerous small *Reticulofenestra* spp., large forms of *Coccolithus miopelagicus* Bukry, 1971b (exceeding 10 µm in size), *Rhabdosphaera* spp. *sensu* Young (1998) and, in the upper part of this horizon, oval forms of *Cor. nitescens*, 5-rayed symmetrical discoasters, the enigmatic ?*Catinaster* of Martini and Bramlette (1963) (or central parts of discoasters), and rare *Helicosphaera mediterranea* Müller, 1981. Apart from ?*Catinaster*, all these taxa occur in the Czeczott section. Catinasters can be very similar to central parts of discoasters, especially when poorly preserved (pers. comm. Miloš Bartol, August 2026). It is possible that Švábenická (2002) observed the central parts of discoasters. It also agrees better with age estimates. However, *H. ampliaperta* and *H. waltrans*, which are characteristic of the two lower horizons, were not recorded.

Taking into account these observations, the calcareous nannofossil assemblage from the Skawina Formation of the Czeczott section corresponds to the upper part of the *Sphenolithus heteromorphus* horizon of Švábenická (2002), which represents the uppermost NN5 Zone (Martini 1971; Švábenická 2002). This is primarily supported by the presence of *S. heteromorphus*, *H. walbersdorfensis* and oval forms of *Cor. nitescens*, and the absence of *H. ampliaperta* and *H. waltrans*. *Discoaster* species (*Discoaster deflandrei* Bramlette & Riedel, 1954, *D. exilis*, *Discoaster musicus* Stradner, 1959, *D. variabilis*) characteristic of the Middle Miocene do not occur or occur very rarely, and are mainly represented by ray fragments. The scarcity and poor preservation of these species is interpreted to be ecologically controlled, and may suggest deposition in a coastal environment (Ćorić and Hohenegger 2008). *Helicosphaera walbersdorfensis* is abundant in the lower assemblage (175.0–145.0 m) in the Czeczott section; in the Mediterranean region, it has its FCO in the regional MNN5b Zone, which corresponds to the upper NN5 Zone (Fornaciari *et al.* 1996), confirming its assignment to the upper NN5 Zone. The scarcity or absence of this species in the upper assemblage (97.0–40.5 m) is most likely related to environmental changes (see Palaeoecology section).

According to Hohenegger *et al.* (2014), the upper NN5 Zone corresponds to the upper mid Badenian (uppermost Moravian) and lower upper Badenian (lower Wielician). The NN5 Zone has also been recognised in other Polish Carpathian Foredeep sections (e.g., Garecka and Jugowiec 1999; Garecka 2014; Gaździcka 2015; Bukowski *et al.* 2018; Nosowska *et al.* 2019; Garecka and Pilarz 2019).

Absolute age constraints on the LO of *S. heteromorphus* – and, by extension, the NN5/NN6 boundary – primarily suggest a late Badenian age (see Text-fig. 6). In this study we follow Peryt D. (1997), who suggested that the LO of *S. heteromorphus* occurred at the base of the evaporites in the Gliwice area (near Pszczyna). The geochronological position of the evaporites in Text-fig. 6 was established based on absolute age constraints of the tuffite horizon from the evaporites, and from deposits below (in the upper Skawina Formation) and above the evaporites (Bukowski *et al.* 2010; de Leeuw *et al.* 2010).

The stratigraphic interpretation based on calcareous nannofossil assemblages is consistent with foraminiferal studies (Pilarz and Łuczkowska 2001; see also Garecka and Pilarz 2019). The first foraminiferal assemblage (190.0–144.0 m depth interval) was referred to the *Candorbulina suturalis* Zone (*Praeorbulina glomerosa–Orbulina suturalis* Zone) of the Moravian Substage (Pilarz and Łuczkowska 2001; Nosowska *et al.* 2019; Text-fig. 6). Similar Miocene subgypsum formations in Upper Silesia, which contained the 'Lancendorf' fauna in their lower portions, were described by Alexandrowicz (1958, 1959, 1963b) as assemblage IIA and the over-



Text-fig. 6. Stratigraphic position of the Czeczott Mine pit-shaft S-1 borehole section in relation to index calcareous nannofossil ranges, biostratigraphic schemes, and the LO and LCO of *S. heteromorphus* correlated with chronostratigraphy, lithostratigraphy, foraminiferal biozonations and oxygen isotope events. Explanations: * – NN5/NN6 boundary estimated based on Peryt D. (1997); light grey areas – intervals not studied in Švábenická (2002); ** – The *Orbulina suturalis* Zone of Łuczkowska (1964) was originally named as *Candorbulina universa* Zone (*Candorbulina suturalis* in Pilarz and Łuczkowska 2001); *** – The *Praeorbulina glomerosa–Orbulina suturalis* Zone in Nosowska *et al.* (2019). Abbreviations: BURD. – Burdigalian, SAR. – Sarmatian, WIEL. – Wielician, *U. c.* – *Uvigerina costai*, *N. l.* – *Neobulimina longa*, *H. c.* – *Hanzawaia crassiseptata* (*Cibicides crassiseptatus* in Łuczkowska 1964), *A. d.* – *Anomalinoides dividens*, *G. druryi–G. dec.* – *Globigerina druryi–Globigerina decoraperta*, *V* – *Velapertina*, *A.* aff. *b.–E.r.* – *Anomalina* aff. *badenensis* (*Cibicides* aff. *badenensis* in Cicha *et al.* 1975) – *Elphidium regina* (*Elphidium reginum* in Cicha *et al.* 1975).

lying assemblage IIB. The second foraminiferal assemblage (144.0–34.4 m depth interval) was assigned to the *Uvigerina costai* Zone (*Globigerina druryi–Globigerina decoraperta* Zone) of the Wielician Substage (Pilarz and Łuczkowska 2001; Nosowska *et al.* 2019). This assemblage may correspond to the IIC assemblage of Alexandrowicz (1963b).

## Palaeoecology

The term ‘calcareous nannofossils’ is a catch-all term that includes coccoliths (calcium carbonate plates produced by coccolithophores), nannoliths (calcareous forms of uncertain affinities), calcispheres (a continuous wall produced by dinoflagellates of the genus *Thoracosphaera*), and ascidian spicules (see Bown and Young 1998). Coccolithophores are minute, unicellular, photosynthetic, planktonic algae that are very abundant in modern oceans. As photosynthetic organisms, they mainly occur in the upper photic zone. They occur from tropical to sub-arctic waters (Melinte 2005) and typically prefer normal marine environments with narrow salinity fluctuations. However, coastal species tolerate wider salinity variations; some primarily live in brackish waters, and on the other end of the spectrum, *C. pelagicus* was found in the Dead Sea at a salinity of 250‰ (Tappan 1980).

These environmental parameters – surface water temperature, salinity, nutrient and light availability – have a much greater influence on their distribution than water depth, and as such calcareous nannoplankton are not a good indicator of basin depth (Perch-Nielsen 1985a). In particular, temperature is influential in determining the distribution of calcareous nannoplankton (Wei and Wise 1990; Agnini *et al.* 2006). Andreyeva-Grigorovich (2002) distinguished seven ecogroups based on their temperature preferences. The first three ecogroups comprise genera indicative of tropical and subtropical waters, and include the genera *Sphenolithus*, *Discoaster* and *Braarudosphaera*. Two ecogroups – *Calcidiscus* and *Helicosphaera* – are associated with moderate conditions. The remaining two ecogroups, *Coccolithus* and *Reticulofenestra*, are cold-water. In this framework, the relative proportions of ecogroups provide a useful proxy for paleotemperature trends.

The environmental preferences of selected taxa that are important for determining palaeoecological conditions in the Czeczott section are described below. Our focus is on the most frequently represented taxa in the samples – *C. pelagicus*, *R. pseudoumbilicus*, small *Reticulofenestra* spp., genus *Helicosphaera*, *H. carteri*, *U. rotula*, and the slightly less numerous *Cy. floridanus* – and also on taxa that were less numerous, but have distinct environmental preferences, i.e., *Braarudosphaera bigelowii* (Gran & Braarud 1935) Deflandre, 1947, *Micrantholithus vesper* Deflandre, 1950, *P. multipora*, and the genera *Discoaster* and *Sphenolithus*.

*Coccolithus pelagicus* is an important paleoclimatic indicator (McIntyre and Bé 1967). Through most of the Miocene, *C. pelagicus* mostly occurred in the northern higher latitudes (Haq 1980). Although this species evolved in tropical regions during the early Cenozoic, its temperature preference changed through time (Haq and Lohmann 1976; Wei and Wise 1990). In modern oceans, it prefers cold (McIntyre and Bé 1967; Okada and McIntyre 1979) and nutrient-rich surface waters which are often associated with upwelling (Rahman and Roth 1990; Cachão and Moita 2000; Ćorić and Rögl 2004). The optimum temperature range for *C. pelagicus* is 2–12ºC, with a maximum range of 1–15ºC (Okada and McIntyre 1979). Cachão and Moita (2000) extended the optimum temperature range to 16ºC and the maximum to 18ºC. According to Ćorić and Hohenegger (2008), *C. pelagicus* prefers water temperatures between −1.5ºC and 15ºC, with highest specimen concentrations between 2ºC and 12ºC.

*Cyclicargolithus floridanus* may indicate high nutrient availability (Auer *et al.* 2014), and cool (Wise 1973; Spaulding 1991) or temperate waters (Wei and Wise 1990). This species appears to have been cosmopolitan (Haq 1980).

Although *Reticulofenestra pseudoumbilicus* is generally considered to be a cosmopolitan species (Bukry 1976; Krammer *et al.* 2006) with no distinct ecological preferences (Beaufort and Aubry 1992), during the Miocene this species was common in mid-latitudes (Haq 1980) and tolerated or preferred cool waters (Wise 1973). Additionally, Andreyeva-Grigorovich (2002) classified *R. pseudoumbilicus* as a cool-water species. According to Imai *et al.* (2015) the co-occurrence of a low Nannofossil Accumulation Rate, high *Discoaster* abundance and presence of large *Reticulofenestra* specimens suggests a deep thermocline and nutricline, typical of oligotrophic conditions.

'Small *Reticulofenestra* species' is a general term referring to species of small size that are difficult to recognize under a light microscope with a magnification of 1000×. According to Wade and Bown (2006), *Reticulofenestra minuta* Roth, 1970 may have been able to withstand highly stressful conditions. In particular, this form could respond quickly to environmental changes, and consequently dominated assemblages when other species were unable to compete under such circumstances. It may have tolerated brackish to hypersaline, high productivity environments, including those associated with evaporite deposition. Small reticulofenestrids have broad ecological tolerance and are considered capable of flourishing under nutrient-rich conditions (see Wade and Bown 2006; Holcová 2013). Ćorić and Rögl (2004) interpreted a small amount of *C. pelagicus* and a bloom of *R. minuta* as resulting from the influence of warm waters without upwelling conditions. According to Holcová (2013), two *R. minuta* blooms (in the NN1 to the lower NN2 zones, and in the NN5 Zone) can be correlated with the inflow of warm waters. Ćorić and Hohenegger (2008) also interpreted small reticulofenstrid blooms in Badenian deposits as indicators of warmer, more-stratified waters. Haq (1980) noted the dominance of *Dictyococcites minutus* (Haq, 1971) Haq, Lohmann & Wise, 1977 in Miocene assemblages from coastal areas. Small *Reticulofenestra* spp. are variably interpreted to indicate either eutrophic (e.g., Kameo 2002; Wade and Bown 2006; Holcová 2013) or, conversely, oligotrophic conditions (e.g., Beaufort and Aubry 1992; Ćorić and Rögl 2004). However, according to Imai *et al.* (2015), the co-occurrence of a high Nannofossil Accumulation Rate, low *Discoaster* abundance, and large numbers of small *Reticulofenestra* specimens indicates a shallow thermocline and nutricline, typical of eutrophic conditions.

*Umbilicosphaera rotula* [= *Cyclolithella rotula* (Kamptner, 1956) Haq & Berggren, 1978 in Rahman and Roth 1990] preferred warm waters (Rahman and Roth 1990).

The genus *Helicosphaera* is neither strictly oceanic nor typically near-shore. Instead, it is characteristic of unstable environmental conditions (Báldi-Beke 1984), such as those typical of the Carpathian Foredeep Basin (Švábenická 2002). Most species of this genus have preferred shallow and warm-water conditions throughout their geological history (Perch-Nielsen 1985b; Wei and Wise 1990). They commonly occur in both shallow epicontinental seas and oceanic deposits (Švábenická 2002), and may also be associated with upwelling areas (Perch-Nielsen 1985b). Furthermore, *Helicosphaera* may be tolerant to environmental changes, such as water column stratification (Krhovský *et al.* 1992).

Some authors observe that *Helicosphaera carteri* is currently most abundant in lower latitude warm waters (McIntyre and Bé 1967; Ziveri *et al.* 2004), and therefore suggest it should be considered as a warm-water indicator (Wise 1973). However, Okada and McIntyre (1979) noted that *H. carteri* can tolerate a much wider temperature range (5–30ºC), reflecting its ecological flexibility.

According to Wei and Wise (1990), *Sphenolithus* species preferred warm waters and were more diverse at low latitudes. According to Perch-Nielsen (1985b), and Wei and Wise (1990), they may have been more common near continental margins than in open oceans. Generally, it preferred warm oligotrophic environments (Ćorić and Hohenegger 2008). According to Andreyeva-Grigorovich (2002), *Sphenolithus moriformis* (Brönnimann & Stradner, 1960) Bramlette & Wilcoxon, 1967 and *Sphenolithus heteromorphus* are common in tropical waters (see also Aubry 1989), and *Sphenolithus abies* Deflandre in Deflandre & Fert, 1954 was associated with warm waters.

The genus *Discoaster* is a typical component of warm-water, open-ocean assemblages in tropical and subtropical regions. This K-selected group occurs commonly in oligotrophic warm and deep-oceanic waters (Ćorić and Hohenegger 2008). According to Haq (1980), the *Discoaster–Sphenolithus* assemblage favoured warm waters and low latitudes. It seems that some species became extinct due to significant climatic cooling (Aubry 1984). However, *Discoaster deflandrei*, *Discoaster exilis*, and *Discoaster variabilis* may have had different water temperature preferences. Bukry (1971a, p. 971) found that "*D. exilis s.l.* and *D. variabilis s.l.* are more abundant in the cooler, more northerly sites". Similarly, Wise (1973) stated that *D. deflandrei* and *D. exilis* may have tolerated or preferred cool waters. In epicontinental deposits, discoasters are relatively scarce, and are usually smaller and thinner than in open-ocean deposits (Aubry 1984; Peryt D. *et al.* 2021). Their distribution was strongly palaeogeographically-dependent, as they are more common in the Mediterranean domain than in isolated Paratethys basins. Martini (1977) also noted the reduced size of some *Discoaster* species while studying Middle Miocene sediments of the Korytnica Basin in the southern Holy Cross Mountains. This is a particularly dissolution-resistant group according to Bukry (1981), although they are susceptible to mechanical damage during transport.

The genera *Braarudosphaera*, *Micrantholithus* and *Pontosphaera* exhibit similar environmental preferences (Báldi-Beke 1984). They are mainly associated with near-shore environments, and are relatively tolerant of environmental stress compared to other taxa. By analogy with modern blooms, *Braarudosphaera* blooms in Late Cretaceous coastal environments are thought to have been caused by either an influx of continental waters rich in nutrients or coastal upwelling, both of which would have resulted in lower salinity and eutrophication (Cunha and Shimabukuro 1997). *Braarudosphaera* appears to tolerate more stressful conditions than most other calcareous nannoplankton taxa (Bartol *et al.* 2008). Furthermore, the distribution of *Braarudosphaera bigelowii* is water-depth dependent: it has been found in abundance in near-shore sediments shallower than 24 m, in sharp contrast to its distribution in deeper sediments (Takayama 1972). *Braarudosphaera bigelowii* is most abundant in low-salinity coastal waters and does not occur in high-salinity settings (Bukry 1974). Enormous *B. bigelowii* blooms can occur further from the shore, in mid-ocean upwelling zones with cool, low-salinity, and nutrient-rich waters (Siesser *et al.* 1992). Bartol *et al.* (2008) suggested that *B. bigelowii* thrived under unusual palaeoceanographic conditions, and its abundance implicitly reflects an opportunistic response to reduced competition. Andreyeva-Grigorovich (2002) classified this species within the tropical/subtropical ecogroup.

In contrast to *Braarudosphaera*, little is known about the palaeoecological preferences of *Micrantholithus* (Bartol *et al.* 2008). It seems that this genus may have occurred from 50ºN to 50ºS, and its distributional preferences may have been influenced by neritic factors, such as lowered salinity and increased nutrient availability (Street and Bown 2000; Bartol *et al.* 2008).

*Pontosphaera* species are more diverse in nearshore rather than ocean deposits (Perch-Nielsen 1972). They are probably associated with stable marine conditions and only slight salinity fluctuations (Nagymarosy and Voronina 1992). Bartol (2009) observed the continuous presence of *P. multipora* throughout a section, except for a single sample in which *B. bigelowii* is particularly abundant. This was interpreted to reflect a short-term episode of slight freshwater influence.

The genus *Thoracosphaera* constitutes an important component of marine calcareous nannoplankton assemblages. These dissolution resistant forms are abundant in oligotrophic surface waters (Karwath *et al.* 2000). Increases in their abundance have been interpreted to reflect stressed environmental conditions within the photic zone (Agnini *et al.* 2007).

In the Czeczott section, calcareous nannofossils are characteristic of a higher latitude epicontinental sea. This is clearly suggested by the very rare occurrence and poor preservation of the genus *Discoaster*, as is characteristic of deposits of such marine environments (Aubry 1984; Peryt D. *et al.* 2021), and the sporadic to rare occurrence of the genus *Sphenolithus*, which preferred warm, low-latitude waters (Wei and Wise 1990).

Intriguingly, a clear difference in the abundances of certain taxa was observed between the lower (175.0–145.0 m) and the upper (97.0–40.5 m) assemblages (Text-fig. 2). This suggests that the deposition of the Skawina Formation – at least as encountered in the studied section – took place under shifting environmental conditions, specifically different palaeotemperatures. In the lower assemblage, small *Reticulofenestra* spp., *Helicosphaera* species, and *U. rotula* – most often regarded as warm water indicators – are significantly more numerous than in the upper assemblage. In contrast, the upper assemblage is dominated by *C. pelagicus* and *R. pseudoumbilicus*, which are typically associated with cooler waters; these species are significantly more abundant than co-occurring small *Reticulofenestra* spp. and *Helicosphaera* species. However, *C. pelagicus* is also very abundant in the lower assemblage. This may result from periodic upwelling, which would be supported by the presence of numerous *Helicosphaera* species. There is no sustained evidence for near-shore environments, as could be reflected by high abundances of *B. bigelowii*, *M. vesper* and *P. multipora*. Likewise, increased salinity cannot be inferred, because *B. bigelowii*, the most important indicator of those conditions, rarely occurs in the Czeczott section. Relatively high nutrient availability in surface waters during the initial phase of deposition in the Czeczott section, is reflected by the abundance of *C. pelagicus* and small *Reticulofenestra* spp. (see Cachão and Moita 2000 and Imai *et al.* 2015). The higher abundance of *R. pseudoumbilicus* in the upper assemblage than in the lowermost part of the section may be related to lower nutrient availability. This conclusion is based on the study by Imai *et al.* (2015). *Discoaster*, which should also be abundant, is rare due to palaeogeographic conditions.

The upper assemblage (97.0–40.5 m) predominantly consists of damaged, poorly distinguishable calcareous nannofossil elements, high abundances of redeposited, mainly Paleogene taxa, particularly at the 97.5 m level. It is also associated with rich terrigenous material, including both organic fragments and glauconite. The high proportion of reworked specimens, their poor state of preservation, and the presence of terrigenous material indicate unfavourable conditions for coccolithophore development. These conditions could have been related to eustatic sea-level fall, basin isolation, changes in seawater chemistry (including increased salinity), variations in nutrient availability, and low water clarity, due to shallow-water environment patterns (Garecka and Olszewska 2011). Furthermore, the occurrence of strongly damaged calcareous nannofossil fragments suggests mixing and mechanical destruction that occurred during transport. These unfavourable environmental and taphonomic conditions eliminated some species from the assemblage, particularly those more sensitive to environmental instability. Excluding redeposited taxa, the most numerous groups include opportunistic, solution-resistant species such as *C. pelagicus*, *R. pseudoumbilicus* and *Cy. floridanus*.

In conclusion, the main palaeoecological observation is that the lower part (175.0–145.0 m) of the section likely accumulated in warmer waters, accented by potential upwelling zones and more nutrient-rich waters, than the upper part (97.0–40.5 m). These palaeotemperature inferences correspond well to foraminiferal studies on the same section (Pilarz and Łuczkowska 2001). Those authors distinguished two foraminiferal assemblages in the studied section: (1) a lower one (190.0–144.0 m) rich in benthic species and abundant in taxonomically diverse – and quantitatively dominant – planktonic species (23 species); and (2) an upper one (144.0–34.4 m) still rich in benthic taxa, but with a gradual upward decline in the proportion of planktonic foraminifera. The lower assemblage is indicative of a deep-water, open-marine settings, and its planktonic genera point to warm and deep-water environments. Subsequently, starting from 144 m upwards in the section, shallow-water benthic foraminifera appear. A concomitant decrease in the abundance of thermophilic planktonic taxa further supports a progressive reduction in water depth (Pilarz and Łuczkowska 2001). Starting from the depth 108 m upwards, warm-water planktonic foraminifera do not occur, which may indicate a climate cooling.

## Regional trends

Foraminiferal oxygen isotope analyses ($\delta^{18}O$) from the Skawina Formation from sections located near the Czeczott Mine pit shaft S-1 borehole (Gliwice-17, Pławniowice-1, Gliwice-24, Pilchowice-1 and Żory-4 boreholes) revealed a significant increase in $\delta^{18}O$ values at a level corresponding to the boundary between the IIAB and IIC foraminiferal zones of Alexandrowicz (1963b), which in turn corresponds to the Moravian/Wielician and Langhian/Serravallian boundaries (see Text-fig. 6; Gonera and Bukowski 2012).

Based on both palaeoecological analyses of foraminifera and foraminifera test $\delta^{18}O$ measurements, cooling is observed at the beginning of Zone IIC in Upper Silesia (Durakiewicz *et al.* 1997; Gonera *et al.* 2000; Gonera 2001, 2018; Gonera and Bukowski 2012). This climatic cooling reaches its maximum (Mi3) at the NN5/NN6 calcareous nannofossil zones boundary (Gonera 2001). Specifically, this maximum should be defined as the Mi3b event *sensu* Miller and Mountain (1996) and Abels *et al.* (2005), coinciding with the beginning of the Serravalian (Wielician) (see Text-fig. 6).

In the Czeczott section, the *Praeorbulina glomerosa–Orbulina suturalis* Zone (175–145 m) and the *Globigerina druryi–Globigerina decoraperta* Zone (97–40.5 m) correspond to the *Candorbulina suturalis* (Moravian) and *Uvigerina costai* (Wielician) zones, respectively (Pilarz and Łuczkowska 2001; Nosowska *et al.* 2019). The foraminifera from the depth interval – 175–145 m indicate a warm climate in the Moravian, while those from the depth interval – 97–40.5 m indicate a cooler climate in the Wielician. This cooling pattern across the Czeczott section is also reflected by calcareous nannofossil analyses. The observed temperature change in the studied Czeczott section coincides with the Mi3b event.

## CONCLUSIONS

1. The Skawina Formation of the Czeczott Mine pit-shaft S-1 borehole section belongs to the uppermost NN5 Zone *sensu* Martini (1971), corresponding to the upper mid Badenian (uppermost Moravian) and lower upper Badenian (lower Wielician) *sensu* Hohenegger *et al.* (2014). The assemblage closely corresponds to the upper part of the *Sphenolithus heteromorphus* horizon of Švábenická (2002). In the Czeczott section, the uppermost NN5 Zone was identified based on the co-occurrence of *S. heteromorphus*, *H. walbersdorfensis* and oval forms of *Cor. nitescens*, together with the absence of *H. ampliaperta* and *H. waltrans*.

2. The upper assemblage is characterised by the common to abundant occurrence of predominantly Paleogene reworked taxa, as well as frequent *C. pelagicus* and *R. pseudoumbilicus* specimens. In several samples, reworked specimens predominate over these long-ranging autochthonous taxa, indicating a significant contribution of allochthonous material to the calcareous nannofossil assemblage. The high proportion of reworked species points to an intensified supply of allochthonous material to the basin, most likely derived from erosion of elevated source areas and subsequent redeposition.

3. The common to abundant occurrence of long-ranging, dissolution-resistant opportunistic taxa may artificially inflate their relative abundance in the studied samples. This taphonomic overprint hampers reliable palaeoecological reconstruction.

4. A pronounced quantitative differentiation in species composition – particularly within *Helicosphaera*, *R. pseudoumbilicus*, *U. rotula* and small *Reticulofenestra* spp. – is observed between the lower and upper intervals of the Czeczott section. The calcareous nannofossil assemblages indicate that the lower interval was deposited under warmer, eutrophic and normal-marine salinity conditions, whereas the upper interval records sedimentation in relatively cooler surface waters with lower nutrient availability.

5. Calcareous nannofossil assemblages point to a general cooling trend in the Skawina Formation encountered in the Czeczott section. This is in good agreement with the palaeoclimatic changes recorded in earlier studies of foraminifera from this section (Pilarz and Łuczkowska 2001), as well as with changes known from palaeoclimatic analyses on both regional (Gonera and Bukowski 2012) and global scales (Holbourn *et al.* 2007; Hohenegger *et al.* 2014).

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# Appendix

Alphabetical list of calcareous nannoplankton taxa recognised in the Czeczott Mine pit-shaft S-1 borehole section

*Braarudosphaera bigelowii* (Gran & Braarud, 1935) Deflandre, 1947
*Calcidiscus leptoporus* (Murray & Blackman, 1898) Loeblich & Tappan, 1978
*Calcidiscus pataecus* (Gartner, 1967) de Kaenel & Villa, 1996
*Calcidiscus premacintyrei* Theodoridis, 1984
*Coronocyclus nitescens* (Kamptner, 1963) Bramlette & Wilcoxon, 1967
*Coccolithus miopelagicus* Bukry, 1971b
*Coccolithus pelagicus* (Wallich, 1877) Schiller, 1930
*Cyclicargolithus floridanus* (Roth & Hay in Hay *et al.*, 1967) Bukry, 1971b
*Discoaster deflandrei* Bramlette & Riedel, 1954
*Discoaster exilis* Martini & Bramlette, 1963
*Discoaster musicus* Stradner, 1959
*Discoaster variabilis* Martini & Bramlette, 1963
*Discoaster* spp.
*Helicosphaera carteri* (Wallich, 1877) Kamptner, 1954
*Helicosphaera carteri* var. *burkei* (Black, 1971) Theodoridis, 1984
*Helicosphaera intermedia* Martini, 1965
*Helicosphaera mediterranea* Müller, 1981
*Helicosphaera walbersdorfensis* Müller, 1974
*Micrantholithus vesper* Deflandre, 1950
*Pontosphaera multipora* (Kamptner, 1948 *ex* Deflandre in Deflandre & Fert, 1954) Roth, 1970
*Reticulofenestra pseudoumbilicus* (Gartner, 1967) Gartner, 1969
Small *Reticulofenestra* spp.
*Rhabdosphaera* spp.
*Sphenolithus heteromorphus* Deflandre, 1953
*Sphenolithus moriformis* (Brönnimann & Stradner, 1960) Bramlette & Wilcoxon, 1967
*Thoracosphaera* spp.
*Umbilicosphaera jafari* Müller, 1974
*Umbilicosphaera rotula* (Kamptner, 1956) Varol, 1982