GEOLOGICA CARPATHICA, JUNE 2015, 66, 3, 181–195 doi: 10.1515/geoca-2015-0019

Last occurrence of *Abathomphalus mayaroensis* (Bolli) foraminiferid index of the Cretaceous–Paleogene boundary: the calcareous nannofossil proof

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(Manuscript received June 22, 2014; accepted in revised form March 12, 2015)

Abstract: In the Gaj section (Polish Carpathians, Skole Nappe, Ropianka Formation), the Late Maastrichtian calcareous nannofossil biostratigraphy is compared with foraminiferal zonation based on the occurrence of the planktonic foraminiferid index species *Abathomphalus mayaroensis*. It appears that the LO of *A. mayaroensis*, which has been used previously in the studied section as the possible K/Pg boundary indicator is located below the boundary. The disappearance of *A. mayaroensis* along with other planktonic foraminiferids before the Cretaceous–Paleogene (K/Pg) boundary mass extinction event may be a consequence of the Late Maastrichtian rapid warming pulses. Moreover, the Paleogene age cannot be supported by the FO of the benthic foraminiferid *Rzehakina fissistomata,* because it first appears together with the nannofossil *Ceratolithoides kamptneri* (zonal marker for the latest Maastrichtian UC20c^{TP} Zone). According to the present study, the whole studied section represents the lower Upper to the upper Upper Maastrichtian UC20b^{TP} and UC20c^{TP} nannofossil zones, so that it corresponds to the lower-middle part of the planktonic foraminiferal *A. mayaroensis* Zone, which, according to the scheme by Caron (1985), should extend up to the K/Pg boundary.

Key words: biozonation, Cretaceous–Paleogene boundary, nannofossils, foraminiferids, late Maastrichtian warming.

Introduction

Biostratigraphy is often based on an incomplete stratigraphic record which depends on taphonomic processes or the paleoecological preferences of fossils used as stratigraphic tools. More accurate data can be obtained from integrated stratigraphy combining multiple methods of dating, for instance magnetostratigraphy and biostratigraphy based on different groups of fossils. This approach sometimes allows recognition of diachronic first or last occurrences of index taxa and more precise definition of their chronostratigraphic position (Huber & Watkins 1992; Bergen & Sikora 1999; Petrizzo 2003; Nifuku et al. 2008; Thibault et al. 2010, 2012; Petrizzo et al. 2011). A good example of such problems comes from a combined application of the Late Maastrichtian foraminiferid and nannofossil zones. Among them, the most problematic seems to be the topmost Maastrichtian planktonic foraminiferid *Abathomphalus mayaroensis* Zone, the upper boundary of which corresponds to the Cretaceous–Paleogene (K/Pg) boundary and can be used as a proxy for the boundary when the boundary layer with the iridium anomaly is not developed or preserved, for instance in a case of flysch deposits. It appears that the first and last occurrences of this important index species are controlled by Late Maastrichtian environmental changes (Huber & Watkins 1992; Keller & Abramovich 2009). Moreover, definition of the upper boundary of the *A. mayaroensis* Zone has changed many times since Caron (1985) proposed this zone as the total range zone of the index and eponym species *Abathomphalus mayaroensis*. For instance, Premoli-Silva & Verga (2004) defined its upper boundary at the level of “the extinction of most of the Cretaceous planktonic foraminifers”. Such definition, however, is imprecise, and it does not necessarily coincide with the K/Pg boundary, as is shown by Ogg et al. (2004; p. 355), where the last occurrence of *A. mayaroensis* appears below the K/Pg boundary (see also Robaszynski & Caron 1995). Similar problems concern the nannofossil biostratigraphy. Diachronism of the first appearances of the index taxa is well recognized in the case of *Nephrolithus frequens*, which is used as the index species of the last Maastrichtian CC26 Zone *sensu* Sissingh (1977). This bipolar, high paleolatitude species migrated toward the Equator from the latest early Maastrichtian to the latest Maastrichtian (Pospichal & Wise 1990a; Nifuku et al. 2008). The nannofossil biozonation proposed by Burnett (1998) tried to avoid the problem of diachronicity of index species caused by their paleoenvironmental preferences using the different UC subzones for the Tethyan, Boreal and Austral provinces. Nevertheless, the problem of the diachronous appearance of index species remains. This can be exemplified by the case of *Micula murus*, a low-latitude, warm surface water inhabitant, migrating poleward from low to intermediate latitudes (Thibault et al. 2010) as well as equatorward shifts of *Nephrolithus frequens* or *Abathomphalus mayaroensis* (Huber & Watkins 1992) during the Late Maastrichtian. This shows that the lower boundary of the UC20b^{TP} defined by the first occurrence of *M. murus* is diachronous in the Tethyan-Intermediate provinces, at least.

In this paper, the calcareous nannofossil biostratigraphy is compared to the foraminiferal zonation applied for the Upper

Maastrichtian deposits of the Skole Nappe (Outer Carpathians) in the previously studied Gaj composite section (Husów region — see Gasiński & Uchman 2009). The main goal of this paper is to verify the position of the K/Pg boundary in the Gaj composite section, which was previously suggested by Gasiński & Uchman (2009) on the basis of foraminiferids above the range of the index planktonic species *Abathomphalus mayaroensis* and below non-index benthic species which are common in the Paleogene.

Remarks on K/Pg boundary biostratigraphy studies

Many taxa from different groups of both land and marine organisms suffered a mass extinction in consequence of the K/Pg boundary event (see D'Hondt 2005; Schulte et al. 2010 for review), but not necessarily precisely at the time of the K/Pg boundary event and there are connections with paleolatitude (Keller 2001; Keller et al. 2007). Therefore, high-resolution determination of the boundary based on them is suspicious. Instead, the K/Pg boundary is defined at the El Kef section in Tunisia, fixed as the K/Pg boundary Global Stratotype Section and Point (GSSP), at the base of a 1–3 mm thick rusty layer containing the maximum Ir content and overlain by the 0.5 m thick black Boundary Clay (Molina et al. 2006; Ogg & Hinnov 2012). Fossils, comprising the nannofossils and foraminiferids, serve only as auxiliary criteria for determining the literal K/Pg boundary in the absence of the Boundary Clay.

The calcareous nannofossil biostratigraphy of the K/Pg boundary is handicapped by the problem of the reworked assemblages (Bown 2005; Kędzierski et al. 2011 and references cited therein) and growing evidence of some taxa such as *Cruciplacolithus primus*, which were previously considered as newcomers, but now as Late Maastrichtian in origin (Mai et al. 2003). Similarly, the Lower Paleocene foraminiferid assemblages also comprise reworked and survivor taxa (Huber 1996; Gallala et al. 2009; Slimani & Toufiq 2013). Moreover, the post-extinction Paleogene recovery of planktonic foraminiferids was polyphasic and began thousands of years after the terminal event (Coxall et al. 2006; Gallala et al. 2009; Schulte et al. 2010). The increase in abundance (bloom) of survivor or disaster opportunistic taxa, such as the planktonic foraminiferids *Guembelitria cretacea*, *Hedbergella holmdelensis*, or *H. monmouthensis* (Pardo & Keller 2008; Slimani & Toufiq 2013), and the calcareous nannoplankton *Braarudosphaera* spp. or *Thoracosphaera* spp. (e.g. Gardin 2002; Keller et al. 2007), characterizes the earliest Danian. Comparative studies by Gallala et al. (2009; fig. 6) showed that the Danian planktonic foraminiferal assemblages from different sections may consist of up to 28 % of Cretaceous survivor or disaster species, on average. Also Luciani (2002) reported gradual and extended disappearance of the Maastrichtian planktonic foraminiferids across the K/Pg boundary. Therefore, the recognition of the exact position of the K/Pg boundary on the basis of calcareous nannofossil or planktonic foraminiferids requires quantitative studies difficult to perform in turbiditic deposits generally characterized by redeposition. However, the sharp decrease in abundance and diversity of planktonic foraminiferids is usually observed just above the K–Pg boundary in sections with a continuous record of deposition across the boundary (Gallala & Zaghbib-Turki 2010). The benthic foraminiferids did not experience a mass extinction during the K/Pg boundary event (Culver 2003; Alegret & Thomas 2013) and are almost useless for biostratigraphy around this boundary event (see Geroch & Nowak 1984).

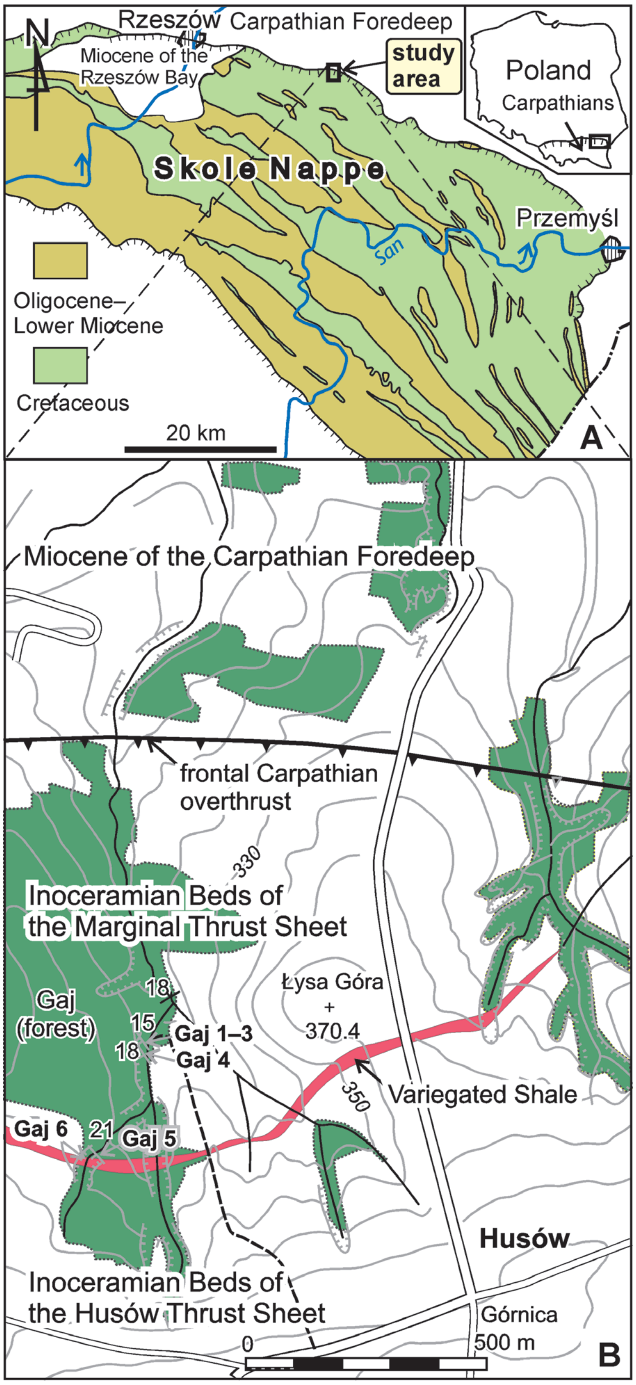


Fig. 1. Geological map with location of the studied section and stratigraphy of the Skole Nappe (after Gasiński & Uchman 2009 — modified).

Geological setting

The research was carried out in the Skole Nappe, in an anticlinal structure of the Marginal Thrust Sheet, a few hundred meters from the frontal Carpathian overthrust, bordering with the Miocene Carpathian Foredeep basin succession (Fig. 1A). The studied section embraces the upper part of the Ropianka Formation known also as the Inoceramian Beds (e.g. Tietze 1883; Uhlig 1888; Wdowiarz 1936, 1949; Bromowicz 1974). Kotlarczyk (1978, 1985) distinguished the Cisowa, Wiar, Leszczyny and Wola Korzeniecka members (given in ascending order) in the Ropianka Formation and provided the comprehensive information about the history of its research, outline of the stratigraphy, lithology and facies development (for details see also Gasiński & Uchman 2009). The Wola Korzeniecka Member of the Ropianka Formation, overlain by the Eocene Variegated Shale Formation, represents the Paleocene. Therefore, the K/Pg interval occurs within the underlying Leszczyny Member of the Ropianka Formation.

The studied area is located in the Gaj forest (GPS coordinates: N 49°59.729′, E 22°15.135′; Fig. 1B), between the villages of Husów, Handzlówka and Albigowa, about 10 km south of the city of Łańcut. The rocks outcrop along the Gajowy stream and its left tributary. The fourth-partial sections, based on isolated natural outcrops, named Gaj A–D were sampled for the purpose of the study by Gasiński & Uchman (2009), which contains more detailed information on the section and the geological background (Fig. 2).

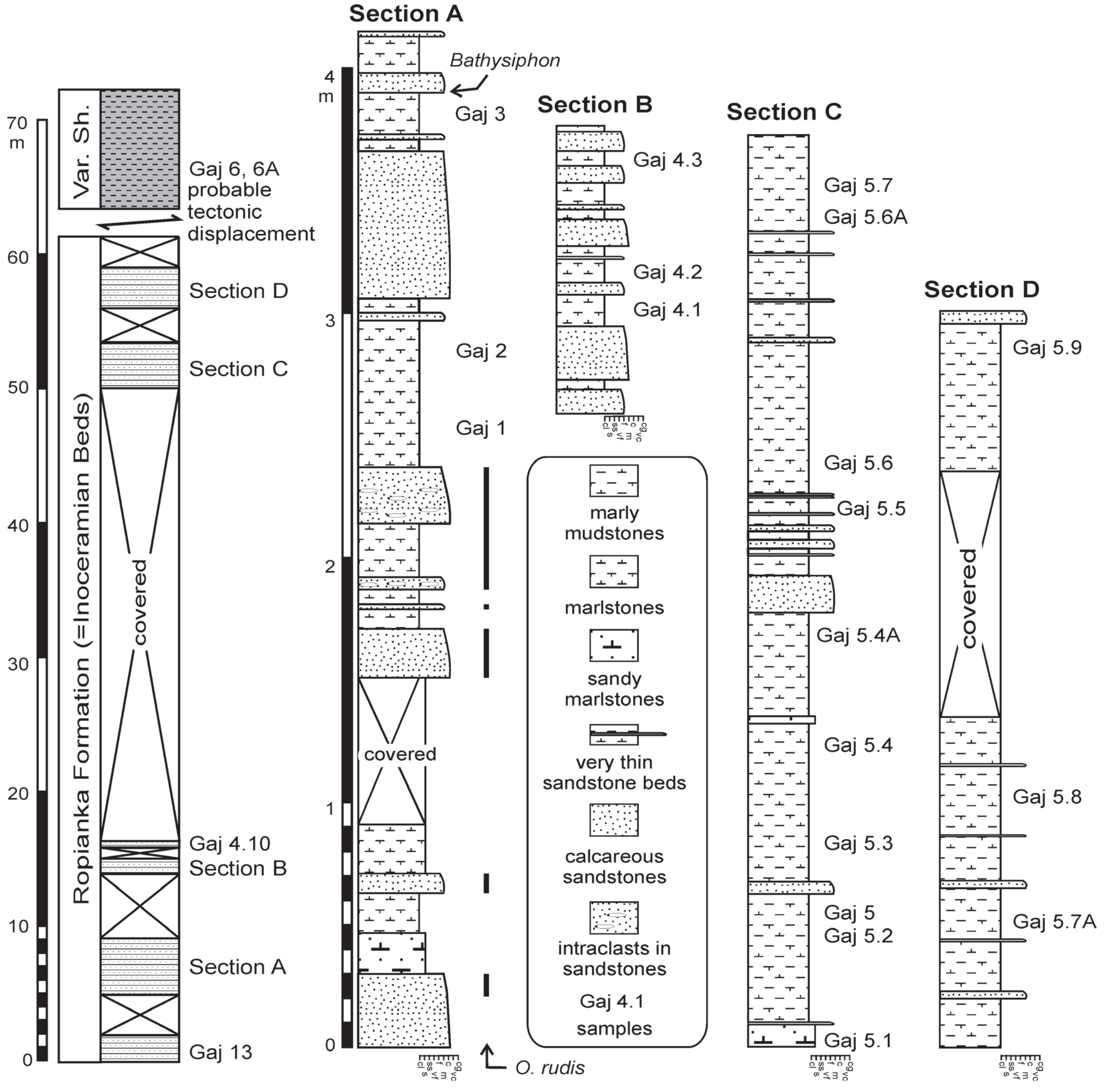


Fig. 2. The Gaj composite section (after Gasiński & Uchman 2009 — modified).

Methods

A qualitative study of calcareous nannofossil assemblages has been conducted on 16 rock samples Gaj 4.1–6 (Fig. 3). The nannofossil microscopic slides were prepared using the simple smear slide method and inspected at a magnification of ×1000 under the light microscope Nikon Eclipse E600 Pol using cross-polarized light (see Bown & Young 1998). The state of preservation of the nannofossil assemblages was determined using the scale proposed by Kędzierski & Leszczyński (2013). This scale describes the total degree of damage (D1–4) of the specimens studied, such as etching, overgrowth, etc., causing problems in taxonomic identification. D1 means a little damage and D4 strong damage, in this scale. No other foraminiferid preparation treatment, besides these carried out by Gasiński & Uchman (2009), has been done for this study.

Results

The results described below refer exclusively to the calcareous nannofossils. All the data concerning foraminiferids are taken from Gasiński & Uchman (2009).

All the samples, except for Gaj 6, contain generally moderately preserved calcareous nannofossils. States of preservation range from D2 to D4 (Table 1), where 2 means medium and 4

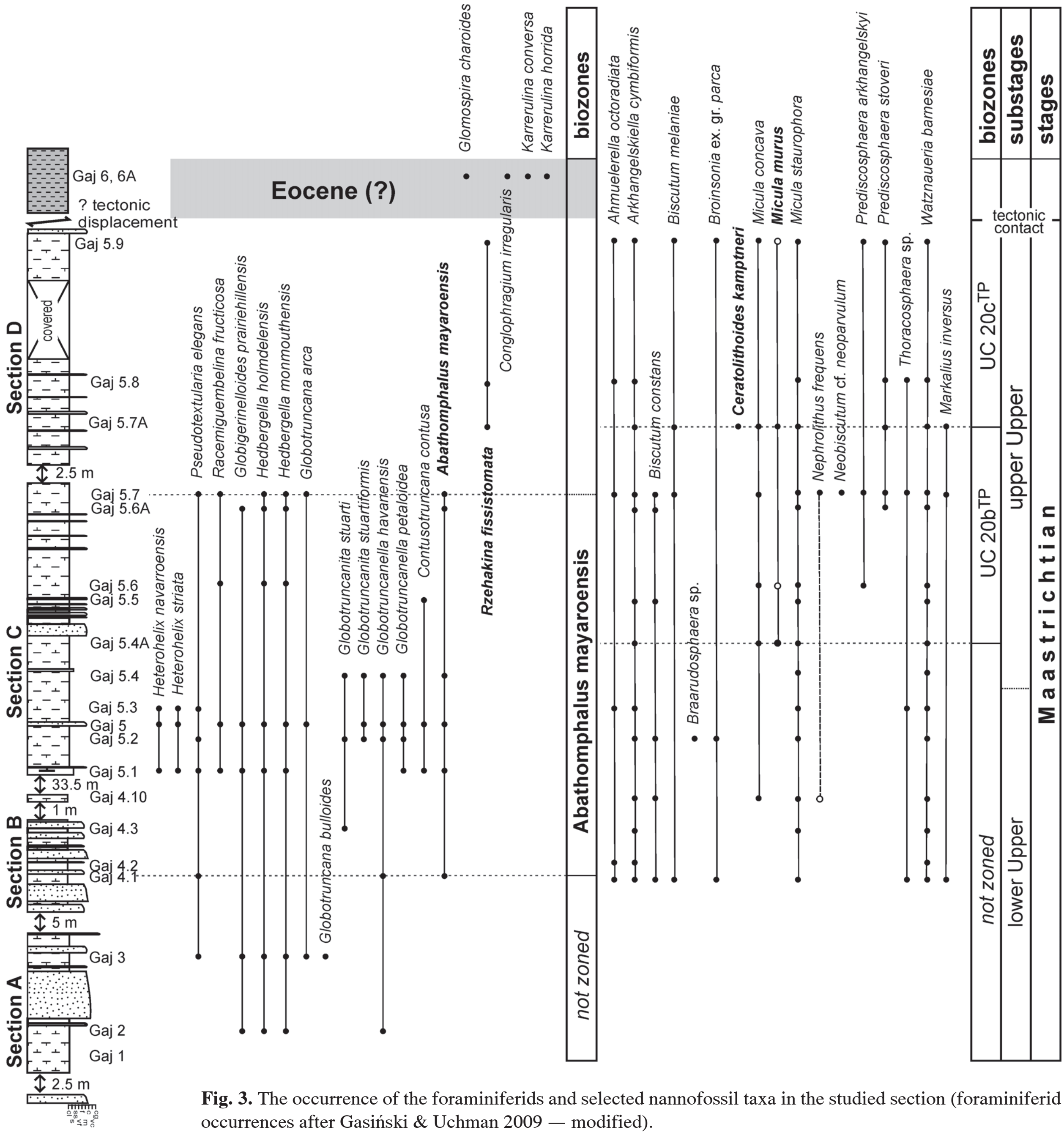


Fig. 3. The occurrence of the foraminiferids and selected nannofossil taxa in the studied section (foraminiferid occurrences after Gasiński & Uchman 2009 — modified).

strong damage (see Kędzierski & Leszczyński 2013). Fifty six taxa belonging to thirty five genera have been recognized. The nannofossil assemblages are dominated by *Micula* spp., *Arkhangelskiella* spp. (mainly *A. cymbiformis*), *Prediscosphaera* spp., and additionally by *Watznaueria barnesiae* in some samples (Table 1, Fig. 4). Among stratigraphically important species, *Micula murus* was found in samples Gaj 5.4A, 5.6(?). 5.7A and 5.9(?) (the question mark is due to poor preservation), and *Ceratolithoides kamptneri* in sample Gaj 5.7A. *Prediscosphaera stoveri* is common and occurs continuously throughout samples Gaj 5.6A–5.9. Some specimens of *Braarudosphaera* sp. have been found in one sample Gaj 5.2. *Thoracosphaera* spp. occur in the samples Gaj 4.1, 5.3, 5.7, 5.8 and 14. These taxa were found in low amount, never exceeding a few specimens, therefore, no record of their blooming, regarded as indicative of the K/Pg boundary event and the base of the Danian, has been observed. The results of study carried out by Gasiński & Uchman (2009) on foraminiferal assemblages in the Gaj section are shown in Figs. 3 and 5.

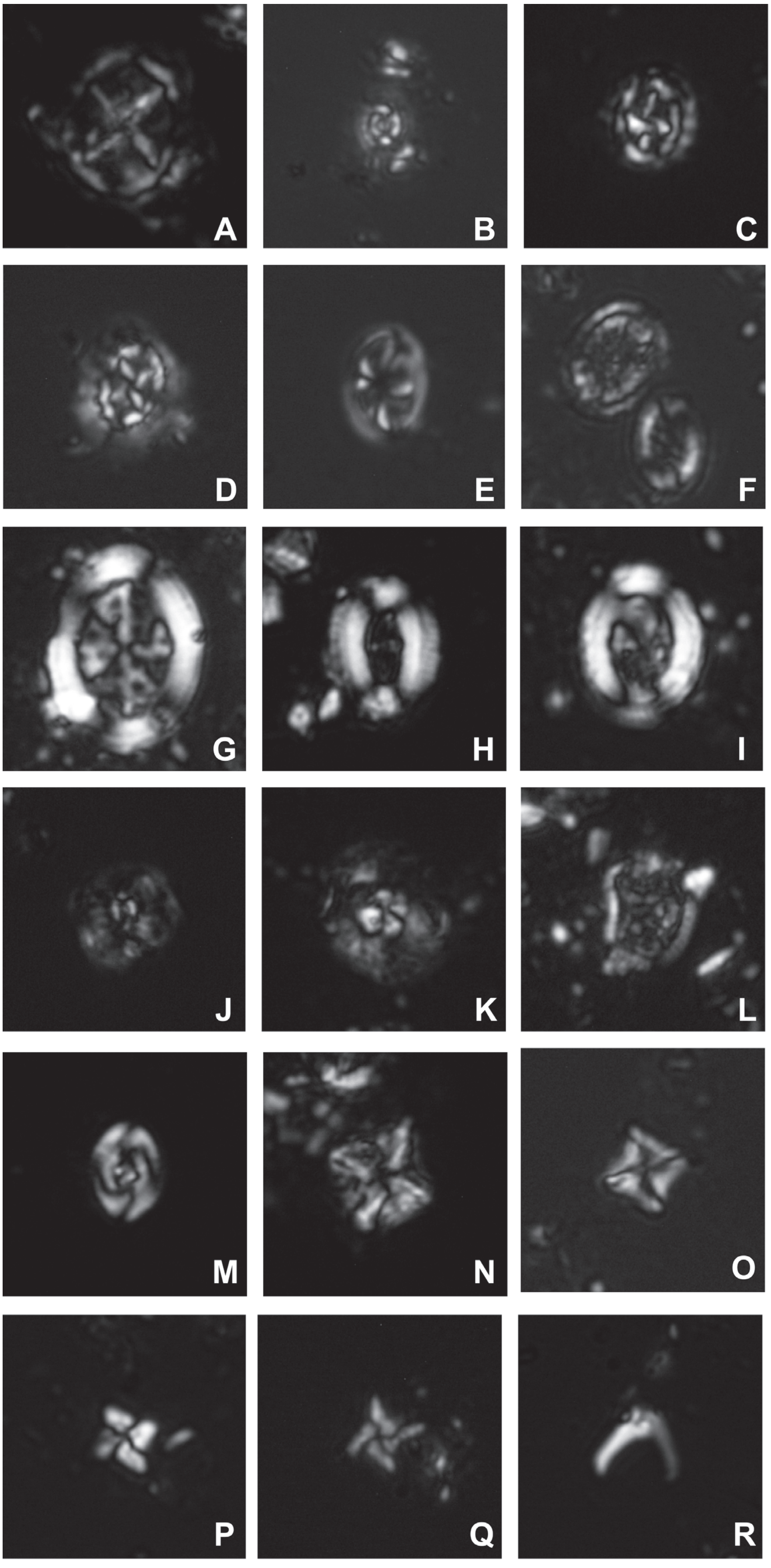
Discussion

In the Gaj section, Gasiński & Uchman (2009) distinguished the planktonic foraminiferal *A. mayaroensis* Zone with its top marked by the last occurrence of the index species in sample Gaj 5.7 (Fig. 3). The last occurrences of other planktonic, typically Upper Cretaceous foraminiferids, such as *Globotruncana arca*, *Racemiguembelina fructicosa*, *Pseudotextularia elegans*, were also noted in this sample. Moreover, these samples contain only the agglutinated benthic foraminiferid *Rzehakina fissistomata*, except for the last samples Gaj 6 and Gaj 6a, which also contained agglutinated foraminiferids, such as *Conglophragmium irregularis* and *Karrerulina* spp. This last occurrence of *A. mayaroensis*, the absence of other planktonic foraminiferids and the presence of *R. fissistomata* suggested that the part of the section above sample Gaj 5.7 may represent the Paleogene. Therefore, the K/Pg boundary was provisionally identified just above the sample Gaj 5.7 (Fig. 3). However, some doubts concerning this indication were discussed by Gasiński & Uchman (2009) and the present calcareous nannofossil study aims to clarify them.

At El Kef, GSSP of the K/Pg boundary, the top of the planktonic foraminiferal *Abathomphalus mayaroensis* and nannofossil *Micula prinsii* zones are situated exactly at the bound-

Table 1: Distribution of the calcareous nannofossils in the study material. Abbreviations used in column abundance follow categories proposed by Burnett (1998). **R** — rare = 1 specimen/>50 fields of view (or 1 traverse), **F** — few = 1 specimen/2–50 fields of view, **B** — barren in nannofossils. Preservation by means of specimen destruction follows the procedure of Kędzierski & Leszczyński (2013).

Samples	**Preservation**	**Abundance**	*Ahmuerella octoradiata*	*Arkhangelskiella cymbiformis*	*Arkhangelskiella* sp.	*Biscutum constans*	*Bisctum dissimilis*	*Biscutum melaniae*	*Biscutum* sp.	*Braarudosphaera* sp.	*Broinsonia* sp.	*B.* ex gr. *parca*	*Calculites obscurus*	*Ceratolitoides aculeus*	*Ceratolitoides kamptneri*	*Chiastozygus litterarius*	*Chiastozygus* sp.	*Cretarhabdus* sp.	*Cribrosphaerella ehrenbergii*	*Cribrosphaerella daniae*	*Ellipsogelosphaera* sp.	*Eiffellithus* sp.	*Eiffellithus turriseiffelii*	*Eprolithus floralis*	*Helicolithus* sp.	*H. trabeculatus*	*Gartnerago obliquum*	*Kamptnerius magnificus*	*Lucianorhabdus* sp.	*Markalius inversus*	*Micula concava*	*M. murus*	*M. praemurus*	*Micula* sp.	*M. staurophora*	*Neochiastozygus* sp.	*Neocrepidolithus* cf. *neocrassus*	*Nephrolithus frequens*	*Petrarhabdus copulatus*	*Placozygus fibuliformis*	*Prediscosphaera arkhangelskyi*	*P. cretacea*	*P. incohatus*	*P. grandis*	*P. stoveri*	*Prediscosphaera* sp.	*Quadrum gartneri*	*Quadrum* sp.	*Reinhardtites levis*	*Retecapsa angustiforata*	*Retecapsa* sp.	*Rhagodiscus* sp.	*R. indistinctus*	*Staurolithites* sp.	*Thoracosphaera* sp.	*Tranolithus orionatus*	*Watznaueria barnesiae*	*Zeugrhabdotus embergeri*	*Z. erectus*	*Zeugrhabdotus* sp.
Gaj 6	–	B																																																											
Gaj 5.9	D2	F	x	x				x	x		x	x					x	x	x	x			x				x		x		x	?		x	x						x	x		x	x	x				x	x					x	x	x		x
Gaj 5.8	D2	R	x	x	x				x				x				x		x				x					x						x	x	x	x			x		x			x	x					x				x		x			
Gaj 5.7A	D3	R		x				x	x						x				x											x	x	x		x	x							x			x					x	x	x					x			
Gaj 5.7	D2	F	x	x	x	x		x	x							x			x			x	x							x	x			x	x			x		x	x	x	x		x	x					x	x	x	x	x		x		x	
Gaj 5.6A	D2	R		x	x	x			x								x		x															x	x	x				x		x			x	x											x		x	
Gaj 5.6	D4	R			x				x													x				x					x	?		x	x		x			x	x					x					x						x			x
Gaj 5.5	D2	F		x	x	x			x		x		x				x	x	x		x	x	x						x					x	x					x		x				x					x			x			x			
Gaj 5.4A	D3	R		x	x				x										x												x	?		x	x					x		x				x											x			x
Gaj 5.4	D4	R			x				x																x									x	x											x											x			
Gaj 5.3	D4	R	x	x	x				x							x					x	x	x											x	x				x	x						x		x							x		x			
Gaj 5.2	D3	R		x	x	x	x		x	x		x											x	x										x	x				x	x		x				x		x			x			x			x			
Gaj 4.10	D3	F		x	x	x			x		x												x			x			x		x		?	x	x			?		x		x				x		x									x			x
Gaj 4.3	D3	R		x	x						x																							x	x							x				x											x			x
Gaj 4.2	D4	R	x	x	x				x		x					x						x	x											x						x		x				x											x			
Gaj 4.1	D2	F	x	x	x	x		x	x		x	x	x				x		x				x				x		x	x				x	x					x		x				x										x		x			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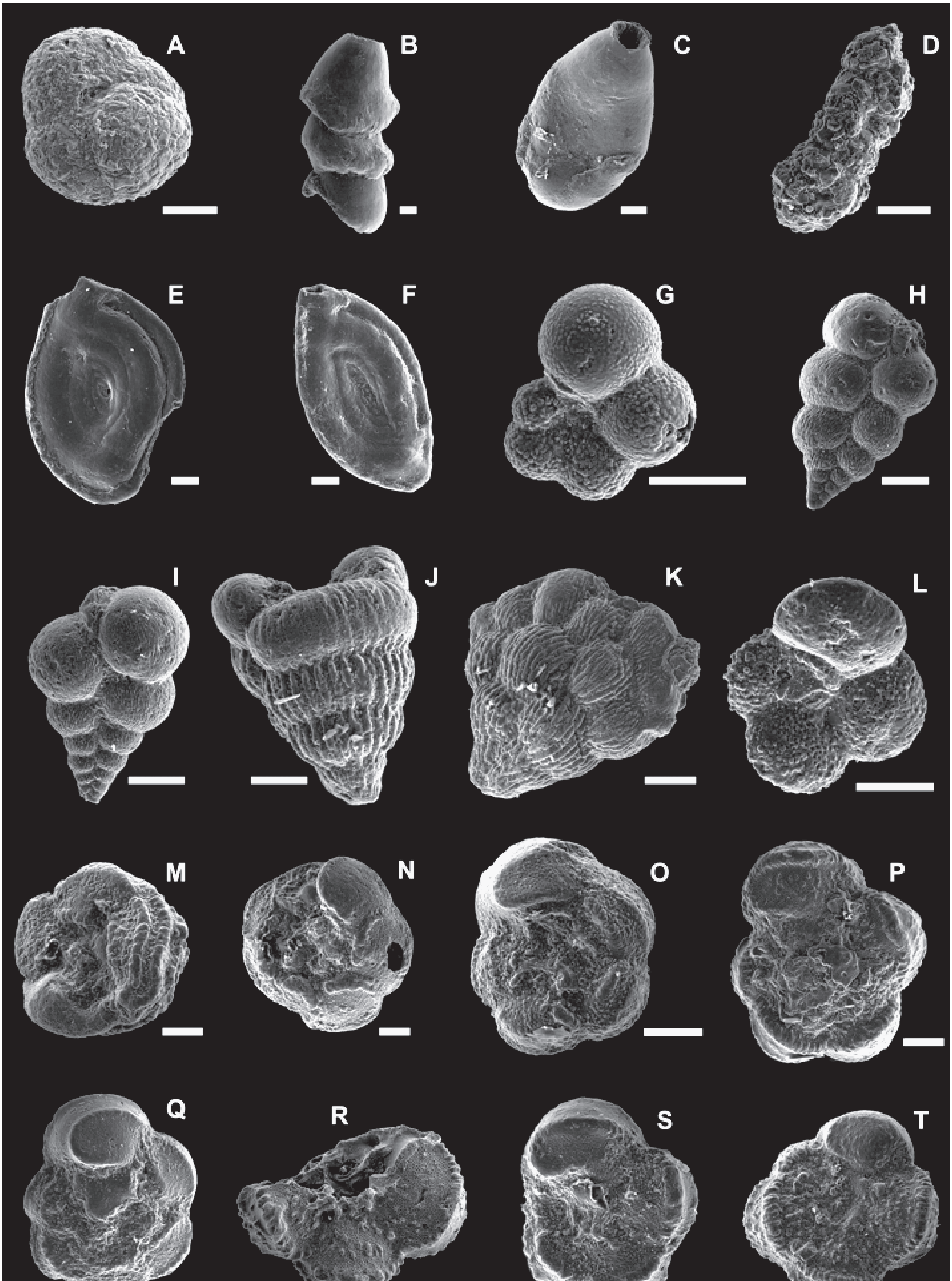
ary, which, in turn, is defined by the presence of the rusty layer at the base of the Boundary Clay (Molina et al. 2006). Strictly according to this statement, the absence of the K/Pg Boundary Clay layer precludes precise determination of the upper boundary of the *A. mayaroensis* Zone equivocally synchronous with the K/Pg boundary in the study section, hence, the undeniable indication of K/Pg boundary. The section studied is composed mostly of turbiditic deposits, in which finding of the clay boundary layer is unlikely. Therefore, the approximation of the K/Pg boundary can be determined here only by means of qualitative paleontological data. For this purpose we used combined foraminiferid and calcareous nannofossil data. Moreover, some discrepancies concerning these groups of fossils are discussed here.

Planktonic foraminiferal biostratigraphy around the K/Pg boundary

In the studied section, the Upper Cretaceous planktonic foraminiferal *A. mayaroensis* Zone is recognized based on the presence of the index species. Part of the section studied below the FO of *A. mayaroensis* is not zoned in the present work (Fig. 3), contrary to Gasiński & Uchman (2009) who distinguished the preceding *Gansserina gansseri* Zone based on species that in fact have a wider stratigraphic range encompassing at least the *Globotruncana aegyptiaca* and *Gansserina gansseri* zones (Gasiński & Uchman 2009; fig. 5). So far, *Gansserina gansseri* has been found in the adjacent thrust sheet of the same unit in the Bąkowiec section (Gasiński & Uchman 2011).

The younger planktonic foraminiferal *Guembelitria cretacea* Zone, which indicates the lowermost Paleocene, that is the interval just above the K/Pg boundary, was not recognized in the study section. The *G. cretacea* Zone is an acme biozone characterized by abundant occurrence of the Maastrichtian survivor or disaster species that bloomed after the K/Pg boundary event (e.g. Smit & Romein 1985; Canudo et al. 1991; Arenillas et al. 2006; Molina et al. 2006; Gallala et al. 2009; Ogg & Hinnov 2012) and by an abrupt increase in abundance of *G. cretacea* just above the K/Pg boundary. Its lowest interval, called the P0 Zone (e.g. Berggren et al. 1995; Ogg & Hinnov 2012), was recently replaced with the planktonic foraminiferal *Hedbergella holmdelensis* Subzone forming the lower subzone of the *G. cretacea* Zone. The *H. holmdelensis* Subzone is also an acme biozone, similarly to the whole *G. cretacea* Zone (Arenilllas et al. 2004, 2006; Gallala et al. 2009). Such blooms of the planktonic foraminiferids are a characteristic feature of the Danian, in which three acme stages have been recognized. The first stage, embracing the *G. cretacea* Zone, concerns only the blooms of the survivor or disaster taxa, such as *G. cretacea* or *H. holmdelensis*. The next two stages encompass blooms of the newcomer Danian taxa, such as *Palaeoglobigerina* or *Woodringina* (Canudo et al. 1991; Arenillas et al. 2006; Gallala et al. 2009; Gasiński & Uchman 2011; Slimani & Toufiq 2013). None of these blooms were observed in the studied Gaj section as the samples above the LO of *A. mayaroensis* do not contain any planktonic foraminiferids either Cretaceous or Paleogene. Such disappearance of all Cretaceous planktonic foraminiferid taxa is consistent with the definition of the upper boundary of the *A. mayaroensis* Zone by Premoli-Silva & Verga (2004). The Late Maastrichtian is known as a time of pronounced mantle plume volcanism influencing marine biota, especially calcareous nanno- and microplankton (e.g. Gale 2000; Keller 2002, 2008; Keller et al. 2007; Pardo & Keller 2008; Keller & Abramovich 2009; Tantawy et al. 2009). According to Frank & Arthur (1999), a tectonically driven global climate change begun in the Early Maastrichtian and resulted in a major reorganization of ocean circulation during the Late Maastrichtian. That might have strongly influenced the Late Maastrichtian marine biota. For instance, the planktonic foraminiferid *A. mayaroensis* is a bathypelagic K-strategy species requiring proper and stable environmental conditions (Keller & Abramovich 2009). A shift in ecological setting, especially the increase in environmental stress inferred by climate changes, led to its absence in some basins (see Keller & Abramovich 2009). Generally, *A. mayaroensis* is a very rare species, even at the El Kef GSSP, so its application for biostratigraphy is somewhat problematic (see Molina et al. 2006; Keller & Abramovich 2009; and references cited therein). As a result, Li & Keller (1998) replaced the *A. mayaroensis* Zone with the CF zones numbered in the descending order (CF1 is the latest Maastrichtian zone), which are based on other planktonic foraminiferids. Finally, the *A. mayaroensis* Zone *sensu* Caron (1985) comprises, in stratigraphically ascending order, the following zones: upper part of CF4 Zone based on the FO of *Raceguembelina fructicosa*; CF3 Zone based on the FO of *Pseudoguembelina hariaensis*; CF2 Zone based on the LO of *G. gansseri* and the last CF1 Zone based on the FO of *Plummerita hantkeninoides* Bronnimann. The CF2 and CF1 zones correspond to the latest Maastrichtian greenhouse period from which the foraminiferal assemblages are dominated by dwarfed disaster species (as a result of the so-called Lilliput effect) in some volcanically affected areas (Keller & Abramovich 2009; Tantawy et al. 2009). The CF2–1 zones time is also characterized by rapid decrease in surface, intermediate and deep foraminiferid species richness (Keller 2001). In

Fig. 4. Calcareous nannofossils in cross-polarized light. **A** — *Prediscosphaera grandis* Perch-Nielsen, sample 5.9; **B** — *Prediscosphaera stoveri* (Perch-Nielsen), sample 5.7; **C** — *Prediscosphaera* cf. *P. incohatus* (Stover), sample 5.7; **D** — *Prediscosphaera cretacea* (Arkhangelsky), sample 5.7; **E** — *Ahmuellerella octoradiata* (Górka), sample 5.7; **F** — *Cribrosphaerella ehrenbergii* (Arkhangelsky), sample 5.7; **G** — *Arkhangelskiella cymbiformis* (Vekshina), sample 5.9; **H, I** — *Broinsonia* ex gr. *B. parca*, sample 5.9; **J** — *Biscutum melaniae* (Górka), sample 5.7A; **K** — *Markalius inversus* (Deflandre in Deflandre & Fert), sample 5.7A; **L** — *Nephrolithus frequens* Górka, sample 5.7; **M** — *Placozygus* cf. *fibuliformis* (Reinhardt) Hoffmann, sample 5.7; **N** — *Micula staurophora* Gardet, sample 5.7; **O–Q** — *Micula murus* (Martini), sample 5.7A; **R** — *Ceratolithoides kamptneri* Bramlette & Martini, sample 5.7A.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general, the whole latest Maastrichtian is considered as a time of climate disturbances, due to the global warming periods interrupted by global cooling, which resulted in pronounced sea-level changes and shifts in oceanic column temperature composition (Miller et al. 2005, 2008; MacLeod et al. 2011). These definitely triggered a floral and faunal migration, including planktonic foraminiferids and calcareous nannoplankton (Thibault et al. 2010). Overall, such environmental changes, if they did not induce a disappearance of some species immediately, greatly reduced foraminiferid populations, hence their ability to reproduce (D'Hondt et al. 1996) and their disappearance in consequence, but in a longer perspective. Therefore, we argue that paleoecological perturbations combined with sea-level change scenarios can be applied to the Gaj section studied as a primordial general cause. Taphonomic filtering contributed to scarcity or absence of planktonic foraminiferids, especially if the Lilliput effect, facilitating destruction of foraminiferid tests, is taken into account. It is worth noting that observation of the rate of accumulated of modern planktonic foraminiferids show that only 1–3 % of carbonates of foraminiferid origin reach the deep-seafloor below 700 m of depth, because they are dissolved while settling through the water column (Schiebel 2002). Thus, the absence of *A. mayaroensis* and other planktonic foraminiferids would result from hostile environmental conditions occurring in the CF2–1 zones, namely during the latest Maastrichtian, as a primordial reason, which entailed the disappearance of some taxa directly and caused the scarcity of others which have been lost while settling or due to taphonomical processes. In fact, the section studied provides no complete record of the CF2–1 zones up to the K/Pg boundary, so re-entry of the latest Maastrichtian planktonic foraminiferid assemblages in possible more complete sections of the Skole Nappe is expected.

Benthic foraminiferal biostratigraphy around the K/Pg boundary

In the study of the Gaj section, the FO of the benthic agglutinated foraminiferid *Rzehakina fissistomata* has been proposed as proof supporting the Paleogene age of the interval studied above the LO of *A. mayaroensis* (Gasiński & Uchman 2009; fig. 4). This may be consistent with the biostratigraphic scheme proposed by Olszewska (1997), where the acme *Rzehakina fissistomata* Zone, characterized by frequent occurrence of its eponym species, is proposed as the first Paleogene foraminiferal zone comprising the whole Paleocene. Moreover, *R. fissistomata* is also commonly accepted as the Paleocene age indicator in the Carpathians (Geroch & Koszarski 1988; Bubík 1995; Bąk & Wolska 2005; Waśkowska-Oliwa 2005, 2008; Bindiu & Filipescu 2011; Cieszkowski & Waśkowska 2011; Cieszkowski et al. 2012).

However, there are some discrepancies concerning the time of the first appearance of *R. fissistomata*. For instance, according to Skupien et al. (2009, fig. 6), the first occurrence of this species is marked below the K/Pg boundary, within the uppermost part of the Upper Maastrichtian between the first occurrences of the nannofossils *Cruciplacolithus primus* (which appears a little above the K/Pg boundary in that study) and *Micula prinsii*, the index species of the Upper Maastrichtian nannofossil UC20d^{TP} Zone. The possible Maastrichtian origin of *R. fissistomata* is also suggested by Kaminski & Gradstein (2005). The exact chronostratigraphic position of the first occurrence of *R. fissistomata* has been equivocal. In the study section, *R. fissistomata* first occurs in sample Gaj 5.7A, together with the first appearance of the nannofossil *Ceratolithoides kamptneri*, which is the index species of the upper Late Maastrichtian nannofossil UC20c^{TP} Zone. This is consistent with reports pointing out the Maastrichtian origin of *R. fissistomata* and similar to its stratigraphic position in respect to the calcareous nannofossil biostratigraphy by Skupien et al. (2009).

Calcareous nannofossil biostratigraphy

The K/Pg boundary event is known as one of the most devastating events in the calcareous nannoplankton phylogeny, since it brought about the almost complete extinction of these mostly pelagic autotrophs. Only nine species of calcareous nannoplankton are considered as survivor or disaster species, and most of these gradually became extinct during the Early Paleocene (Bown et al. 2004; Bown 2005). The K/Pg boundary event is recorded in the normal marine settings as the peak of abundance of *Braarudosphaera* spp. and the calcareous dinoflagellates *Thoracosphaera* spp. or calcisphere fragments (Pospichal 1995; Bown 2005; Lamolda et al. 2005), which replaced coccolithophores during their low production post-event times (Fornaciari et al. 2007). The nannofossil assemblage occurring directly above the K/Pg boundary, marked at the base of the Boundary Clay, however, mostly consists of reworked Cretaceous specimens (Pospichal 1994; Bown 2005; Rodríguez-Tovar et al. 2010; Kędzierski et al. 2011). The abrupt appearance of the Paleocene species is recorded just above the reworking horizon (Thierstein 1981; Pospichal 1995, 1996; Gardin 2002; Bown 2005). The early Paleocene post-extinction recovery of the calcareous nannoplankton brought new evolutionary lines starting from the so-called newcomer taxa, such as the genera *Neobiscutum*, *Chiasmolithus* and *Cruciplacolithus* (Bown et al. 2004). The recovery took place during the global increase

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Fig. 5. Foraminiferids (bars = 100 μm). **A** — *Ataxophragmium* cf. *fertile* Woloshyna, sample 5.7A; **B** — *Hormosina velascoensis* (Cushman), sample 5.8B; **C** — *Caudammina ovula* (Grzybowski), sample 5.8; **D** — *Karrerulina conversa* (Grzybowski), sample 6; **E–F** — *Rzehakina fissistomata* (Grzybowski), sample 5.9; **G** — *Hedbergella monomouthensis* (Olsson), sample 5.6A; **H** — *Heterohelix striata* (Ehrenberg) sample 5; **I** — *Heterohelix navarroensis* Ehrenberg, sample 5.6A; **J** — *Racemiguembelina fructicosa* (Egger), sample 5.6A; **K** — *Planoglobulina acervulinoides* (Egger), sample 5; **L** — *Globotruncanella petaloidea* (Gandolfi), sample 5; **M** — *Contusotruncana contusa* (Cushman), sample 5.6A; **N** — *Globotruncanita stuarti* (de Lapparent), sample 5.2; **O** — *Globotruncana arca* (Cushman), sample 5; **Q** — *Globotruncana bulloides* (Vogler), sample 5.7; **P, R–T** — *Abathomphalus mayaroensis* (Bolli) = P — sample 5, R–S — sample 5.6A, T — sample 5.4.

of thermal stratification in the ocean, the condition which advantaged the oligotrophic genera such as *Neobiscutum* or *Cruciplacolithus.* They could became dominant and bloom in competitor free environments forming the highly-dominant and low diverse assemblages during the Early Paleocene (Jiang et al. 2010). Nonetheless, the first newcomer taxa are very small in size and thus are called dwarfed taxa. Their first occurrence used to be a marker of the base of the Lower Danian nannofossil zone (see discussion in Romein et al. 1996). However, Mai et al. (2003) noted the Maastrichtian occurrence of *Neobiscutum romeinii*, *N. parvulum* and *Cruciplacolithus primus* in many sections around the world, 2–12 m below the K/Pg boundary, and claimed that none of these species can be used as the indicator of the Paleocene (see also Mai 1999; Gardin 2002). Instead, the first occurrence of *Biantholithus sparsus* should be used as the certain age marker as is proposed in the zonation scheme by Varol (1998). Generally, this species is considered as rarely found (Mai et al. 2003; Molina et al. 2006), however, it was also noted in the Carpathians (Oszczypko et al. 1995; Bubík et al. 1999; Summesberger et al. 1999). On the other hand, van Heck & Prins (1987) and Švábenická (2001) claimed the occurrence of *B. sparsus* even in the Upper Maastrichtian. Nevertheless, this may be a case of a reworked Paleocene nannofossil pulled down into a burrow disturbing the K/Pg boundary, as was described by Pospichal & Wise (1990b) who noticed the occurrence of *B. sparsus* in the Upper Maastrichtian.

Interestingly, the latest Maastrichtian time of origin of the nannoplankton dwarfed taxa coincides with the time of occurrence of the so-called Lilliput effect in planktonic foraminiferids. This can be related to a common source, supposedly the Late Maastrichtian mantle plume volcanism, leading to a biotic stress in marine environments resulting in a biocalcification crisis in planktonic foraminiferids and calcareous nannoplankton (Abramovich & Keller 2003; Thibault & Gardin 2007, 2010; Keller & Abramovich 2009; Tantawy et al. 2009). Moreover, according to the conclusion concerning the paleoecology of *Prediscosphaera stoveri* presented by Sheldon et al. (2010), the common occurrence of this species in the material studied suggests a rather warm period. The appearance of the tropical *C. kamptneri* also supports the influence of generally warm surface waters. Nevertheless, this species is often reported from other sections in the Outer Carpathians (Bubík et al. 1999; Jugowiec-Nazarkiewicz 2007), therefore, there may be evidence of its long-term occurrence in the northern Tethys. Moreover, it is worth emphasizing here, that the mixed influence of the high- and low-latitude nannofossils, namely Boreal and Tethyan, seems to be the typical feature of the Maastrichtian in the Outer Carpathians (Bubík et al. 1999; Švábenická 2001; Švábenická et al. 2002). Perhaps, the further prolongation of the warming may have caused the planktonic foraminiferid devouring biocalcification crisis observed in the Gaj section above the last occurrence of *A. mayaroensis*, where only benthic foraminiferids occur. Some taphonomic filtering may also have played a role, especially in the redeposited flysch deposits. Chiu and Broecker (2008) found that calcareous nannoplankton is ten times more resistant to dissolution than foraminifera, hence, one may reckon the absence of fragile tests of planktonic foraminiferids and presence of nannofossils as an effect of taphonomic filtering. Such a conclusion will be more probable if these tests belong to the Lilliput planktonic foraminiferids. Therefore, the supposed taphonomic filtering also proves the biocalcification crisis, though indirectly.

None of the calcareous nannofossil indicators of the K/Pg boundary or its stratigraphic proximity, such as *Biantholithus sparsus* or peak in abundance of *Thoracosphaera* and/or *Braarudosphaera* spp., have been noted in the sec-

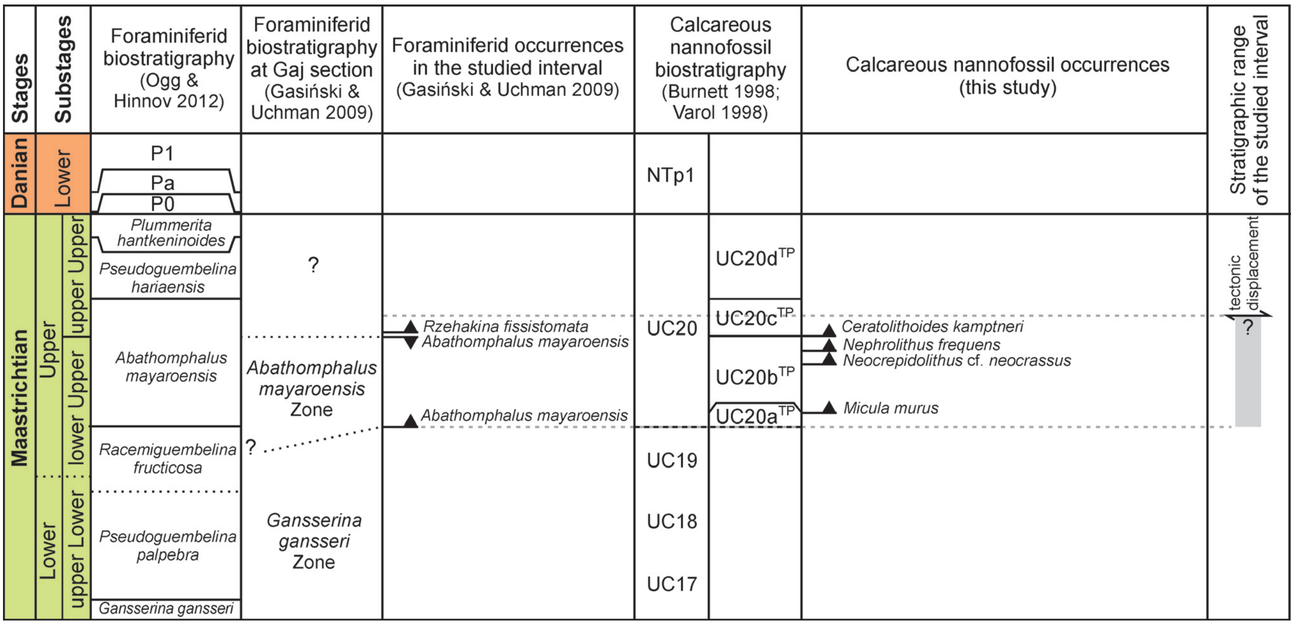

Fig. 6. Correlation of the calcareous nannofossil and foraminiferal zones against the chronostratigraphy in the studied section.

tion studied (Table 1). On the contrary, all samples are dominated by the Upper Cretaceous taxa. The interval between samples Gaj 5.6A and 5.7 contains the occurrence of *Micula murus,* the index species for the UC20b^{TP} Zone, which first occurs in sample Gaj 5.4A (Figs. 3, 6). Moreover, the succession of the uppermost Maastrichtian calcareous nannofossil index species corresponds to their succession used in the standard nannofossil UC zones proposed by Burnett (1998). Therefore, the interval above the LO of *A. mayaroensis*, suggested by Gasiński & Uchman (2009) as the Paleogene, indicates the nannofossil UC20c^{TP} Zone defined by the first occurrence of *C. kamptneri* (Gaj 5.7A). This is synchronous with the upper part of the planktonic foraminiferal CF3 Zone (Tantawy et al. 2009). The samples Gaj 5.8 and Gaj 5.9 have also been ascribed to the UC20c^{TP} Zone due to no other stratigraphic premises (Fig. 6). Sample Gaj 6 is barren in calcareous nannofossils. This period corresponds well with the beginning of the end-Maastrichtian warm event dated to the end of the nannofossil UC20c Zone (Thibault & Gardin 2007, 2010), which is also characterized by a decline in planktonic foraminiferid occurrence followed by an invasion of the dwarfed taxa (Abramovich & Keller 2003). The latter event has not been observed in the studied section, likely due to tectonic displacement of the younger sediments, including the K/Pg boundary.

Conclusions

1. The interval studied represents the Upper Maastrichtian deposits belonging to the nannofossil zones UC20b^{TP} — marked at the base by the first occurrence of *Micula murus*, and UC20c^{TP} — marked at the base by the FO of *Ceratolithoides kamptneri*. Thus, the interval studied embraces part of the planktonic foraminiferal *Abathomphalus mayaroensis* Zone and is synchronous with the CF4–3 zones.

2. The virtual K/Pg boundary interval is cut off by tectonic displacement noted at the top of the section studied and overlain by the Variegated Shale Formation ascribed to the Eocene on the basis of abundant occurrence of benthic agglutinated foraminiferids *Glomospira* spp. and *Karrurelina* spp.

3. The benthic agglutinated *Rzehakina fissistomata* first occurs around the boundary between the nannofossil UC20b^{TP}–UC20c^{TP} zones, and so in the Late Maastrichtian.

4. The absence of *Abathomphalus mayaroensis* and other planktonic foraminiferids is probably caused by adverse environmental conditions during the end-Maastrichtian warm event.

5. Integrated nannofossil and foraminiferid biostratigraphy is a useful tool for a more precise dating of flysch deposits impoverished in the stratigraphic markers.

Acknowledgments: The research was sponsored by the Polish National Science Centre (Grant NN 307038840) and supported by the Jagiellonian University (DS funds Project No. K/2DS/001673). We are also indebted to Lilian Švábenická for her efforts helping us to improve the manuscript, to an anonymous reviewer for comments and remarks, and to the Editors of Geologica Carpathica for their kindness.

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List of taxa

Foraminiferids

Abathomphalus mayaroensis (Bolli)
Conglophragmium irregularis (White)
Globigerinelloides prairiehillensis Pessagno
Globotruncana arca Cushman
Globotruncana bulloides (Vogler)
Globotruncana stuarti (de Lapparent)
Globotruncana stuartiformis Dalbiez
Globotruncanella havanensis (Voorwijk)
Globotruncanella petaloidea (Gandolfi)
Glomospira charoides (Jones & Parker)
Contusotruncana contusa (Cushman)
Guembelitria cretacea Cushman
Hedbergella holmdelensis Olsson
Hedbergella monmouthensis (Olsson)
Heterohelix navarroensis Ehrenberg
Heterohelix striata (Ehrenberg)
Karrerulina conversa (Grzybowski)
Karrerulina horrida (Mjatliuk)
Planoglobulina acervulinoides (Egger)
Pseudotextularia elegans (Rzehak)
Racemiguembelina fructicosa (Egger)
Rzehakina fissistomata (Grzybowski)

Nannofossils

Ahmuerelella octoradiata (Górka) Reinhardt & Górka
Arkhangelskiella cymbiformis Vekshina
Arkhangelskiella sp.
Biscutum constans (Górka) Black in Black & Barnes
Bisctum dissimilis Wind & Wise in Wise & Wind
Biscutum melaniae (Górka) Reinhardt
Biscutum sp.
Braarudosphaera sp.
Broinsonia sp.
Broinsonia ex gr. *parca* (Stradner) Bukry
Calculites obscurus (Deflandre) Prins & Sissingh in Sissingh
Ceratolitoides aculeus (Stradner) Prins & Sissingh in Sissingh
Ceratolitoides kamptneri Bramlette & Martini
Chiastozygus litterarius (Górka) Manivit
Chiastozygus sp.
Cretarhabdus sp.
Cribrosphaerella ehrenbergii (Arkhangelsky) Deflandre in Piveteau
Cribrosphaerella daniae Perch-Nielsen
Ellipsogelosphaera sp.
Eiffellithus sp.
Eiffellithus turriseiffelii (Deflandre in Deflandre & Fert) Reinhardt
Eprolithus floralis (Stradner) Stover
Helicolithus sp.
Helicolithus trabeculatus (Górka) Verbeek
Gartnerago obliquum (Stradner) Noël
Kamptnerius magnificus Deflandre
Lucianorhabdus sp.
Markalius inversus (Deflandre in Deflandre & Fert) Bramlette & Martini
Micula concava (Stradner in Martini & Stradner) Verbeek
Micula murus (Martini) Bukry
Micula praemurus (Bukry) Stradner & Steinmetz
Micula sp.
Micula staurophora Gardet
Neochiastozygus sp.
Neocrepidolithus cf. *neocrassus* (Perch-Nielsen) Romein
Nephrolithus frequens Górka
Petrarhabdus copulatus (Deflandre) Wind & Wise in Wise
Placozygus fibuliformis (Reinhardt) Hoffmann
Prediscosphaera arkhangelskyi (Reinhardt) Perch-Nielsen
Prediscosphaera cretacea (Arkhangelsky) Gartner
Prediscosphaera incohatus (Stover) Burnett
Prediscosphaera grandis Perch-Nielsen
Prediscosphaera stoveri (Perch-Nielsen) Shafik & Stradner
Prediscosphaera sp.
Quadrum gartneri Prins & Perch-Nielsen in Manivit et al.
Quadrum sp.
Reinhardtites levis Prins & Sissingh in Sissingh
Retecapsa angustiforata Black
Retecapsa sp.
Rhagodiscus sp.
Rhagodiscus indistinctus Burnett
Staurolithites sp.
Thoracosphaera sp.
Tranolithus orionatus (Reinhardt) Reinhardt
Watznaueria barnesiae (Black in Black & Barnes) Perch-Nielsen
Zeugrhabdotus embergeri (Noël) Perch-Nielsen
Zeugrhadbotus erectus (Deflandre in Deflandre & Fert) Reinhardt
Zeugrhabdotus sp.