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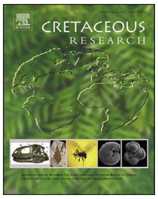

Late Maastrichtian cephalopods, dinoflagellate cysts and foraminifera from the Cretaceous–Paleogene succession at Lechówka, southeast Poland: Stratigraphic and environmental implications

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ABSTRACT

The Lechówka section comprises the most complete Cretaceous–Paleogene (K-Pg) boundary succession in Poland and is among 29 sites worldwide with the youngest ammonite record. Here, cephalopods (ammonites and nautilids), organic-walled dinoflagellates (dinocysts) and foraminifera from the uppermost Maastrichtian interval are studied. In terms of ammonite biostratigraphy, the upper Maastrichtian *Hoploscaphites constrictus crassus* Zone is documented up to a level 120 cm below the K-Pg boundary. There is no direct, ammonite-based evidence of the highest Maastrichtian *H. constrictus johnjagti* Zone. However, the predominance of the dinocyst marker taxon *Palynodinium grallator* suggests the presence of the equivalent of the uppermost Maastrichtian *Thalassiphora pelagica* Subzone, which is correlatable with the *H. c. johnjagti* ammonite Zone. The planktonic foraminiferal assemblage is coeval with that from the *H. c. johnjagti* Zone as well. These data indicate that the top of the Maastrichtian at Lechówka is complete within the limits of biostratigraphic resolution, albeit slightly condensed. The dinocyst and foraminiferal assemblages are dominated by taxa that are characteristic of high-energy, marginal marine environments. A reduction in test size among the calcareous epifaunal benthic foraminifera is observed at a level 50 cm below the K-Pg boundary, which is possibly related to environmental stress associated with Deccan volcanism.

1. Introduction

A sedimentary succession exposed at Lechówka near Chełm, southeast Poland, constitutes the most complete record of the Cretaceous–Paleogene (K-Pg) boundary interval in Poland (Racki, Machalski, Koeberl, & Harasimiuk, 2011). This section is a close lithological analogue of the classic K-Pg boundary succession at Stevns Klint, Denmark (Hart, Feist, Price, & Leng, 2004; Hart et al., 2005; Surlyk, 1997; Surlyk, Damholt, & Bjerager, 2006). The Danish site yielded the geochemical data (i.e., Ir anomaly) that provided the impetus to formulating the hypothesis that a meteorite impact had triggered a mass extinction at the end of the Cretaceous (Alvarez, Alvarez, Asaro, & Michel, 1980; Schulte et al., 2010; Smit, 1999).

In accordance with the impact hypothesis, Racki et al. (2011) recorded anomalously high amounts of iridium and other siderophile elements from the K-Pg interval at Lechówka, consistent with a chondrite meteorite composition. Those authors placed the local K-Pg boundary at the base of a clay layer which they correlated with K-Pg boundary clays known worldwide. However, they also noted that the iridium spike at Lechówka occurred 10 cm below the boundary clay. According to Racki et al. (2011), this anomalous location of the iridium anomaly resulted from remobilization and

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reconcentration of the impact-derived components by acid-rich ground waters during a prolonged phase of continental weathering which affected the area during the Paleogene (Pożaryski, 1951). The placement of the K-Pg boundary at the base of the clay layer and its direct link to the end-Cretaceous impact has been confirmed by Brachaniec, Karwowski, and Szopa (2014), who recorded the occurrence of spherules (microkrystites) with nickel-rich spinel grains from the boundary clay at Lechówka.

The significance of the Lechówka site is twofold. First, the mobility of iridium as documented at this locality suggests that a careful reconsideration of the Ir anomaly as a marker for K-Pg boundary correlations and reconstruction of extinction patterns across this boundary is called for (Racki et al., 2011). This is also exemplified by the situation in the Manasquan River Basin, New Jersey, USA, where secondary remobilization (downwards) of iridium has led to the erroneous identification of ammonites from the *Pinna* Bed as short-term Danian survivors (Landman, Garb, Rovelli, Ebel, & Edwards, 2012, Landman et al., 2014). Secondly, Lechówka is among 29 sites known worldwide with a documented record of the stratigraphically youngest ammonites (Landman, Goolaerts, Jagt, Jagt-Yazykova, & Machalski, 2015; Landman et al., 2014). Despite this, only limited data on the biostratigraphy and palaeoenvironment of this important succession have been published to date (Racki et al., 2011). Therefore, we here present the first detailed study of cephalopods (ammonites and nautilids), dinoflagellate cysts (dinocysts) and planktonic and benthic foraminifera from Lechówka and discuss their biostratigraphic and environmental significance. In view of the strong decalcification and weathering of the upper part of the section, we have concentrated on the upper Maastrichtian record of this site.

2. Geological setting

The Lechówka locality is an old, abandoned quarry situated at the edge of a forest near the town of Chełm, southeast Poland (Fig. 1). The geological and palaeogeographical settings of this locality were described by Popiel (1977), Harasimiuk and Rutkowski (1984), Krzowski (2000), Racki et al. (2011) and Brachaniec et al. (2014).

The present study is based on two sections of the Lechówka outcrop, measured and sampled in 2009 and 2011, respectively, in addition to a pilot section sampled in 2008 (Figs. 1C and 2). Section Lechówka 2009 (Fig. 2) was described in detail in Racki et al. (2011) and forms the basis for the present cephalopod and dinocyst study. In the lower part of this section there are two units of opoka (a widely used name in Polish geological literature for siliceous limestone; see Pożaryska (1952) for a more detailed definition), separated by tectonic breccia (units A–C in Fig. 2). The top of the opoka is decalcified and passes gradually into a marly unit (D in Fig. 2). Units A–D contain typical late Maastrichtian macrofauna (Racki et al., 2011). Higher up in the section, there is a thin clay layer (unit E), interpreted by Racki et al. (2011) and Brachaniec et al. (2014) as the K-Pg boundary clay. The next overlying unit is a thin layer of micritic limestone (F), the top surface of which is penetrated by burrows via which glauconitic sediment is piped down from the overlying glauconitite unit (G). The latter passes gradually into pure opoka with faint traces of rhythmic bedding (unit H). Macro- and microfossils reported from units G and H point to an early Danian age (Racki et al., 2011). The upper part of the Lechówka 2009 section is heavily weathered and decalcified (Racki et al., 2011; see Fig. 2 here).

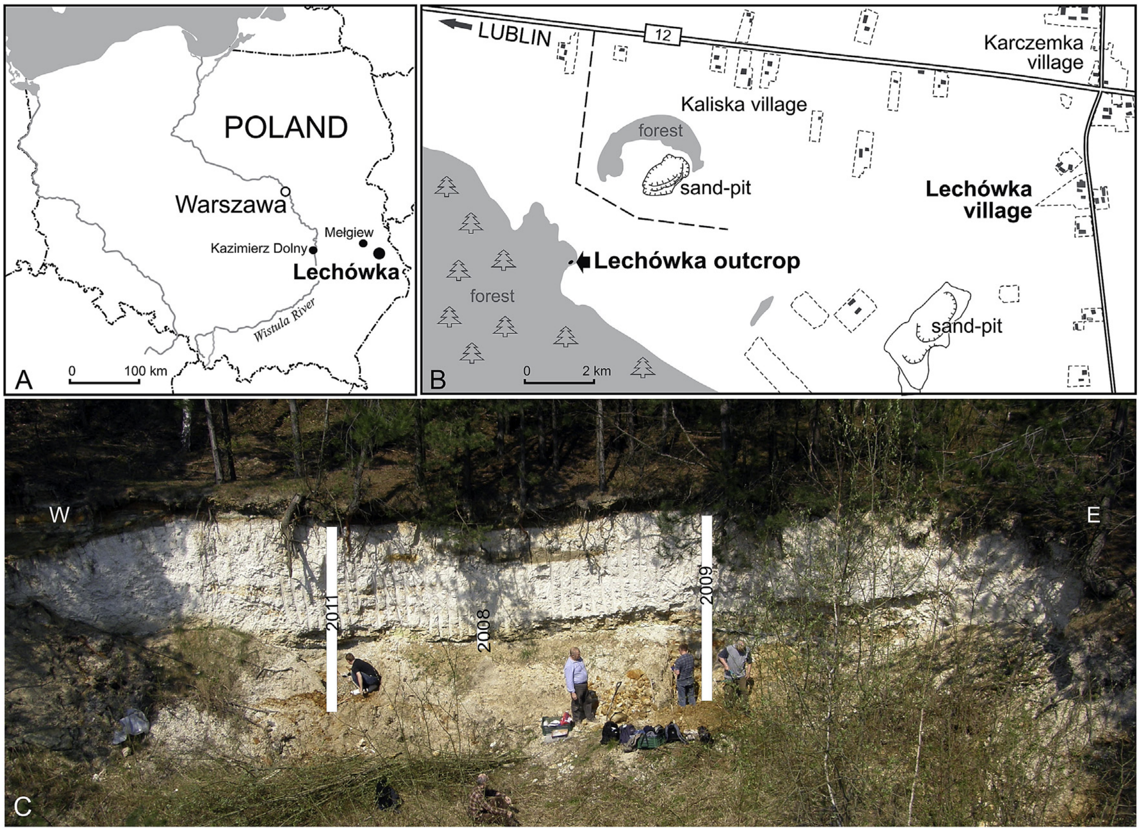

Fig. 1. Geography and geology of Lechówka. A, B. Location of Lechówka in Poland. C. General view of the outcrop with marked sampling sections 2008, 2009 and 2011.

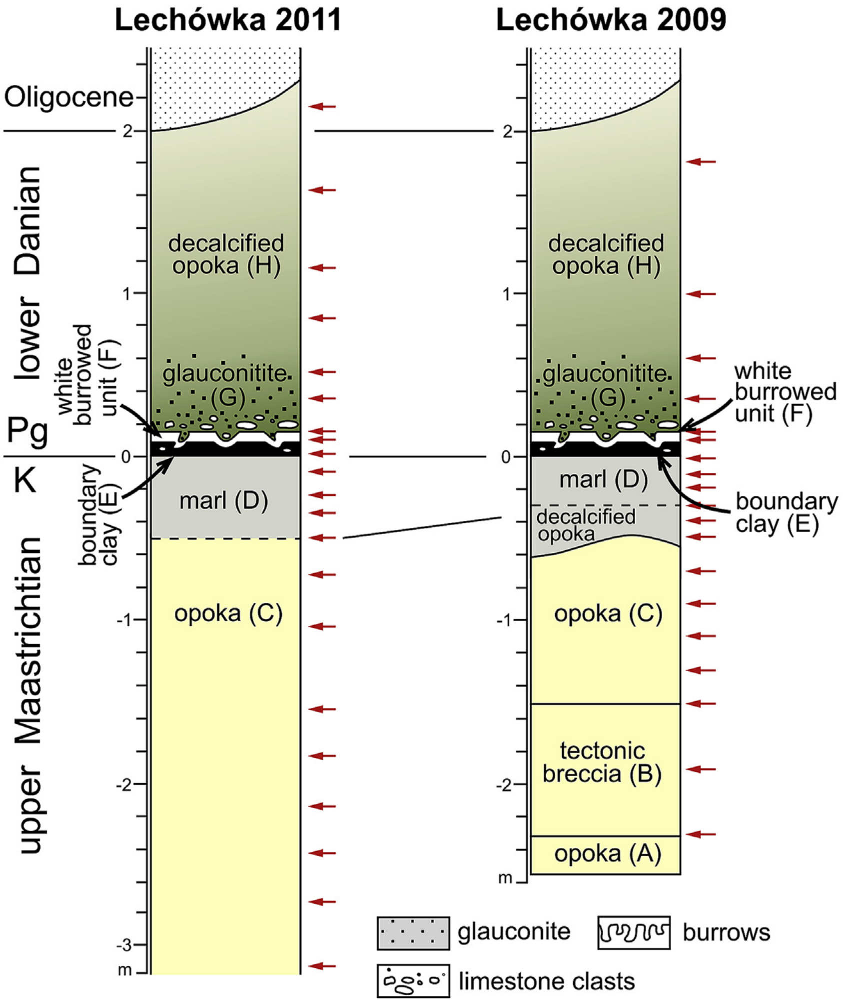

Fig. 2. Sections sampled at Lechówka; see text for further explanation.

Another section, excavated in 2011 in the western part of the quarry (Fig. 2), is the basis for the foraminiferal part of the present study. The only significant difference between these two sections is that unit B in Lechówka 2009, interpreted as tectonic breccia by Racki et al. (2011, fig. 2), is missing from Lechówka 2011. Therefore, the Maastrichtian part of Lechówka 2011 (Fig. 2) consists solely of a thick opoka interval C, followed by a thin marly unit D, which is decalcified in the upper portion. There are no differences between the Danian intervals at both sections (Fig. 2). Given the proximity between the 2008, 2009 and 2011 sections (see Fig. 1C), they are regarded as different sample sets from the same outcrop.

3. Material and methods

Several cephalopod specimens, representing ammonites and nautilids, have been collected or observed *in situ* in the Maastrichtian part of Lechówka 2009 section (Fig. 2). Specimens studied are stored in the collections of the Institute of Paleobiology of the Polish Academy of Sciences, Warszawa (abbreviation: ZPAL).

The dinocyst study is based on a series of 19 samples collected from section 2009 (Fig. 2). These samples were processed following standard palynological processing techniques. Approximately 10 g of each sample was crushed, oven dried (60 °C) and weighed. The samples were then treated with 10% HCl and 40% HF to dissolve carbonate and silicate minerals, respectively. No heavy liquid separation or oxidation was employed. After each acid step, samples were washed with water and centrifuged or settled for 24 h and decanted. The residue was sieved over nylon mesh sieves of 250 μm and 15 μm and treated with ultrasound for five minutes to break up agglutinated particles of the residue. From the residue of the 15–250 μm fraction, quantitative slides were made of well-mixed, representative fractions. All slides are stored in the collections of the Laboratory of Palaeobotany and Palynology, Utrecht University. Where possible, palynomorphs were counted up to a minimum of 200 dinocysts per sample. The taxonomy of dinocysts follows that cited in Fensome and Williams (2004). A species list can be found in Appendix 1.

The study of planktonic and benthic foraminifera is based on 10 samples from section 2011 (Fig. 2). Each sample was approximately 200 g in weight. Washed residues were obtained by disaggregating the rock by the liquid nitrogen method (Remin, Dubicka, Kozłowska, & Kuchta, 2012), cleaned in an ultrasonic bath, dried and sieved into the >63 μm size fraction. Quantitative analyses were performed on representative splits of 300 or more specimens. Specimens studied are stored in the collections of the Institute of Paleobiology of the Polish Academy of Sciences, Warszawa. A species list is presented in Appendix 2.

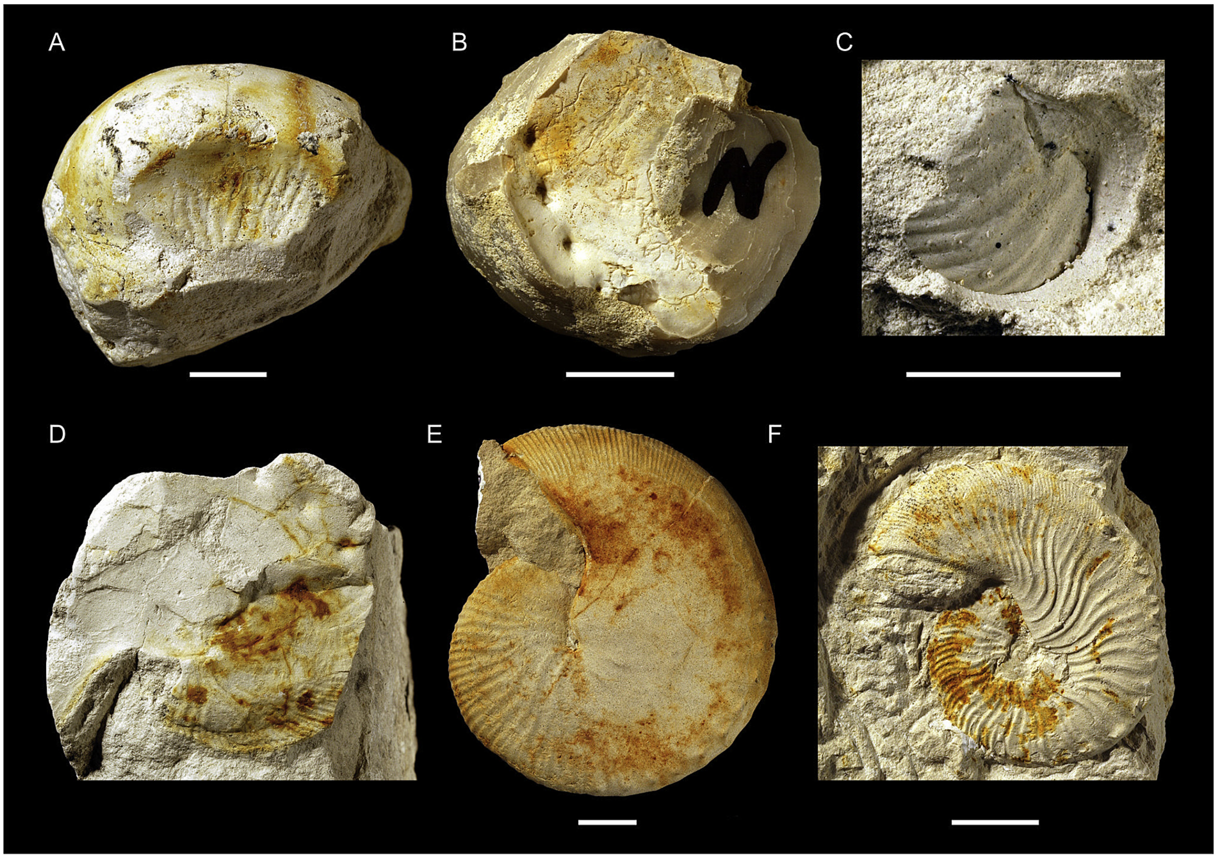

Fig. 3. Scaphitid ammonites *Hoploscaphites constrictus*. A, C–D from Lechówka, B, E, from Nasiłów, F from Mełgiew. A. *H. constrictus* subsp. indet, ZPAL Am. 12/1003. B. *H. c. crassus*, ZPAL Am. 12/774. C. *H. constrictus* subsp. indet., ZPAL Am. 12/1004. D. *H. c. crassus*, ZPAL Am. 12/1002. E. *H. c. crassus*, ZPAL Am. 12/62. F. *H. c. johnjagti*, ZPAL Am. 12/264. Specimens in A–C are bioimmurations of oyster shells, D-F are internal moulds.

4. Results

4.1. Ammonites

The record of this group is based on crushed moulds. Their originally aragonitic shells have disappeared due to dissolution during diagenesis. Mouldic preservation is typical of *in situ* originally aragonitic fossils from the Maastrichtian opoka and chalk in Poland and elsewhere in central Europe (Abdel-Gawad, 1986; Machalski, 2005a,b). There is no indication that these moulds represent reworked material, as is the case with, for example, phosphatised and commonly worn moulds of Maastrichtian biota that occur at the base of the Danian succession in the Kazimierz Dolny area, central Poland (Machalski, 1998; see Fig. 1A for location).

Preservation of ammonites at Lechówka worsens towards the K-Pg boundary, as a consequence of decalcification and weathering of the rock. Moulds of originally aragonitic shells are absent from a level 50–40 cm below the K-Pg boundary up to the boundary itself. However, two ammonite specimens have been recovered from just below the K-Pg boundary, having been bioimmured by oysters prior to dissolution of their conchs (compare Machalski & Kennedy, 2013).

Ammonites include the baculitid *Baculites* sp. and scaphitids *Hoploscaphites constrictus crassus* (Łopuski, 1911) and *Hoploscaphites constrictus* subsp. indet. *Baculites* sp. is represented by rare, poorly preserved specimens occurring throughout the opoka, the highest specimen having been recorded from 120 cm below the K-Pg boundary (Fig. 2).

Hoploscaphites constrictus crassus (Fig. 3B, D–E) is represented by several individuals. The highest specimen was recorded from 120 cm below the K-Pg boundary. Specimen ZPAL Am. 12/1002, from a level approximately 2 m below that boundary, is illustrated in Fig. 3D. Although severely crushed, its morphology matches well that of the better-preserved individual ZPAL Am. 12/62 from Nasiłów in the Kazimierz Dolny area, which is illustrated here for comparison (Fig. 3E). *Hoploscaphites c. crassus* is a temporal subspecies of the *H. constrictus* lineage, transitional between *H. c. lvivensis* and *H. c. johnjagti* and is defined by the absence of ribbing on a large sector of body chamber in adult macroconchs (Machalski, 2005b).

Hoploscaphites constrictus subsp. indet (Fig. 3A and C) is represented by two fragments, which are preserved through bioimmuration by the oyster *Pycnodonte vesicularis*. The oyster shells broke off during excavation of specimens, but their imprints with ammonite-shaped attachment surfaces survived. Specimen ZPAL Am. 12/1003 (Fig. 3A) is from 30 cm below the K-Pg boundary and ZPAL Am. 12/1004 (Fig. 3C) was recovered 40 cm below this boundary. Both are fragments with ribbing characteristic of *Hoploscaphites constrictus*. However, comparison with diagnostic specimens of *H. c. crassus* (Fig. 3E) and *H. c. johnjagti* (Fig. 3F) is inconclusive. Therefore, ZPAL Am. 12/1002 and 12/1003 are regarded as subspecifically indeterminate. A specimen of *Hoploscaphites constrictus crassus* from Nasiłów, preserved as attachment scar on an oyster shell, is figured here for comparison (Fig. 3B).

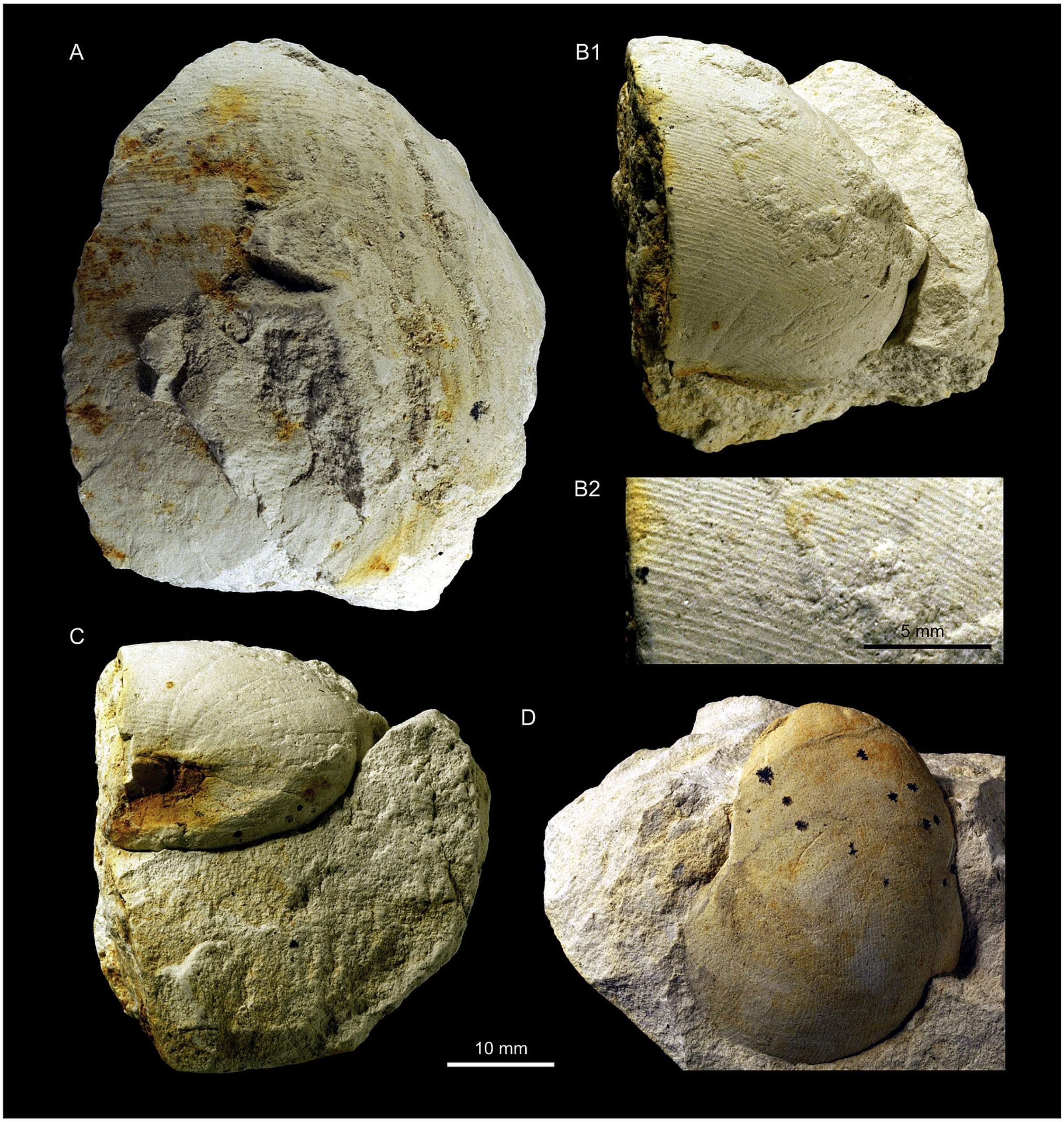

Fig. 4. Nautilid ?*Eutrephoceras aquisgranensis*. A–C. Specimen ZPAL N. 3/59 from Lechówka. D. Specimen ZPAL N. 3/58 from Kazimierz Dolny (Town Quarry).

4.2. Nautilids

These cephalopods comprise ?*Eutrephoceras aquisgranensis* (Holzapfel, 1887) and ?*Cymatoceras intrasiphonatus* (Łopuski, 1912). The former is a single, fragmentary mould, ZPAL N. 3/59, from 30 cm below the K-Pg boundary (Fig. 4A–C). This specimen is a partial body chamber (Fig. 4A), plus phragmocone (Fig. 4B and C). It is involute, globose in shape and ornamented by fine, longitudinal striae and has a slightly sinuous suture, being close in these features to *Nautilus aquisgranensis* Holzapfel, 1887 (pl. 4, figs. 1–2) from the “Aachener Kreide” of the Dutch, Belgian and German border area. The “Aachener Kreide” of Holzapfel corresponds to the current Vaals Formation of early Campanian age (Jagt, 1989). A similar specimen was recorded as *N. aquisgranensis* Holzapfel, 1888 [*sic*] from the upper Maastrichtian of the Kazimierz Dolny area (Łopuski, 1912; pl. 1, fig. 7). An apparently conspecific individual (ZPAL N. 3/58) from Kazimierz Dolny is illustrated in Fig. 4D for comparison. A similar, longitudinally striated specimen from the Maastrichtian of Amarosievka, Donbass (eastern Ukraine), was referred to as *Eutrephoceras donbassicum* by Shimansky (1975, p. 69, pl. 8, fig. 2). It should be noted, however, that a fine longitudinal striation of the shell (not to be confused with the reticulated pattern that is typical of the nautilid embryonic shell, see Landman, 1988) is neither typical of *Eutrephoceras* nor of any other known Cretaceous nautilid (Dzik, 1984; Shimansky, 1975). Rather, this pattern is reminiscent of that of the Triassic/Jurassic *Cenoceras*, commonly regarded as ancestor of all other post-Triassic nautilids (Kummel, 1956).

Of ?*Cymatoceras intrasiphonatus* merely a single specimen ZPAL N. 3/61 is on record. It comes from a level 60 cm below the K-Pg boundary, and is represented by a phragmocone with the initial

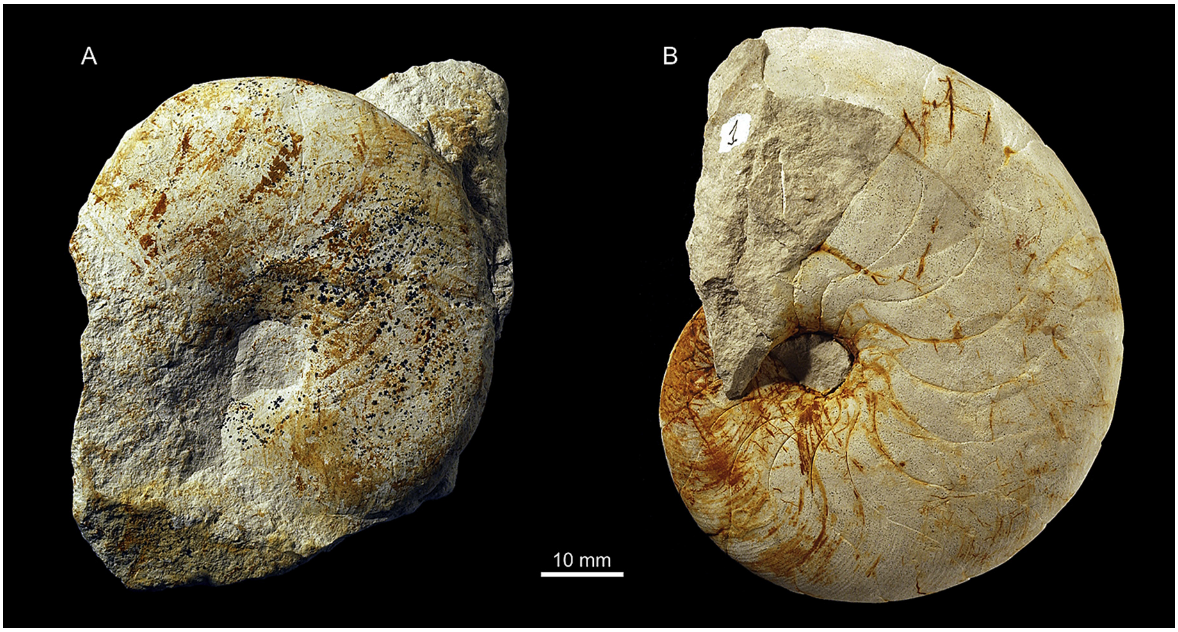

Fig. 5. Nautilid ?*Cymatoceras intrasiphonatus*. A. Specimen ZPAL N. 3/61 from Lechówka. B. Specimen ZPAL N. 3/60 from Kazimierz Dolny (Town Quarry).

part of the body chamber preserved (Fig. 5A). This is a moderately evolute, compressed individual covered with numerous, rather delicate sigmoidal ribs. The suture has a wide ventral saddle, a broad lateral lobe and a small, distinct saddle near the umbilical shoulder, very close in its course to that seen in extant *Nautilus* and in extinct *Cimomia*. The specimen from Lechówka matches "*Nautilus patens* Kner *intrasiphonata*" of Łopuski, 1912 (pl. 1, figs. 5–6) from the upper Maastrichtian of Kazimierz Dolny. However, Łopuski's form is not conspecific with *Cymatoceras patens*, which has a more central siphuncle and shows no saddle near the umbilicus (Wilmsen & Esser, 2004). The presence of ribs points to *Cymatoceras* (Wilmsen & Esser, 2004; Wilmsen & Yazykova, 2003), although Tintant (1993) had earlier proposed that this genus was in fact a taxonomic "sink" for unrelated nautilids. Błaszkiewicz (1989) referred to "*N. patens* Kner *intrasiphonata*" of Łopuski (1912) as *Cimomia intrasiphonata* (Łopuski). A specimen from the upper Maastrichtian opoka of Kazimierz Dolny is figured here for comparison (Fig. 5B).

4.3. *Dinoflagellate cysts*

Overall, the palynological samples show poor preservation, but 48 taxa have been identified in the present material (Fig. 6; Appendix 1). The samples above the K-Pg boundary level are barren (Fig. 7) and contain mainly black phytoclasts and minerals and few pollen grains, suggesting a strong leaching and/or oxidation of the top part of the section. The dinocyst abundance in the Maastrichtian samples (units A–D) varies, but in general is relatively low (Fig. 7). Terrestrial palynomorphs, such as pollen and spores, are rare in all samples, with the ratio of terrestrial over marine palynomorphs (t/m ratio) ranging between 0.02 and 0.15. Occasional specimens of the acritarch taxon *Paralecaniella indentata* were encountered in the most productive samples.

Throughout the Maastrichtian part of the section, the dinocyst assemblages have a relatively low diversity and are completely dominated by gonyaulacoid (G) dinocysts, only few peridinioid (P) dinocysts having been encountered (Fig. 7, see Supplementary Material 1 for raw data). The most abundant dinocyst taxon is *Palynodinium grallator* (12–61% of assemblage). Other abundant taxa include *Areoligera senoniensis*, *Hystrichosphaeridium tubiferum* and *Tanyosphaeridium xanthiopyxides* (Fig. 7). The dinocyst assemblages recovered are characteristic of the upper Maastrichtian boreal bio-province (e.g., Hansen, 1977; Hultberg & Malmgren, 1987; Schiøler & Wilson, 1993; Schiøler, Brinkhuis, Roncaglia, & Wilson, 1997; Wilson, 1974), characterised by typical taxa such as *A. senoniensis*, *Glaphyrocysta perforata*, *Hystrichosphaeridium recurvatum*, *H. tubiferum*, *Neonorthidium perforatum*, *Operculodinium centrocarpum*, *Palynodinium grallator* and *T. xanthiopyxides* (Fig. 7).

4.4. *Foraminifera*

Fifty-five foraminiferal taxa have been identified in the present material (Appendix 2, examples are illustrated in Figs. 8–11). Preservation of this material varies depending of lithological unit. Foraminifera from the opoka unit C and from sample K-Pg −0, 5, located near the base of marly unit D, are abundant and well preserved. Therefore, it was possible to pick, identify and count 300 specimens per sample. In contrast, samples taken from higher in unit D proved to be barren in foraminifera.

Examples of planktonic foraminifera from Lechówka are illustrated in Fig. 8. The assemblage from unit C is composed of forms with serial (*Heterohelix* and *Guembelitria*) and planispiral tests (*Globigerinelloides*). Trochospiral taxa with globular chambers (*Rugoglobigerina, Archaeoglobigerina*) occur sporadically, while keeled species are totally absent. The planktonic foraminiferal assemblage from the base of unit D (sample K-Pg −0, 5) consists of *Globigerinelloides* (*G. prairiehillensis*, *G. abberantus*), *Guembelitria cretacea*, *Heterohelix* (*H. striata*, *H. globulosa*), and rare representatives of *Rugoglobigerina* (*R. pennyi* and *R. hexacamerata*).

Benthic foraminifera from Lechówka are illustrated in Figs. 9–11 and the relative abundances of the commonest taxa in the Maastrichtian interval are presented in Fig. 12 (see Supplementary Material 2 for raw data). The assemblage from unit C is composed of calcareous and agglutinated foraminifera, representing epifaunal as well as infaunal forms (Figs. 9–11). The most abundant taxa are *Praebulimina parvula* (17–33%), *Bolivina incrassata* (4–23%), *Cibicidoides voltzianus* (2–22%), *Gyroidinoides girardanus* (3–12%),

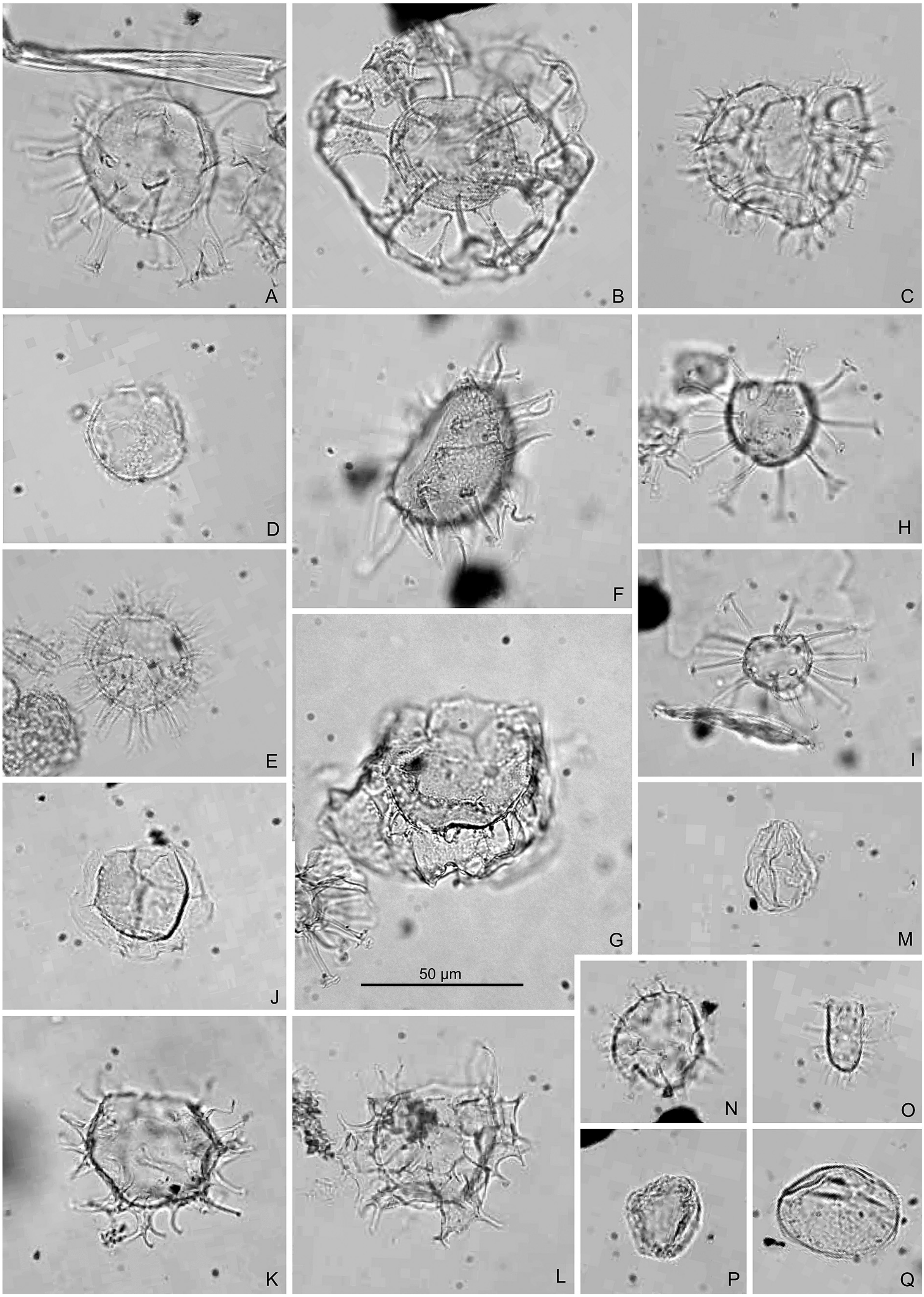

Fig. 6. Dinocyst taxa and other palynomorphs from 2009 section at Lechówka. A. *Achilleodinium bianii* Hultberg, 1985, K-Pg −1, 9, slide 1, EF K35-1, right lateral-ventral view. B. *Adnatosphaeridium buccinum* Hultberg, 1985. K-Pg −0, 4, slide 1, EF P31-3, apical view. C. *Areoligera senonensis* Lejeune-Carpentier, 1938. K-Pg −0, 5, slide 1, EF U34-3, ventral view. D. *Apteodinium fallax* (Morgenroth, 1968) Stover and Evitt, 1978. K-Pg −1, 9, slide 1, EF N32-1, left lateral view. E. *Coronifera striolata* (Deflandre, 1937) Stover and Evitt, 1978. K-Pg −0, 3,

Cibicidoides bembix (1–11%) and *Anomalinoides acutus* (2–10%).

While the planktonic foraminiferal assemblages from unit C are similar to those from the base of unit D, benthic foraminiferal assemblages are different both in terms of taxonomic composition and average test size. The dominant species is *Praebulimina parvula*, accounting for almost 30% of the assemblage. *Bolivina incrassata*, *Cibicidoides voltzianus*, *C. bembix*, *Gyroidinoides girardanus* and *Anomalinoides acutus* decrease in abundance and each do not exceed 2–4% of the assemblage. *Osangularia* sp., *Pyramidina* sp., *Gavelinella salhstroemi* and *Bolivinoides vistulae* are minor components in unit C, while in unit D (sample K-Pg −0, 5) these genera form 5–6% of the assemblage (Fig. 12). This latter differs from that from unit C in having smaller tests of calcareous epifaunal forms (*Gavelinella*, *Cibicidoides*, *Gyroidinoides*). The maximum average test size (= arithmetic test size of specimens) of epifaunal benthic foraminifera obtained from the opoka (unit C) reaches 376 μm (sample K-Pg −0, 7), 415 μm (sample K-Pg −1, 5) and 392 μm (K-Pg −2, 4) whereas the same parameter measured in the marl (unit D) is 159 μm (Fig. 13).

5. Discussion

5.1. Biostratigraphy

Among dinocysts, the marker species *Palynodinium grallator* is present in all productive samples from Lechówka, while no Danian markers were encountered, indicating that all productive samples correspond to the uppermost Maastrichtian *Palynodinium grallator* Zone as described by Hansen (1977) for Denmark and Schiøler and Wilson (1993) for the North Sea Basin (see Figs. 14A and 15). This interpretation is further supported by the presence of the characteristic marker species *Hafniasphaera fluens*, *Glaphyrocysta perforata* and *Tanyosphaeridium xanthiopyxides* (Fig. 14A). One specimen of the global Maastrichtian marker species *Disphaerogena carposphaeropsis* (formerly known as *Cyclapophysis monmouthensis*) was encountered in a sample taken 40 cm below the K-Pg boundary, in agreement with the inferred late Maastrichtian age of the interval studied.

The latest Maastrichtian dinocyst marker species *Thalassiphora pelagica* was not observed in the present material, inhibiting further subdivision of the *Palynodinium grallator* Zone at this site. However, given the uncommonness of this taxon at most sites in northern Europe (e.g., Schiøler & Wilson, 1993; Schiøler et al., 1997), the absence of this marker taxon cannot be used as a definitive biostratigraphic signal. In contrast, the acme of *P. grallator* as encountered in the Lechówka section is very characteristic of the topmost Maastrichtian of the boreal realm, as e.g., in North Sea wells (Schiøler & Wilson, 1993) and in southern Sweden (Hultberg & Malmgren, 1987), where it corresponds to the *T. pelagica* Subzone. This suggests that also at Lechówka the acme of *P. grallator* represents the equivalent of the *T. pelagica* Subzone.

As far as foraminiferal biostratigraphy is concerned (e.g., Gawor-Biedowa, 1992; Koch, 1977), the benthic taxa *Bolivinoides draco* and *Gavelinella danica* indicate a general late Maastrichtian age for the interval studied (Fig. 14B). Planktonic foraminiferal assemblages from unit C and from the base of unit D are characterised by a predominance of biserial heterohelicids (60–70%) and triserial guembelitrids (30–40%). Representatives of *Rugoglobigerina*, *Archaeoglobigerina* and *Globigerinelloides* account for up to a few percent in these assemblages. Such a composition indicates the uppermost Maastrichtian XIII assemblage Zone *sensu* Dubicka and Peryt (2012, fig. 3; see Fig. 14B and Table 1 herein), also recognised in the uppermost Maastrichtian part of the Mełgiew succession, near Lublin (see Fig. 1A for location) which belongs to the *Hoploscaphites constrictus johnjagti* ammonite Zone (Machalski, 2005a,b; 2012). The bloom of *Guembelitria* in the latest Maastrichtian was also observed in Egypt (Keller, 2002), Tunisia (Pardo & Keller, 2008), Texas, USA (Keller & Abramovich, 2009) and southern Israel (Abramovich, Almogi-Labin, & Benjamini, 1998), and seems to be an extra-regional event with high correlative potential.

In samples from unit H, a few moulds of *G. cretacea*, *Heterohelix striata, Parvularugoglobigerina* sp. and *Globoconusa daubjergensis* were identified (Fig. 14B). The presence of the two last-named indicates an early, but not earliest, Danian age for unit H (e.g., Huber & Quillévéré, 2005; Pożaryska, 1965). This is in full accordance with the former dating by Racki et al. (2011), which was based on molluscs and lithological correlations, and with the possible presence of a hiatus between units F and G (see below).

Among the cephalopods collected at Lechówka, only scaphitid ammonites are of biostratigraphical significance (Machalski, 2005a,b; 2012; see also Machalski, Jagt, Alekseev, & Jagt-Yazykova, 2012). That author distinguished three temporal subspecies (chronosubspecies *sensu* Dzik & Trammer, 1980) within the *Hoploscaphites constrictus* evolutionary lineage. These are *Hoploscaphites constrictus lvivensis* Machalski (2005b), *H. c. crassus* (Łopuski, 1912) and *H. c. johnjagti* Machalski (2005b). On this basis, Machalski (2012) defined three biostratigraphic zones in the upper Maastrichtian, with the last one extending briefly into the lowermost Danian. Biostratigraphic zones discussed in the present paper are presented in Table 1.

The occurrence of *Hoploscaphites constrictus crassus*, which ranges at Lechówka up to 120 cm below the K-Pg boundary (Fig. 14A), points to the presence of the *H. c. crassus* Zone in the interval from the bottom of the section to this particular level (Figs. 14A and 15). According to Machalski (2012), the base of the *H. c. crassus* Zone is defined by the First Occurrence (FO) of the index subspecies as defined by Błaszkiewicz (1980) and Machalski (2005b), and its top by the FO of *H. c. johnjagti* as defined by Machalski (2005b). The *H. c. crassus* Zone is widely distributed in central and eastern Poland; this is the highest ammonite zone documented at Nasiłów and Bochotnica in the Kazimierz Dolny area (Machalski, 2005a,b; 2012), where the topmost Maastrichtian *T. pelagica* subzone is also missing (Hansen, Rasmussen, Gwozdz, Hansen, & Radwański, 1989).

The uppermost Maastrichtian interval at Lechówka has yielded only oyster-bioimmured specimens of *Hoploscaphites constrictus,* indeterminate at subspecific level (Fig. 14A). Therefore, it is not clear whether this interval still belongs to the *H. c. crassus* Zone or to the successive *H. c. johjagti* Zone. According to Machalski (2012), the base of the latter zone is defined by the FO of the index subspecies and its top by the Last Occurrence (LO) of unreworked specimens of this taxon (note: the criterion of being unreworked

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slide 1, EF S29-1, dorsal view. F. *Fibrocysta ovalis* (Hansen, 1977) Lentin and Williams, 1981, K-Pg −1, 1, slide 2, EF P35-3, left lateral view. G. *Glaphyrocysta perforata* Hultberg and Malmgren, 1985, K-Pg −0, 5, slide 2, EF Q39-1, dorsal view. H. *Hystrichosphaeridium tubiferum* (Ehrenberg, 1838) Deflandre, 1937, K-Pg −0, 5, slide 1, EF G32-1, right lateral view. I. *Hystrichosphaeridium recurvatum* (White, 1842) Lejeune-Carpentier, 1940, K-Pg −2, 3, slide 1, EF Q37-1, left lateral view. J. *Neonorthidium perforatum* Marheinecke, 1992, K-Pg −1, 3, slide 2, EF Q33-3, dorsal view, internal view on ventral surface. K. *Palynodinium* cf. *grallator*, K-Pg −1, 9, slide 1, EF T36-3, dorsal view. L. *Palynodinium grallator* Gocht, 1970, K-Pg −1, 9, slide 1, EF T36-3, ventral view. M. *Senegalinium obscurum* (Drugg, 1967) Stover and Evitt, 1978, K-Pg −1, 1, slide 1, EF 027-4, right lateral view. N. *Spiniferites ramosus* (Ehrenberg, 1838) Mantell, 1854, K-Pg −0, 3, slide 1, EF 043-1, ventral view, internal view on dorsal surface. O. *Tanyosphaeridium xanthiopyxides* (Wetzel, 1933) Stover and Evitt, 1978, K-Pg −1, 9, slide 1, EF D41-2, right lateral-ventral view. P. Unidentified tricolpate pollen grain, K-Pg −0, 5, slide 2, EF T39-2. Q. *Paralecaniella indentata* (Deflandre and Cookson, 1955) Cookson and Eisenack, 1970, K-Pg −0, 3, slide 1, EF 044-4.

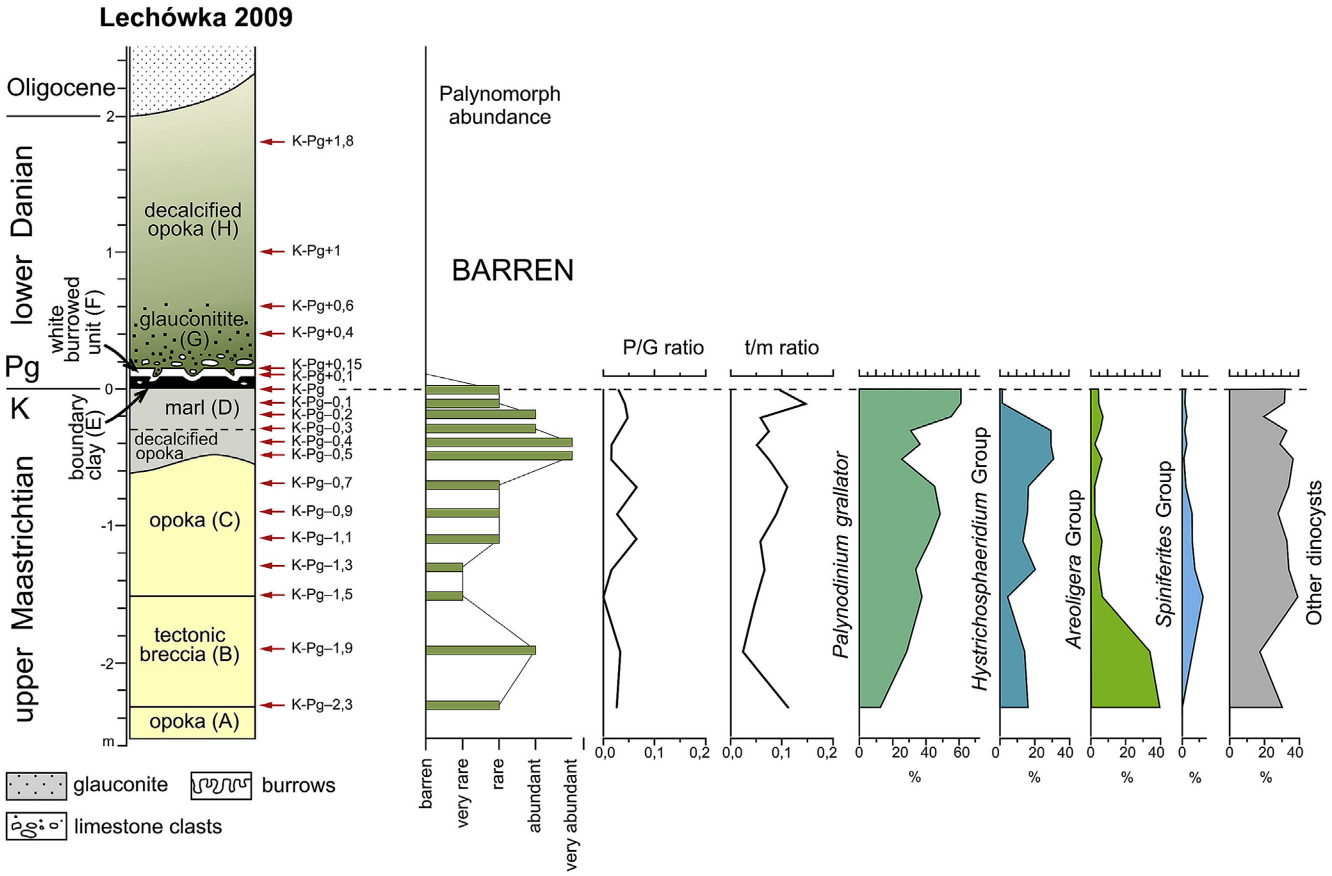


Fig. 7. Palynomorph abundance, P/G ratio, t/m ratio, relative abundance of the most important dinocyst morphogroups at Lechówka.

was introduced in view of the common reworking across the K-Pg boundary, which may blur extinction *versus* survival patterns, as discussed by Machalski & Heinberg, 2005).

In the extended type area of the Maastrichtian Stage, in the Dutch province of Limburg and adjacent parts of Belgium and Germany, the *Hoploscaphites constrictus johnjagti* Zone *sensu* Machalski (2012) is represented by the upper part of the Meerssen Member, based on the occurrence of the index taxon (Jagt, 2012). According to Schiøler et al. (1997), the Meerssen Member roughly corresponds to the *T. pelagica* Subzone. At Stevns Klint, the *T. pelagica* Subzone equates with the topmost 5 m of the upper Maastrichtian (Hansen, 1977), thus encompassing the scaphitid ammonite *H. c. johnjagti* Zone of Machalski (2012).

Given that the topmost Maastrichtian foraminiferal Zone XIII is present at Lechówka, and that the dinocyst records suggest the presence of the equivalent of the *T. pelagica* Subzone, these data infer the presence of the equivalent of the *H. c. johnjagti* Zone in the uppermost Maastrichtian of the Lechówka section (compare Table 1, Figs. 14A and 15).

At Stevns Klint, the *H. c. johnjagti* Zone is restricted to the Grey Chalk (or Højerup Member, Tor Formation sensu Surlyk et al., 2006), which is a 0–4-m-thick uppermost Maastrichtian unit below the K-Pg boundary. The acme of this taxon is observed at the top of the Grey Chalk (Machalski, 2005a,b) and rare individuals extend into the lowermost Danian (Machalski & Heinberg, 2005). In the type area of the Maastrichtian Stage, *H. c. johnjagti* occurs in the uppermost 5–10-m interval of the Maastrichtian part of the Meerssen Member of the Maastricht Formation (units IVf-5 and 6), extending also into the lowermost Danian unit IVf-7 of the same unit (Jagt, 2012; Jagt & Jagt-Yazykova, 2012). To date, in Poland the *Hoploscaphites constrictus johnjagti* Zone has been recorded only from Mełgiew (Fig. 1A), where it occurs in an at least 3-m-thick interval below the K-Pg boundary (Machalski, 2005a; Machalski, unpubl. data). Therefore, although the equivalent of the *H. c. johnjagti* Zone likely is represented at Lechówka, it is condensed in comparison to Mełgiew and to other sites in northern Europe.

5.2. Environment

Nautilids are too rare at Lechówka to provide any reliable environmental signal. As far as scaphitid ammonites are concerned, *Hoploscaphites constrictus crassus* is regarded as a taxon that inhabited slightly deeper waters than the successive *H. c. johjagti* (see Machalski, 2005b).

No belemnite rostra were found at Lechówka. These cephalopods are also absent in the uppermost Maastrichtian *Hoploscaphites constrictus johnjagti* Zone at Mełgiew (Machalski, 2005b, 2012). The lack of belemnites in these successions is intriguing in view of the nearshore depositional environment postulated for the Maastrichtian part there on the basis of lithological features and dinocyst and foraminiferal assemblages (see below). According to Christensen (1997), belemnites are common in nearshore sediments of the European Cretaceous, and populations from these sediments comprise all growth stages. Indeed, belemnites are very common in nearshore opokas just beneath the K-Pg boundary at Nasiłów and Bochotnica near Kazimierz Dolny (Abdel-Gawad, 1986; Hansen et al., 1989). In contrast, more offhore strata, such as white chalk, contain either only adult individuals or are totally deprived

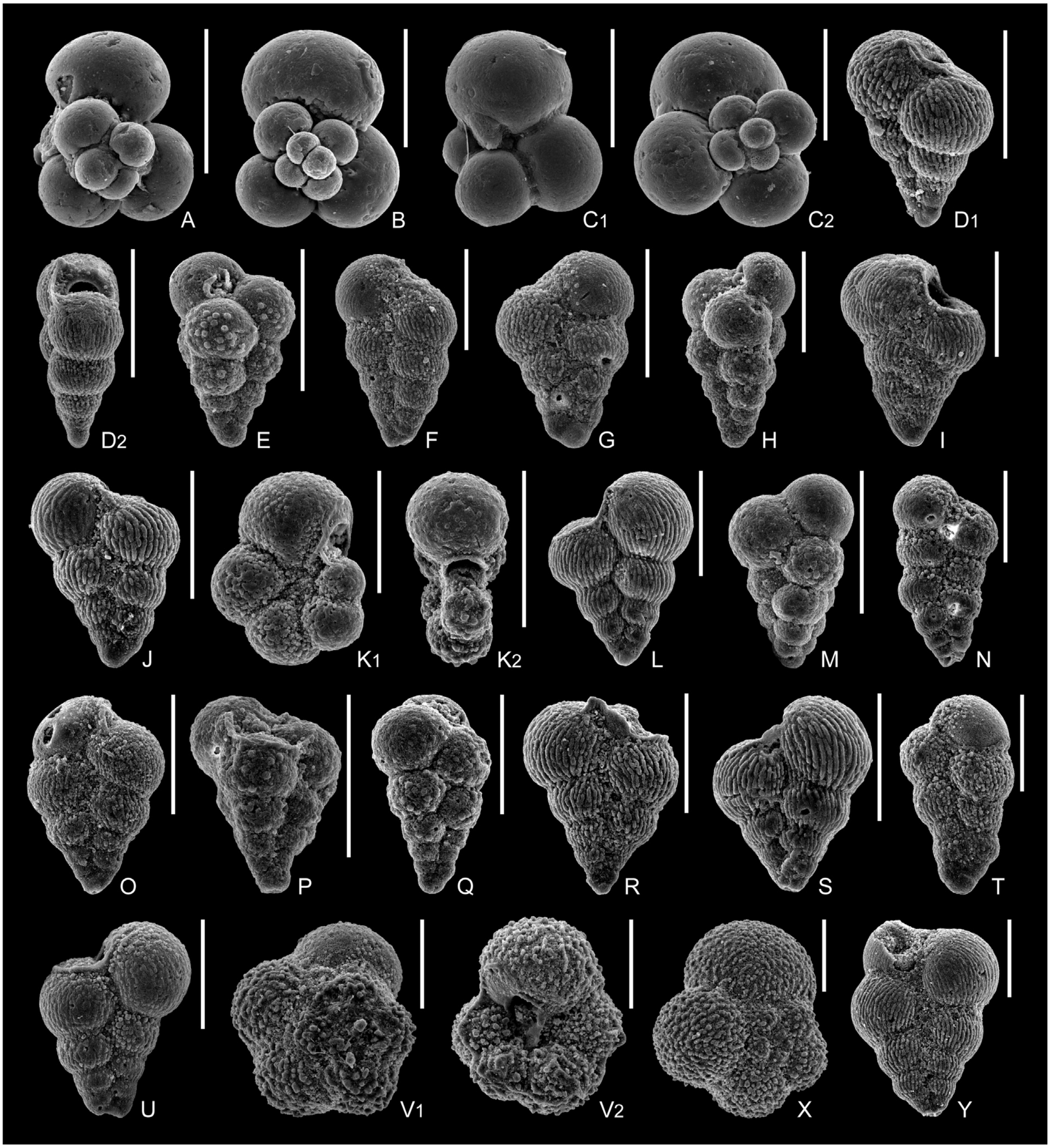


Fig. 8. Planktonic foraminifera from the 2011 section at Lechówka. A–D, sample K-Pg +0, 35; E–U, sample K-Pg –0,7. V–Y, sample K-Pg -2,1. A–C. *Globoconusa daubjergensis* (Brönnimann, 1953). D1-2. *Heterohelix striata* (Ehrenberg, 1840). E. *Guembelitria cretacea* Cushman, 1933. F. *Heterohelix planata* (Cushman, 1938). G. *Heterohelix navarroensis* Loeblich, 1951. H. *Guembelitria cretacea* Cushman, 1933. I. *Heterohelix ultimatumida* (White, 1929). J. *Heterohelix striata* (Ehrenberg, 1840). K1-2. *Globigerinelloides prairiehillensis* Pessagno, 1967. L. *Heterohelix striata* (Ehrenberg, 1840). M. *Guembelitria cretacea* Cushman, 1933. N. *Heterohelix navarroensis* Loeblich, 1951. O. *Heterohelix planata* (Cushman, 1938). P, Q. *Guembelitria cretacea* (Cushman, 1933). R, S. *Heterohelix ultimatumida* (White, 1929). T. *Heterohelix navarroensis* Loeblich, 1951. U. *Heterohelix striata* (Ehrenberg, 1840). V1-2. *Rugoglobigerina* sp. X. *Archaeoglobigerina blowi* Pessagno, 1967. Y. *Heterohelix ultimatumida* (White, 1929). Scale bars equal 100 µm.

of belemnite rostra (Christensen, 1997, p. 79). Apparently, some unknown factors, other than bathymetry, must have been responsible for the absence of belemnite rostra at Lechówka.

The palynological record at Lechówka allows for a more precise reconstruction of the depositional environment. Terrestrial palynomorphs are rare in all samples, suggesting a low terrestrial input at this site. Throughout the Maastrichtian interval, the P/G ratio is relatively low (Fig. 7). As P-cysts are considered to represent predominantly heterotrophic dinoflagellates that fed on diatoms, other phytoplankton and organic detritus, the ratio of peridinioid/gonyaulacoid cysts (P/G ratio) is suggested to be indicative of productivity (Dale, 1996; Sluijs, Pross, & Brinkhuis, 2005). The low P/G ratios at Lechówka might suggest that overall primary productivity and/or nutrient loading was low. However, given that protoperidinioid cysts have been proved to be less resistant to oxidation than goyaulacoid cysts (Zonneveld, Versteegh, & de Lange, 1997), it is likely that the same holds true for the related group of peridinioid cysts. Hence, low concentrations of P-cysts might be connected to

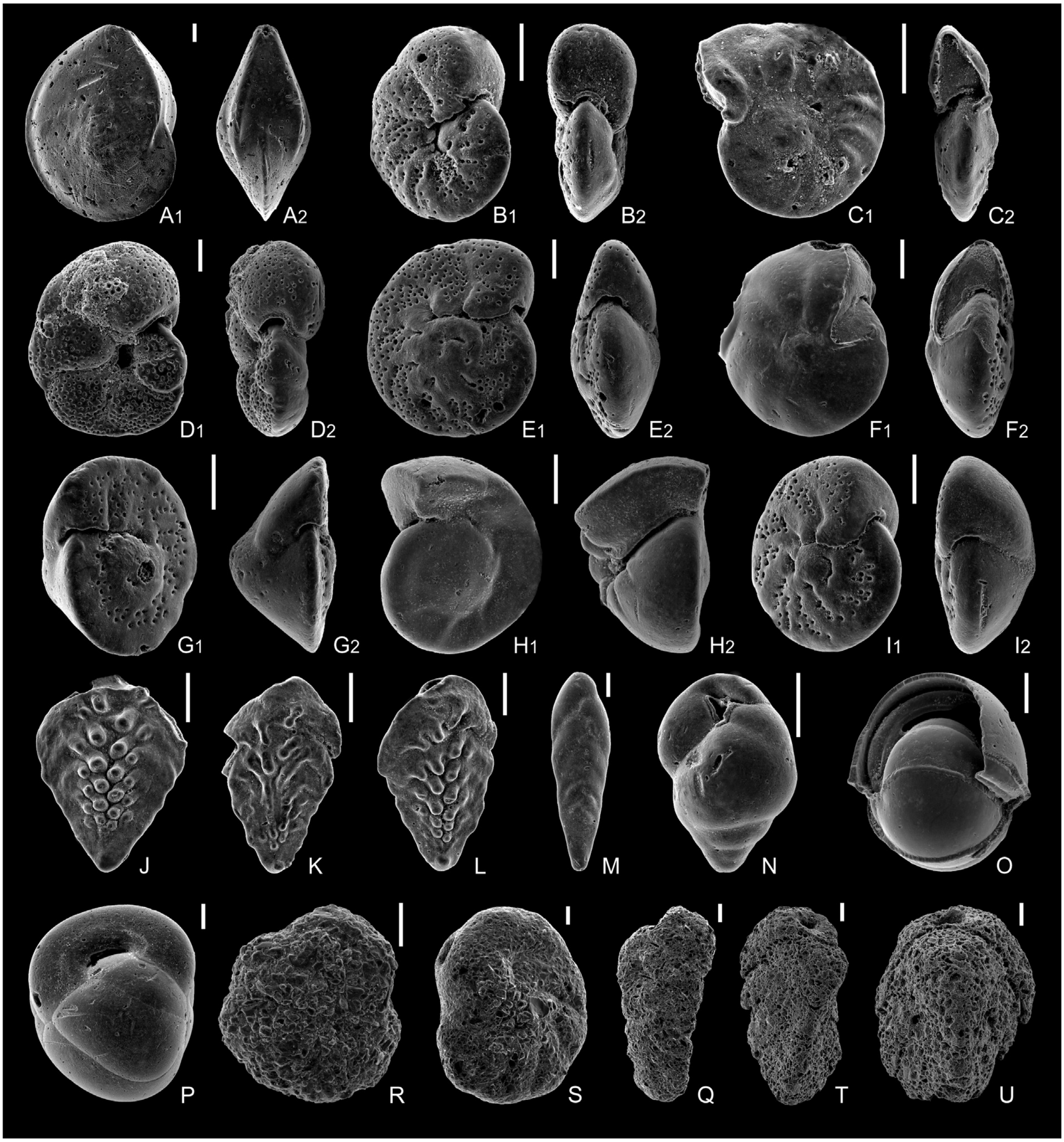


Fig. 9. Benthic foraminifera from sample K-Pg −0,7 from 2011 section at Lechówka. A1-2. *Lenticulina* sp. B1-2. *Gavelinella mariae* (Jones, 1852). C1-2. *Anomalinoides acutus* (Plummer, 1947). D1-2. *Gavelinella danica* (Brotzen, 1940). E1-2, F1-2. *Cibicidoides voltzianus* (d'Orbigny, 1840). G1-2. *Cibicidoides bembix* (Marsson, 1878). H1-2. *Gyroidinoides girardanus* (Reuss, 1851). I1-2. *Cibicidoides voltzianus* (d'Orbigny, 1840). J–L. *Bolivinoides vistulae* Pożaryska, 1954. M. *Bolivina incrassata* (Reuss, 1851). N. *Praebulimina parvula* (Brotzen, 1948). O. *Pullenia cretacea* Cushman, 1936. P. *Ataxophragmium crassum* (d'Orbigny, 1840). R. *Ataxoorbignyna inflata* (Reuss, 1851). S. *Lamina irreperta* Voloshina, 1972. Q. *Plectina ruthenica* (Reuss, 1850). T. *Gaudryina pyramidata* (Cushman, 1926). U. *Gaudryina* sp. Scale bars equal 100 μm.

poor preservation conditions at the Lechówka site. Therefore, based on the P/G ratio at Lechówka, no definitive conclusions with regard to productivity can be drawn.

Following Schiøler et al. (1997), dinocyst taxa encountered at Lechówka can be placed in the following morphological groups: (1) the *Areoligera* group, combining all species within the genera *Areoligera* and *Glaphyrocysta*; (2) the *Hystrichosphaeridium* group, combining all species within the genus *Hystrichosphaeredium* and the morphologically related genus *Oligosphaeridium*; (3) *Palynodinium grallator*; (4) the *Spiniferites* group, combining all species of *Spiniferites* and species of the morphologically related genus *Achomosphaera*; and (5) other dinocysts, combining all dinocyst taxa that are not assignable to any of the previous groups. The most abundant dinocyst taxa at Lechówka, i.e., *Palynodinium grallator*, members of the *Hystrichosphaeridium* group and members of the *Areoligera* group, generally are considered to be characteristic of high-energy, marginal marine environments (Brinkhuis, 1994; Brinkhuis & Zachariasse, 1988; Schiøler et al., 1997; Sluijs et al., 2005). Taxa typically representing relatively offshore and/or oceanic conditions (e.g., *Spiniferites* and *Impagidinium*; see Brinkhuis & Zachariasse, 1988; Brinkhuis, 1994; Schiøler et al., 1997; Sluijs et al., 2005) are very rare at this site, implying that the

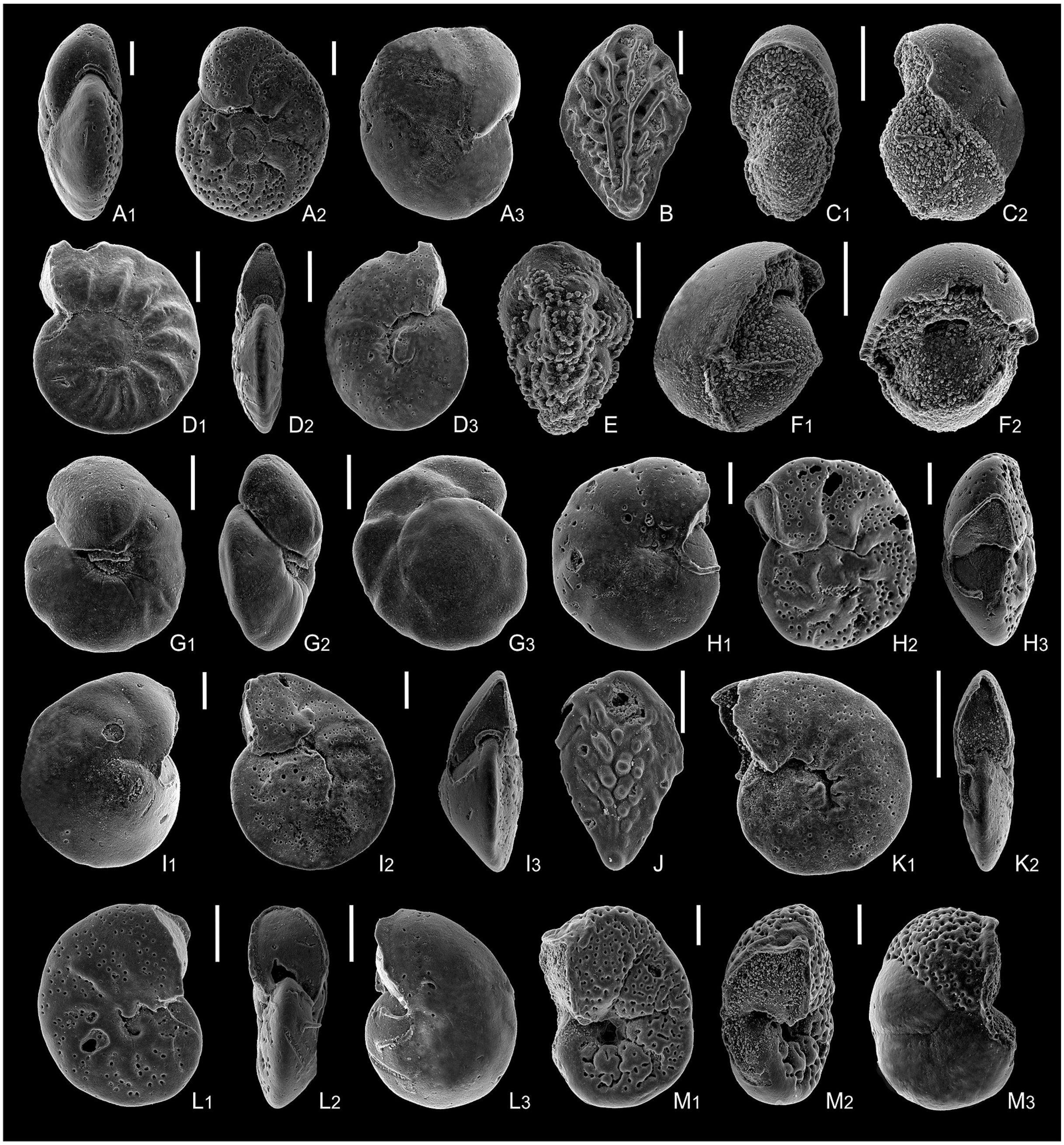


Fig. 10. Benthic foraminifera from sample K-Pg −0, 7 from 2011 section at Lechówka. A1-3. *Cibicidoides involutus* (Reuss, 1851). B. *Bolivinoides draco* (Marsson, 1878). C1-2. *Pullenia jarvisi* Cushman, 1936. D1-3. *Anomalinoides acutus* (Plummer, 1947). E. *Pseudouvigerina cristata* (Marsson, 1878). F1-2. *Pullenia cretacea* Cushman, 1936. G1-3. *Valvulineria subangulata* (Plummer, 1927). H1-3. *Cibicidoides* sp. I1-3. *Cibicidoides bembix* (Marsson, 1878). J. *Bolivinoides vistulae* Pożaryska, 1954. K1-2. *Anomalinoides* sp. L1-3. *Gavelinella gankinoensis* (Neckaja, 1948). M1-3. *Gavelinella burlingtonensis* Jennings, 1936. Scale bars equal 100 μm.

Lechówka succession was deposited in an inner neritic setting. The relative proportion of inshore taxa throughout the sampled interval is presented in Fig. 15.

Based on the relative abundances of inshore and offshore taxa, changes in relative sea level can be inferred (Habib, Moshkovitz, & Kramer, 1992; Moshkovitz & Habib, 1993; Schiøler et al., 1997) (Figs. 7 and 15). The Lechówka record indicates that the lower part of the interval studied is characterised by the highest sea level, followed by a regression towards the boundary. This shallowing is likely a regional expression of latest Maastrichtian sea level fall (Vellekoop et al., 2015), which ultimately led to the Sequence Boundary between units F and G at Lechówka and between the Cerithium Limestone Member of the Rødvig Formation and the Korsnæb Member of the Stevns Klint Formation at Stevns Klint, Denmark.

The dinocyst assemblages at Lechówka are typical of the upper Maastrichtian boreal bio-province, with lower-latitude dinocyst taxa completely absent, suggesting that the site was characterised by relatively low (i.e., temperate) sea surface temperatures.

The planktonic and benthic foraminiferal assemblages recorded from Lechówka are typical of the Maastrichtian European epicontinental shallow (inner neritic) sea with mesotrophic conditions (Dubicka & Peryt, 2011, 2012). The low contribution of planktonic species to foraminiferal assemblages, the predominance of

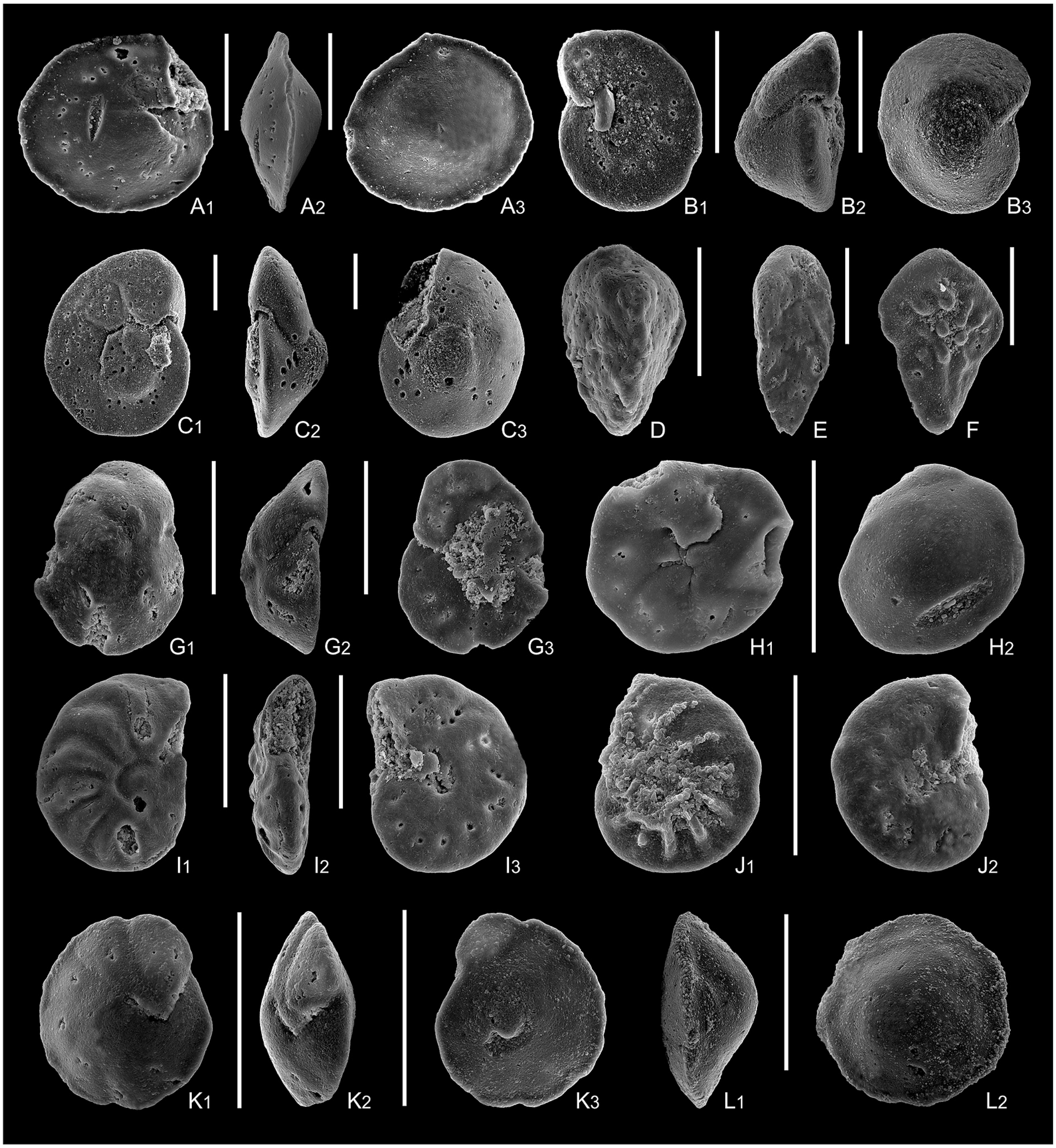


Fig. 11. Benthic foraminifera from sample K-Pg −0, 5 from 2011 section at Lechówka. A1-3. *Osangularia* sp. B1-3. *Cibicidoides bembix* (Marsson, 1878). C1-3. *Cibicidoides succedens* (Brotzen, 1948). D–E. *Pyramidina cimbrica* (Brotzen, 1945). F. *Bolivinoides vistulae* Pożaryska, 1954. G1-3. *Cibicides ventratumidus* Mjatliuk. H1-2. *Rosalina brotzeni* Hofker, 1961. I1-3. *Gavelinella umbilicata* (Brotzen, 1942). J1-2. *Gavelinella sahlstroemi* (Brotzen, 1948). K1-3. *Alabamina* sp. L1-2. *Pulsiphonina prima* (Plummer, 1926). Scale bars equal 100 μm.

shallow-marine heterohelicids and *Globigerinelloides* and the absence of keeled planktonic foraminiferal species are all consistent with a very shallow-marine setting, in agreement with the lithology and the dinocyst assemblage.

The most important change recorded in the foraminiferal record of the Lechówka section is the decrease in test size of calcareous epifaunal benthic foraminifera, between samples K-Pg −0, 7 (top of unit C) and K-Pg −0, 5 (top of D), at approximately 50 cm beneath the K-Pg boundary (Figs. 13 and 15). This suggests high-stress conditions for benthic foraminifera as dwarfism generally is considered to be a response to such circumstances, e.g., oxygen depletion, temperature or salinity changes or increased wave activity (Keller & Abramovich, 2009; MacLeod, Huber, & Isaza-Londoño, 2005). Dwarfing of benthic foraminifera has occasionally been considered characteristic of low-oxygen environments (Bernhard, 1986; Dubicka & Peryt, 2014; MacLeod et al., 2005; Takeda & Kaiho, 2007). Under conditions of oxygen depletion, calcareous epibenthic foraminiferal tests usually are small, unornamented and thin-walled, as a result of acidic conditions associated with organic enrichment (Bernhard, 1986; Dubicka & Peryt, 2014; Kaiho, 1994; Takeda & Kaiho, 2007). Nevertheless, the response to ocean acidification is species specific (McIntyre-Wressnig, Bernhard, Wit, & McCorkle, 2014), as an experiment on e.g. two bolivinid species (*Bolivina argentea* and *Bulimina*

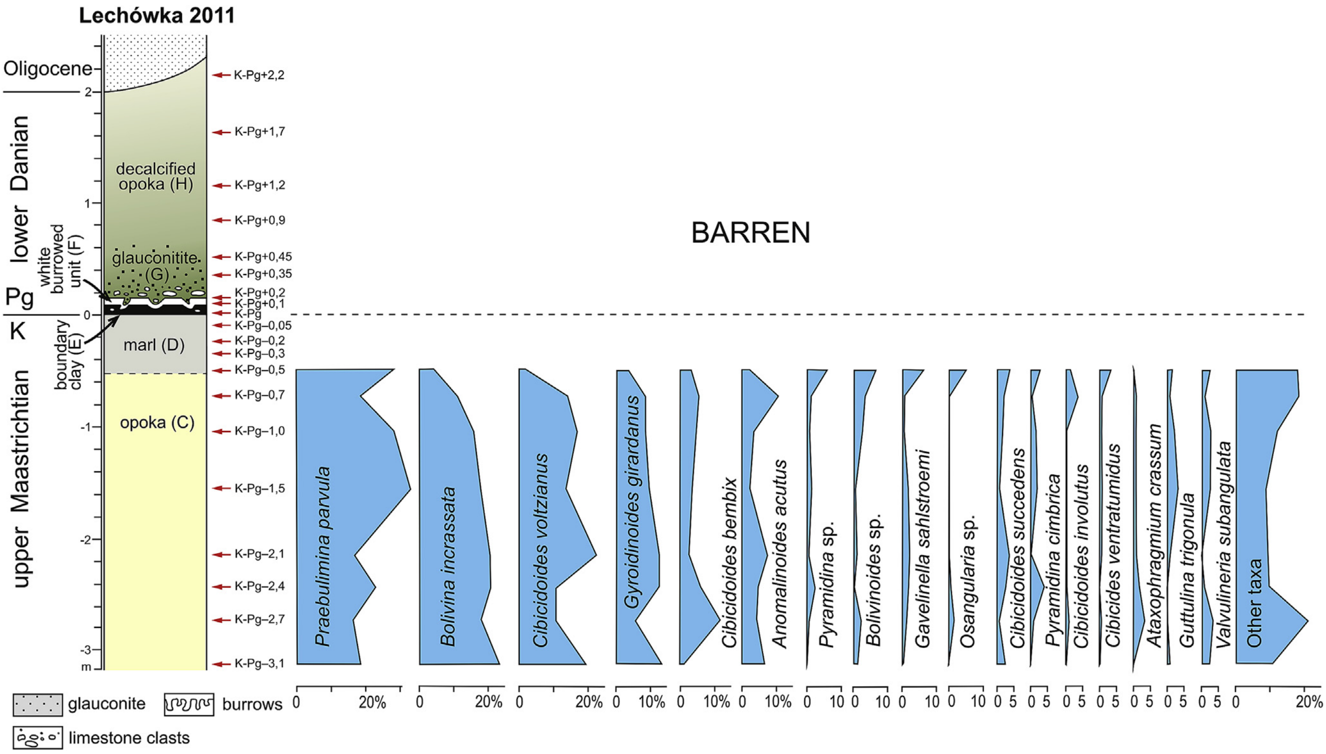


Fig. 12. Relative abundances of benthic foraminifera species at the Lechówka 2011 section. Only taxa that account for more than 3% of the assemblage in at least in one of the samples studied are shown.

marginata) have demonstrated that the changes of pH and calcite saturation states do not have significant effect on these species (McIntyre-Wressnig et al., 2014). *Bolivina* and *Bulimina* illustrate a deep-infaunal mode of life and are generally regarded as thriving well in lower pH and oxygen-depleted environments, for example during deposition of Cretaceous black shales. Therefore, they are more resistant to conditions that are unfavourable to the other taxa (Bernhard, 1986; Dubicka, Peryt, & Szuszkiewicz, 2014; Erbacher, Hemleben, Huber, & Markey, 1999; Friedrich, 2010; Gebhardt, Kuhnt, & Holbourn, 2004; Holbourn & Kuhnt, 2001; Koutsoukos, Leary, & Hart, 1990). However, the benthic foraminiferal assemblage from sample K-Pg −0, 5, at the base of unit D, comprises fairly abundant epifaunal taxa (*Gavelinella*, *Cibicidoides*) that are interpreted as indicators of well-oxygenated bottom waters under oligotrophic to mesotrophic conditions (Jorissen, Stigter, & Widmark, 1995; Kaiho, 1994; Peryt, Alegret, & Molina, 2002). Moreover, there is no increase of infaunal and agglutinated taxa which usually dominate organic-rich deposits. Therefore, we argue that the reduction in test size among benthic foraminifera at Lechówka is not related to a decrease in oxygen availability at the sea floor.

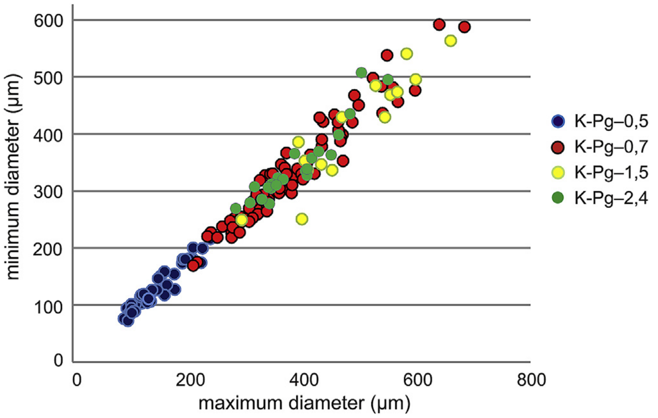


Fig. 13. Plot of test diameter of calcareous epifaunal benthic foraminifera from four samples at the top of the Maastrichtian portion of 2011 section at Lechówka.

In view of the fact that planktonic foraminiferal assemblages at Lechówka are characterised by a predominance of *Heterohelix* and *Guembelitria*, suggested to be typical of shallow-marine and/or high-stress environments (Punekar, Matteo, & Keller, 2014), there is a possibility that changes in the benthic foraminiferal community as observed at Lechówka might be related to the Deccan volcanism prior to the K-Pg boundary. Keller and Abramovich (2009) and Punekar et al. (2014) observed intraspecific test size reductions (Lilliput effect) and blooms of small-sized disaster opportunistic planktonic foraminifera (*Guembelitria*) in the uppermost Maastrichtian. According to these authors, such high-stress assemblages probably were a response to the second and most extensive phase of Deccan volcanism, which led to global climate changes and ocean acidification near the end of the Cretaceous, during Chron 29r (Punekar et al., 2014; Schoene et al., 2015). However, any firm link between test size decrease among benthic foraminifera at the top of the Maastrichtian part of the Lechówka section and Deccan volcanism cannot be established in view of the absence of precise biostratigraphic correlations. Alternatively, the transition to more stressed environmental conditions, as recorded by benthic foraminifera at Lechówka, might also be a consequence of other, local or regional, changes.

6. Conclusions

The section exposed at Lechówka is the most complete

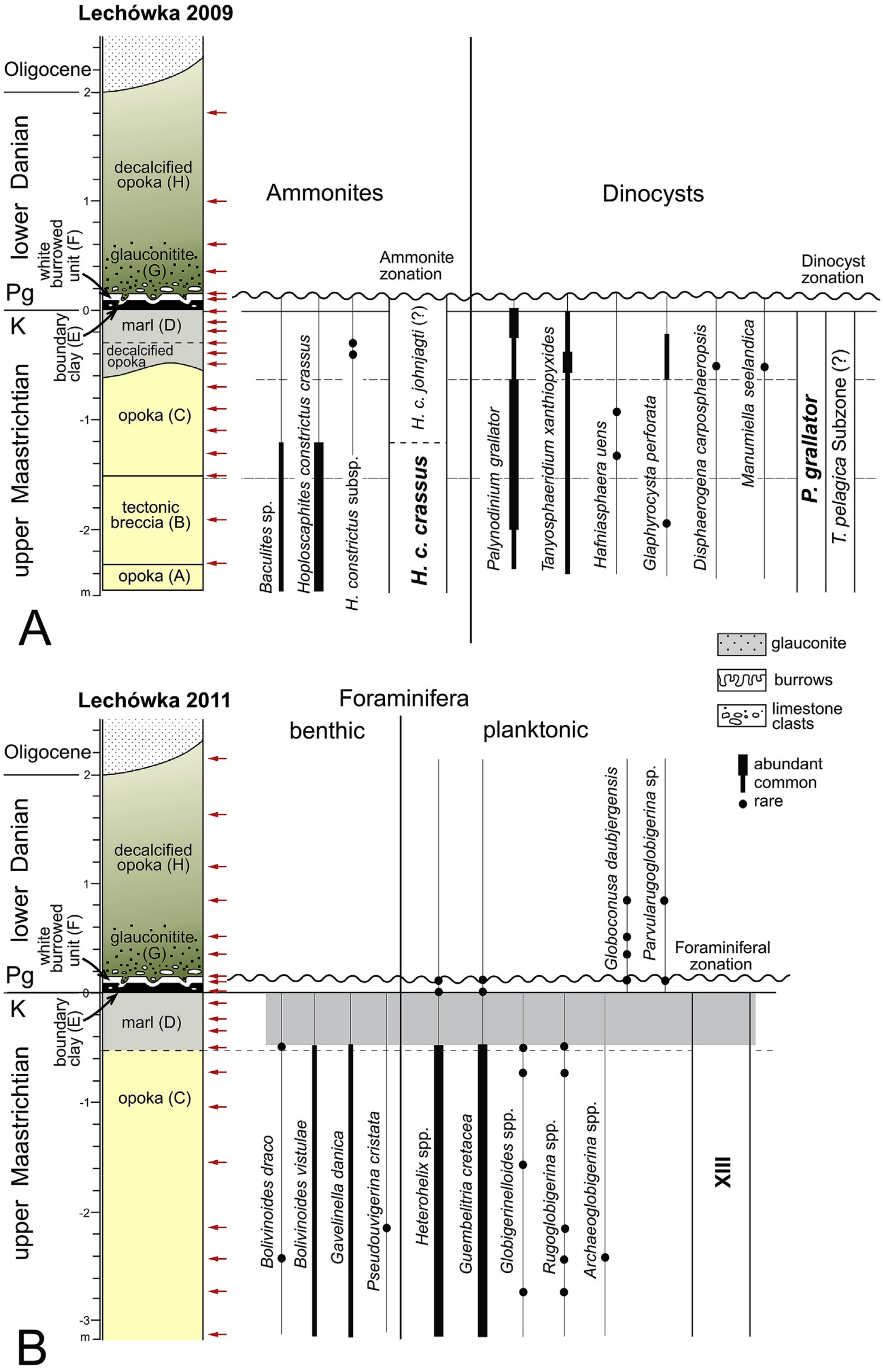


Fig. 14. Ranges of biostratigraphically important ammonites, dinocysts and foraminifera and zonations based on these taxa plotted on the Lechówka 2009 (A) and Lechówka 2011 sections (B). See text for further explanation.

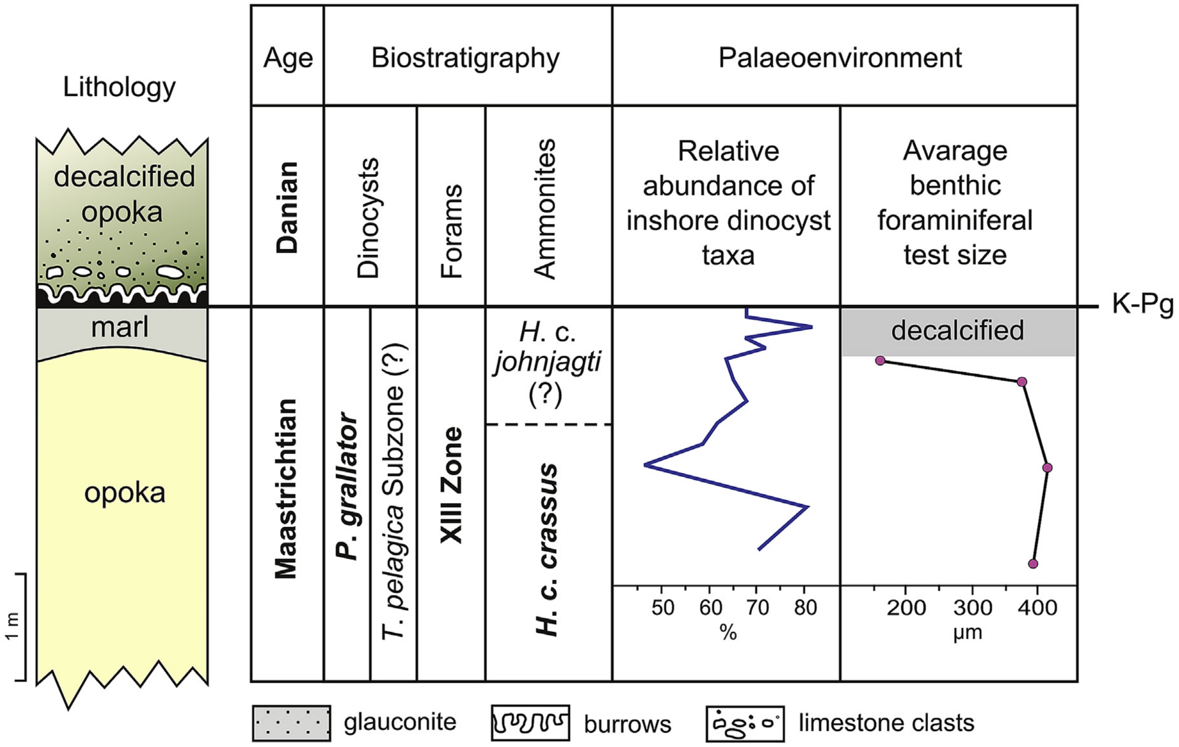
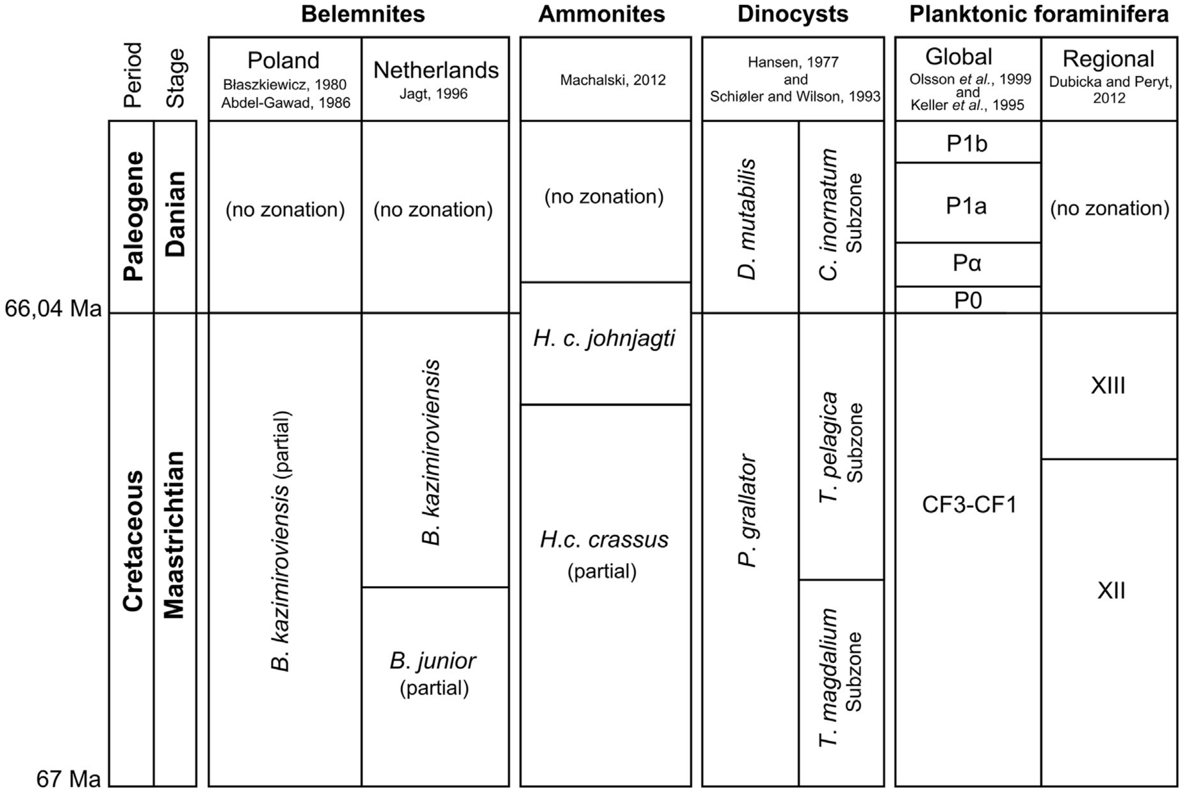


Fig. 15. Biostratigraphic zonation and palaeoenvironmental indices in the Maastrichtian at Lechówka. In this figure, inshore taxa include all taxa belonging to the *Areoligera* group and the *Hystrichosphaeridium* group, plus *Palynodinium grallator*. See text for further explanation.

Table 1
Biostratigraphic zonations used in the present paper.



Period	Stage	Belemnites		Ammonites	Dinocysts		Planktonic foraminifera	
		Poland Błaszkiewicz, 1980 Abdel-Gawad, 1986	Netherlands Jagt, 1996	Machalski, 2012	Hansen, 1977 and Schiøler and Wilson, 1993		Global Olsson *et al.*, 1999 and Keller *et al.*, 1995	Regional Dubicka and Peryt, 2012
Paleogene	**Danian**	(no zonation)	(no zonation)	(no zonation) *H. c. johnjagti*	*D. mutabilis*	*C. inornatum* Subzone	P1b P1a Pα P0	(no zonation)
Cretaceous	**Maastrichtian**	*B. kazimiroviensis* (partial)	*B. kazimiroviensis* *B. junior* (partial)	*H. c. johnjagti* *H.c. crassus* (partial)	*P. grallator*	*T. pelagica* Subzone *T. magdalium* Subzone	CF3-CF1	XIII XII

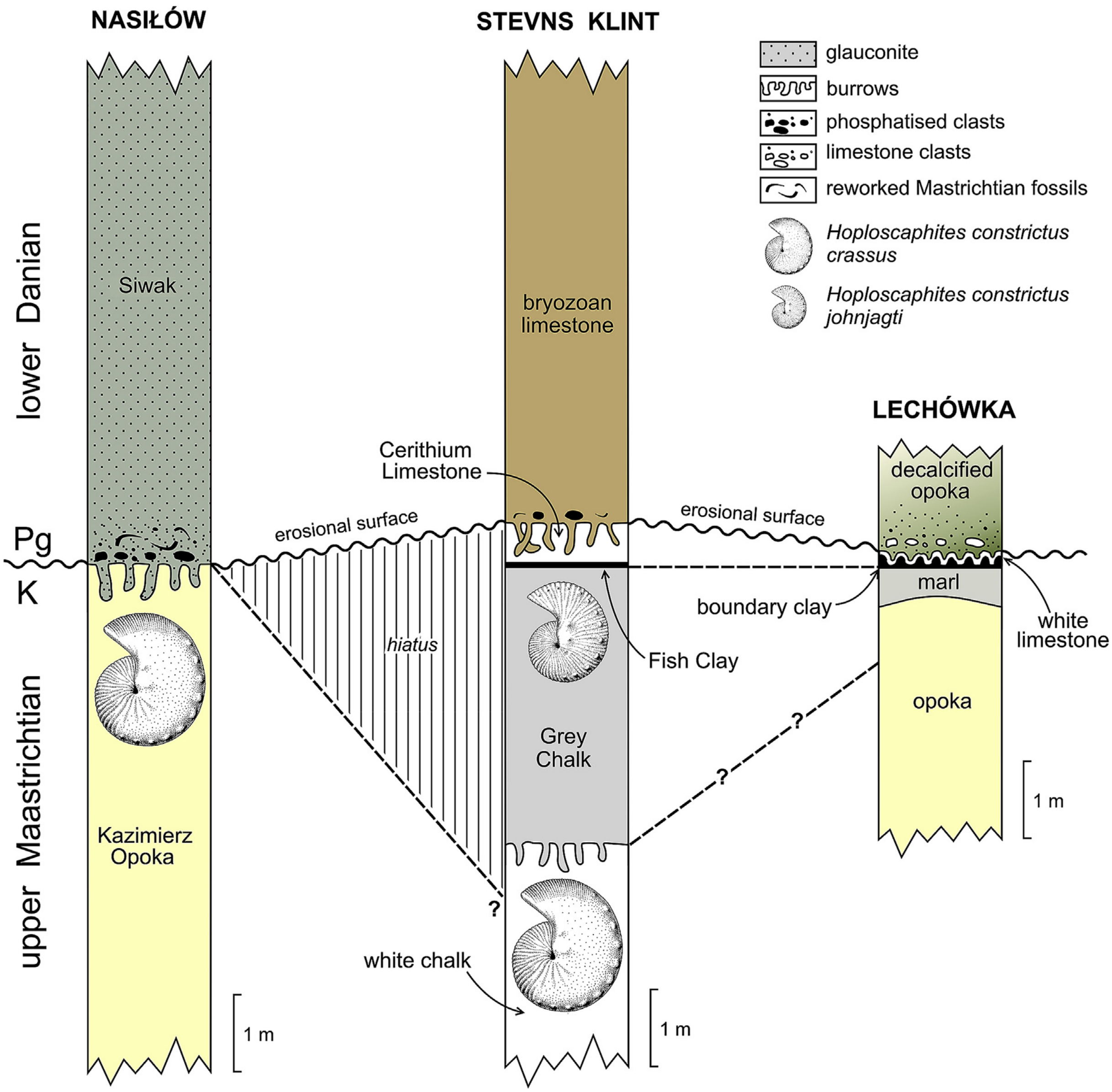


Fig. 16. Litho- and biostratigraphic correlation between the Lechówka section and reference K-Pg sections at Stevns Klint, Denmark and Nasiłów, Poland (modified after Machalski, 2005a, fig. 15). See text for further explanation.

Cretaceous–Paleogene (K-Pg) boundary succession in Poland. The boundary clay, Ir anomaly and other signatures of extraterrestrial impact have been recorded from this oucrop (Brachaniec et al., 2014; Racki et al., 2011). The calcareous macro- and microfossil record is compromised in the Danian and topmost Maastrichtian part of the section because of extensive decalcification and weathering. However, the remainder of the Maastrichtian succession at Lechówka has yielded reasonably well-preserved fossils, including ammonites and nautilids, dinoflagellate cysts and foraminifera, which are used here for biostratigraphic correlations and environmental interpretation (Figs. 14–16).

The scaphitid ammonites, dinocysts and foraminifera studied here confirm the conclusions by Racki et al. (2011) that the Lechówka section comprises the uppermost Maastrichtian and the K-Pg boundary (Figs. 14 and 15). Because specimens of *Hoploscaphites constrictus* from the uppermost 120 cm of the Maastrichtian could not be identified to subspecies level, the uppermost part ot the Maastrichtian of Lechówka could not be assigned to an ammonite zone. Therefore, we are not able to identify the uppermost ammonite zone of *Hoploscaphites constrictus johnjagti* at Lechówka unequivocally.

However, dinocyst and foraminiferal data suggest that the uppermost Maastrichtian zones, the equivalent of the *T. pelagica* Subzone for dinocysts and the regional planktonic foraminiferal zone XIII Zone *sensu* Dubicka and Peryt (2012), are present at Lechówka (Fig. 14A and B). These zones correlate with the *H. c. johnjagti* Zone elsewhere, e.g., in Poland, Denmark and The Netherlands (Table 1). This suggest that the upper 120 cm of the Maastrichtian of Lechówka should comprise the equivalent of the *H. c. johnjagti* Zone. Indeed, the *H. c. johnjagti* Zone appears to represent a relatively short interval, much shorter than the *T. pelagica* Subzone and regional foraminiferal zone XIII *sensu* Dubicka and Peryt (2012) (see also Table 1). Taken together, these results suggest that the uppermost Maastrichtian part of the Lechówka succession is complete, but comparatively condensed (see Figs. 14 and 15).

In addition to these biostratigraphic data, two levels within the lithological succession at Lechówka are of key importance for correlations with other K-Pg sections worldwide (Figs. 2 and 16). The most important of these is the base of clay unit E, which is characterised by an impact-ejecta layer (Brachaniec et al., 2014) that corresponds to the base of the K-Pg boundary clay known worldwide (Schulte et al., 2010). The other correlative level at Lechówka is the boundary between units F and G (Fig. 2). This lithological transition appears to correlate with the erosive contact between the lower Danian Cerithium Limestone Member of the Rødvig Formation, and the Danian bryozoan limestones of the Korsnæb Member of the Stevns Klint Formation at Stevns Klint, Denmark (Surlyk et al., 2006). In Denmark it is interpreted as a significant sequence boundary, reflecting an early, albeit not the earliest, Danian transgression onto the older Maastrichtian/Danian surface (‘Sekvens 2’ of Thomsen, 1995; sequence boundary SB2 of Surlyk, 1997, fig. 5). The burrowed boundary between units F and G at Lechówka may also be coeval with the onset of the Danian transgressive cycle at classic localities such as Nasiłów and Bochotnica in the Kazimierz Dolny area (Hansen et al., 1989; Machalski, 1998). These correlations are summarised in Fig. 16.

The dinoflagellate cyst and foraminiferal records from Lechówka allow a reconstruction of the depositional environment of the succession. The dinocyst and foraminiferal assemblages studied are dominated by taxa that are characteristic of high-energy, marginal marine environments (Fig. 15). The foraminiferal record shows a decrease in test size among benthic calcareous foraminifera at 50 cm below the K-Pg boundary (Fig. 15). This signal could perhaps be explained as dwarfism, related to some form of environmental stress during the latest Maastrichtain, linked either to Deccan volcanism or a local environmental perturbation prior to the K-Pg boundary.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.cretres.2015.08.012.

Appendix 1

Dinocyst species and complexes recognised from the Lechówka section. The nomenclature follows that cited in Fensome and Williams (2004), unless stated otherwise. Dinocyst counts for Lechówka 2009 can be found in Supplementary material 1. Notes on certain taxa are provided:

Achilleodinium bianii
Achomosphaera ramulifera
Adnatosphaeridium buccinum

Apteodinium fallax
Areoligera coronata
Areoligera senonensis
Areoligera spp. (pars)
Cassiculosphaeridia intermedia
Cerodinium sp. indet.
Cleistosphaeridium sp. indet.
Cordosphaeridium fibrospinosum
Cordosphaeridosphaeridium inodes subsp. *inodes*
Coronifera striolata
Cribroperidinium septatum
Cribroperidinium sp. A of Brinkhuis and Schiøler (1996)
Cribroperidinium sp. indet.
?*Cyclonephelium distinctum* – presumed reworked
Deflandrea galeata
Disphaerogena carposphaeropsis
Eisenackia circumtabulata
Eisenackia spp. (pars)
Exochosphaeridium bifidum
Fibrocysta ovalis
Glaphyrocysta perforata
Glaphyrocysta retiintexta
Glaphyrocysta spp. (pars)
Hafniasphaera fluens
Hystrichosphaeridium recurvatum
Hystrichosphaeridium tubiferum
?Isabellidinium sp. indet.
Manumiella seelandica
Microdinium inornatum
Microdinium sp. indet.
Neonorthidium perforatum
Oligosphaeridium complex
Operculodinium centrocarpum
Palaeoperidinium pyrophorum
Palynodinium grallator
Palynodinium cf. *grallator.* This morphotype differs from *Palynodinium grallator* s.s. in having less pronounced lateroventral protrusions
Riculacysta sp. of Soncini and Rauscher (1988)
Senegalinium bicavatum
Senegalinium obscurum
Senegalinium spp. indet.
Spiniferites ramosus
Spiniferites spp. (pars)
Surculosphaeridium? longifurcatum
Tanyosphaeridium xanthiopyxides
Trithyrodinium evittii

Appendix 2

Foraminiferal species recognised in the Lechówka succession. Benthic foraminifera counts for Lechówka 2011 can be found in Supplementary material 2.

Planktonic foraminifera
Archaeoglobigerina blowi
Globigerinelloides abberantus
Globoconusa daubjergensis
Globigerinelloides prairiehillensis
Guembelitria cretacea
Hedbergella sp.
Heterohelix globulosa
Heterohelix navarroensis
Heterohelix planata
Heterohelix striata
Heterohelix ultimatumida
Parvularugoglobigerina sp.
Rugoglobigerina pennyi
Rugoglobigerina hexacamerata
Rugoglobigerina sp.

Benthic foraminifera
Alabamina sp.
Anomalinoides acutus
Anomalinoides sp.
Arenobulimina sphaerica
Arenobulimina sp.
Anomalinoides burlingtonensis
Anomalinoides ekblomi
Ataxoorbignyna inflata
Ataxophragmium crassum
Ataxophragmium rimosum
Bolivina decurrens
Bolivina incrassata
Bolivinoides draco
Bolivinoides vistulae
Bulimina microcostata
Cibicides ventratumidus
Cibicidoides bembix
Cibicidoides involutus
Cibicidoides succedens
Cibicidoides voltzianus
Cibicidoides sp.
Cribrebella fusiformis
Gaudryina pyramidata
Gaudryina sp.
Gavelinella burlingtonensis
Gavelinella danica
Gavelinella gankinoensis
Gavelinella mariae
Gavelinella sahlstroemi
Gavelinella umbilicata
Globulina gibba
Guttulina trigonula
Gyroidinoides girardanus
Lamina irreperta
Lenticulina rotulata Lenticulina sp.
Nodosaria spinosa
Nodosaria subnodosa
Orbignyna sacheri
Osangularia sp.
Plectina ruthenica
Praebulimina parvula
Pseudouvigerina cristata
Pulsiphonina prima
Pullenia cretacea
Pullenia jarvisi
Pyramidina cimbrica
Rosalina brotzeni
Spiroplectammina suturalis
Valvulineria subangulata