

# Foraminiferal record in a condensed marine succession: a case study from the Albian and Cenomanian (mid-Cretaceous) of Annapol, Poland

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**Abstract** – A condensed succession at Annapol is of key importance for the mid-Cretaceous palaeontology and palaeobiogeography in Poland. Here, the planktonic and benthic foraminifera from the Albian and Cenomanian intervals are studied. The local foraminiferal record is strongly influenced by burrowers. On the one hand, piping down of the foraminiferal tests through burrows disturbed the original succession, for example by introduction of the Cenomanian foraminifera into the Albian phosphorite horizon. On the other hand, the foraminifera in the burrow fills near the base of the Cenomanian provide the sole piece of evidence of a lower upper Cenomanian unit lost from the record by erosion. Changes in foraminiferal assemblages allow for the interpretation of the succession in terms of bathymetry and biological productivity. The highest rate of primary production is deduced for the Albian phosphorite horizon. Integration of foraminiferal and ammonite biostratigraphy with sedimentology allows for the comparison of a pattern of sea-level oscillations recorded at Annapol with the relevant portion of the classic graph of sea-level changes for the British Isles. It turns out that all important elements of the British curve, that is, transgressive peaks and regressive troughs or lows, left their distinctive, albeit highly residual, record in the Annapol succession. This study demonstrates that even extremely condensed marine deposits, such as those at Annapol, may provide a foraminiferal record of better quality, order and resolution than conventionally anticipated.

Keywords: foraminifera, condensed succession, stratigraphy, sea-level changes, Cretaceous.

## 1. Introduction

The uppermost lower Albian – lower Turonian condensed, phosphorite-bearing succession at Annapol is the richest Cretaceous Fossil-Lagerstätte in Poland (Samsonowicz, 1925; Cieśliński, 1959; Marcinowski, 1980; Marcinowski & Radwański, 1983; Marcinowski & Wiedmann, 1990). Recent palaeontological exploration of this site (Machalski, Komorowski & Harasimiuk, 2009) has resulted in a series of papers on the mid-Cretaceous biota (Machalski & Kennedy, 2013; Machalski & Martill, 2013; Popov & Machalski, 2014; Kapuścińska & Machalski, 2015; Bardet, Fischer & Machalski, 2016; Machalski & Olszewska-Nejbert, 2016). Other studies in progress deal with palaeoenvironment, vertebrate taphonomy and palaeontology of selected groups.

The Annapol succession records the early phases of the mid-Cretaceous transgression onto the marginal part of the Central European Basin (Cieśliński, 1976; Marcinowski & Radwański, 1983). Palaeobiogeographically, the Annapol Fossil-Lagerstätte forms an important link between the classic fossil assemblages from the Anglo-Paris Basin and central Russia as recently demonstrated for marine vertebrates (Popov & Machalski, 2014; Bardet, Fischer & Machalski, 2016).

Foraminifera from the Annapol succession have previously been studied by Peryt (1983a, b), Marcinowski & Walaszczyk (1985) and Walaszczyk (1987). These authors analysed the foraminiferal biostratigraphy and palaeoecology of the succession, noting also the significant disturbance of the local foraminiferal record by reworking (Peryt, 1983b) and burrowers (Marcinowski & Walaszczyk, 1985; Walaszczyk, 1987). However, so far the micropalaeontological potential of this succession has not been fully exploited. We therefore present a new study of the foraminifera from Annapol, focusing on biostratigraphy and palaeoenvironment, to form the necessary background for further research at this site.

We analysed the planktonic and benthic foraminifera from the Albian and Cenomanian interval at Annapol, based on sampling in an abandoned phosphate mine at Annapol and in a surface locality Kopiec (Fig. 1a–c). Following earlier authors (Marcinowski & Walaszczyk, 1985; Walaszczyk, 1987) we paid special attention to burrows, sampling them separately from the surrounding deposits. The whole interval studied is merely *c.* 5.5 m thick, as measured from the top of the Jurassic to the base of Turonian deposits.

We integrated our micropalaeontological results with sedimentologic observations and macrobiostratigraphic data, based mostly on ammonites (Cieśliński, 1959; Marcinowski 1980; Marcinowski &

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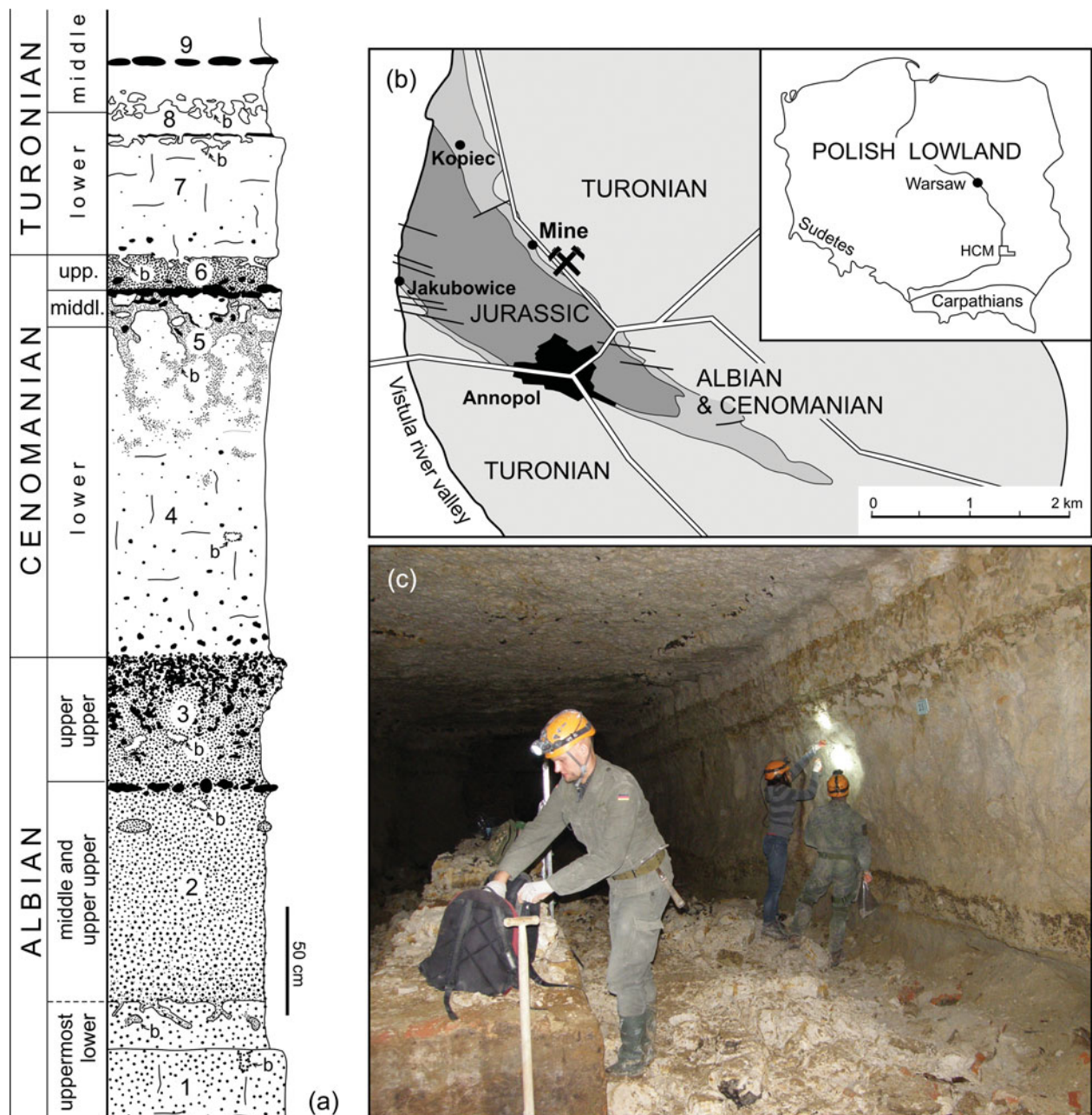


Figure 1. (Colour online) (a) Lithology and stratigraphy of the condensed mid-Cretaceous succession of the Annapol anticline (modified after Machalski & Kennedy, 2013, fig. 1); b – burrows. (b) Geological sketch-map of the Annapol anticline (modified after Walaszczyk, 1987, fig. 1a) with localities studied and location of the study area within Poland; HCM – Holy Cross Mountains. (c) An outcrop in the underground mine at Annapol with our team at work.

Walaszczyk, 1985; Marcinowski & Wiedmann, 1985, 1990; Machalski & Kennedy, 2013). Studies by Hancock (1990, 2004) form a basis for considerations of the sea-level oscillations recorded in the Annapol succession. Other important papers on this subject include Juignet (1980), Ernst, Schmid & Seibertz (1983); Ernst *et al.* (1996), Amédéo (2002), Robaszynski *et al.* (1998), Wilmsen (2003, 2013) and Haq (2014).

The most important papers on the mid-Cretaceous foraminiferal biostratigraphy are on planktonic foraminifera, for example, Sigal (1977), Robaszynski & Caron (1979), Robaszynski *et al.* (1993), Kennedy *et al.* (2004) and Caron *et al.* (2006). Benthic fo-

raminiferal stratigraphy was elaborated by Eicher & Worstell (1970), Gawor-Biedowa (1972), Carter & Hart (1977), Price (1977) and Hart *et al.* (1989). Palaeoenvironmental studies focused mainly on the Cenomanian–Turonian Boundary Event (CTBE) (Jarvis *et al.* 1988; Koutsoukos & Hart, 1990; Leary & Peryt, 1991; Hart, Dodsworth & Duane, 1993; Paul *et al.* 1999; Keller *et al.* 2001; Wang *et al.* 2001; Kuhnt *et al.* 2005; Friedrich, Erbacher & Mutterlose, 2006), although there are also studies on more expanded, stable intervals (Coccioni & Galeotti, 1993; Coccioni, Galeotti & Gravili, 1995; Gebhardt, Wolfgang & Holbourn, 2004; Dalby, Patterson & Haggart, 2009; Kochhann, Koutsoukos & Fauth, 2014).

Table 1. Ammonite and foraminiferal zonation of the Albian–Cenomanian interval studied. Ammonite biostratigraphy follows Machalski & Kennedy (2013) for the Albian stage and Kennedy & Gale (2006) for the Cenomanian stage. Foraminiferal zonation based on Robaszynski & Caron (1995), Kennedy *et al.* (2004) and Ogg & Hinnov (2012).

Substage	Ammonite zone	Ammonite subzone	Foraminifera zonation
Upper Cenomanian	<i>Neocardioceras juddii</i>		<i>Whiteinella archaeocretacea</i>
	<i>Metioceras geslinianum</i> <i>Calycoceras guerangeri</i>		<i>Rotalipora cushmani</i>
Middle Cenomanian	<i>Acanthoceras jukesbrownei</i>	<i>Turrilites acutus</i>	
	<i>Acanthoceras rhotomagense</i> <i>Cunningtoniceras inerme</i>	<i>Turrilites costatus</i>	<i>Thalmaninella reicheli</i>
Lower Cenomanian	<i>Mantelliceras dixonii</i> <i>Mantelliceras mantelli</i>	<i>Mantelliceras saxbii</i> <i>Sharpeiceras schlueteri</i> <i>Neostlingoceras carcitanense</i>	<i>Thalmaninella globotruncanoides</i>
Upper Albian	<i>Praeschloenbachia briacensis</i>		<i>Parathalmaninella appenninica</i>
	<i>Mortoniceras perinflatum</i>		
	<i>Mortoniceras rostratum</i>		<i>P. appenninica</i> (+ <i>ticinensis</i> )
	<i>Mortoniceras fallax</i>		<i>P. appenninica</i> (+ <i>buxtorfi</i> )
	<i>Mortoniceras inflatum</i>		<i>Pseudothalmaninella subticinensis</i>
	<i>Mortoniceras pricei</i> <i>Dipoloceras cristatum</i>		<i>P. praeticinensis</i>
Middle Albian	<i>Euhoplites lautus</i>	<i>Anahoplites daviesi</i> <i>Euhoplites nitidus</i> <i>Euhoplites meandrinus</i>	<i>Ticinella primula</i>
	<i>Euhoplites loricatedus</i>	<i>Mojsicovicsia subdelaruei</i> <i>Dimorphoplites niobe</i> <i>Anahoplites intermedius</i>	
	<i>Hoplites dentatus</i>	<i>Hoplites spathi</i> <i>Lyelliceras lyelli</i>	
		<i>Lyelliceras pseudolyelli</i> <i>Pseudosonneratia steinmanni</i> <i>Otohoplites bulliensis</i> <i>Protohoplites puzosianus</i> <i>Otohoplites raulinianus</i>	
Lower Albian (upper part)	<i>Otohoplites auritifformis</i>		

## 2. Geological setting

The material studied comes from the Albian–Cenomanian interval of the mid-Cretaceous (uppermost lower Albian – lower Turonian) condensed, phosphorite-bearing succession exposed along the limbs of the Annopol anticline, central Poland (Fig. 1a–c). The Annopol anticline is located on the east bank of the Wisła (Vistula) River, central Poland (Fig. 1b). This is the easternmost part of the so-called Mesozoic Border of the Holy Cross Mountains (Marcinowski & Radwański, 1983).

The lithology of the mid-Cretaceous succession at Annopol was described by Samsonowicz (1925, 1934), Pożaryski (1947), Cieśliński (1959) and Walaszczyk (1987). The biostratigraphy was based mainly on ammonites and inoceramid bivalves (Samsonowicz, 1925, 1934; Pożaryski, 1947; Cieśliński, 1959, 1987; Marcinowski, 1980; Marcinowski & Radwański, 1983, 1989; Marcinowski & Walaszczyk, 1985; Marcinowski & Wiedmann, 1985, 1990; Machalski & Kennedy, 2013). The reader is referred to Table 1 for the standard ammonite and foraminiferal subdivisions of the Albian–Cenomanian interval which we have used.

The Annopol succession is extremely thin when compared to coeval strata in adjacent areas due to its

location on a submarine high (Cieśliński, 1976; Marcinowski & Radwański, 1983). Based on the model presented by Juignet (1980) and Hancock (1990, 2004), the Annopol succession can be subdivided into a series of thin, transgressive units (Machalski & Kennedy, 2013). These units are capped by layers of reworked phosphatic nodules and clasts, burrowed hardgrounds and omission and/or erosional surfaces (Fig. 1a), which are interpreted as regression maxima (compare Hancock, 1990, fig. 2)

## 3. Sampled interval

The rock interval sampled for this study comprises six Albian–Cenomanian units, *c.* 5.5 m in total thickness (Fig. 1a). The lower part of unit 1 (unfossiliferous sands on top of the Jurassic substrate) was accessible and sampled only in the surface locality Kopiec, north of Annopol (Fig. 1b). The remainder of the samples are from the underground phosphate mine Jan 1 at Annopol (Fig. 1b,c). All sampled units are listed below in ascending order, with comments on their lithology, ichnology and macro-fossil biostratigraphy.

Unit 1. Quartz sands with a quartzose sandstone layer in the middle, with a burrowed surface at the top.

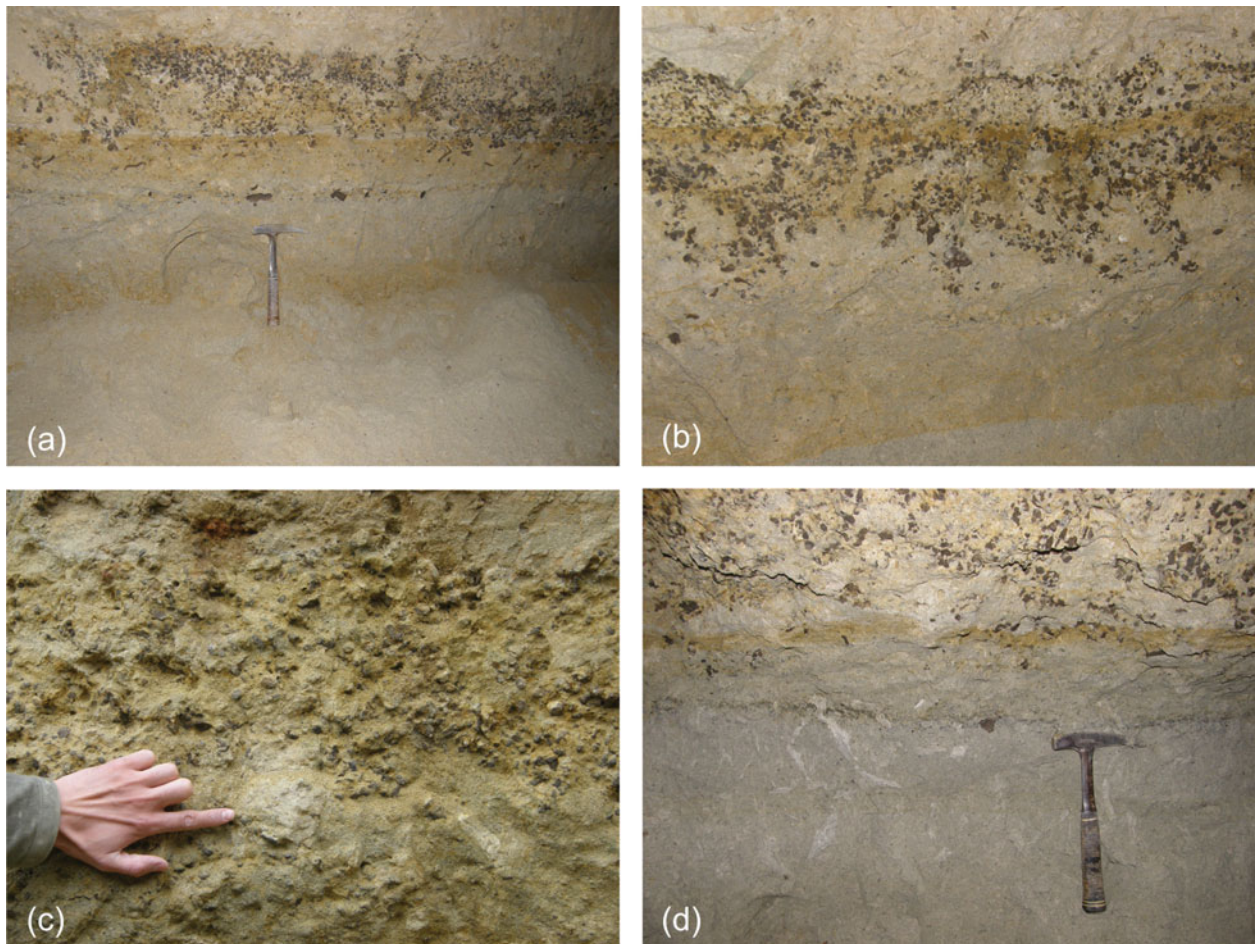


Figure 2. (Colour online) Close-up views of the upper Albian interval of the Annopol successions to show the bioturbated nature of the phosphatic layer at the top of unit 3 (a, b) and discrete burrows filled with the Cenomanian marls in this unit (c) and near the top of the underlying unit 2 (d). Underground mine at Annopol (a, b, d) and surface locality Kopiec (c).

The total thickness of this unit measured at Kopiec is 2.50 m. The sandstone contains ammonites of the upper lower Albian *Otoboplites auritifformis* Zone, *Hoplites* (*Hoplites*) *eodentatus* Subzone; see Marcinowski & Wiedmann (1985, 1990) and discussion in Machalski & Kennedy (2013).

Unit 2. Quartz sands with glauconite and rare ovoid sandstone nodules near the top, *c.* 70 cm thick. Unit 2 is capped by a distinct phosphate horizon, including characteristic spindle-shaped phosphatic nodules. In the upper part of unit 2, burrows filled with a marly deposit identical to that of unit 4 are visible (Fig. 2d). The phosphatic horizon contains a biostratigraphically mixed ammonite assemblage, ranging from the middle Albian *Hoplites dentatus* Zone to the lowermost upper upper Albian *Mortonicerias fallax* Zone (Marcinowski & Radwański, 1983, 1989; Machalski & Kennedy, 2013; Kennedy & Machalski, 2015; see Table 1 for the ammonite zonations used in the present paper).

Unit 3. Quartz sands with glauconite passing upwards into marly sands with glauconite and phosphates, forming a distinct horizon at the top of the unit; the total thickness of unit 3 is *c.* 50 cm. In many places, the phosphatic horizon has a highly bioturbated fabric with more or less discrete burrows (Fig. 2a–c). Phos-

phates contain the upper upper Albian ammonites, most probably of the *Mortonicerias perinflatum* Zone, preserved as attachment scars on oyster shells (Machalski & Kennedy, 2013) and phosphatic ‘pseudosteinkerns’ (see Machalski & Olszewska-Nejbert, 2016). There is a stratigraphical gap at the top of unit 3, embracing the *Praeschloenbachia briacensis* Zone (Machalski & Kennedy, 2013; Table 1). Unit 3 and the top of unit 2 were collectively referred to as ‘the Phosphorite Bed’ by previous authors (e.g. Marcinowski & Walaszczyk, 1985; Marcinowski & Wiedmann, 1985; Walaszczyk, 1987; Marcinowski & Radwański, 1983, 1989).

Unit 4. Quartzose marls with glauconite and phosphates in the lower part, *c.* 170 cm thick. There is a concentration of phosphates and fossils, including belemnite *Neohibolites ultimus* and bivalve *Aucellina* in the lower part of the unit, which becomes less detrital and more calcareous towards the top. Several burrows with distinctive white marly infillings with no quartz and glauconite (Fig. 3a–d) were recognized during our study in the lower part of the unit. There is no continuous layer of such a lithology in the succession. We therefore interpret these burrows as remnants of a sedimentary unit originally deposited in the Annopol area, but subsequently removed by erosion.



Figure 3. (Colour online) (a–d) Lower upper Cenomanian burrows in the lower part of the lower Cenomanian unit 4. Underground mine at Annopol.

Ammonite assemblage from unit 4 comprises lower Cenomanian taxa (*Mantelliceras mantelli* and *M. dixoni* zones, according to Marcinowski & Walaszczyk, 1985, although no unequivocal *dixoni* fossils are listed by these authors). No macrofossils were found in the above-mentioned burrows.

Unit 5. Glauconitic marls filling large burrows in the underlying unit, truncated by a complex hardground with strong phosphate and glauconite impregnation (Fig. 1a). This is a highly fossiliferous level, yielding *inter alia* numerous phosphatized moulds of an irregular echinoid *Holaster subglobosus* (Samsonowicz, 1925, 1934). According to Marcinowski & Walaszczyk (1985) the ammonite assemblage from unit 5, represented exclusively by phosphatized specimens, comprises both lower and middle Cenomanian taxa, the latter characteristic of the *Acanthoceras rhotomagense* Zone and *Turrilites costatus* and *T. acutus* subzones (see Table 1). A stratigraphic gap embracing the *A. jukesbrownei* Zone (see Table 1) was postulated for the top of unit 5 by Marcinowski (1980). There is also no indication of the *Cunningtoniceras inerme* Zone (Table 1) fossils, suggesting a similarly significant stratigraphic gap near the bottom of unit 5.

Unit 6. Strongly glauconitic marls with burrowed omission surface at the top, variable in thickness

over the range 0–40 cm. The ammonite species *Schloenbachia lymensis* was quoted by Marcinowski & Walaszczyk (1985) from this unit as an upper Cenomanian biostratigraphic marker. According to Kennedy (2013, p. 466), this species ‘first appears in the Middle Cenomanian *Acanthoceras jukesbrownei* Zone, and has its acme in the lower upper Cenomanian *Calycoceras guerangeri* Zone’. Inoceramids and belemnites reported by Marcinowski & Walaszczyk (1985) locate unit 6 in the upper Cenomanian Substage.

The Turonian interval, not sampled here, consists of limestone bed with rare phosphatic nodules and glauconite, capped by a burrowed hardground with glauconitic mineralization (unit 7), followed by marls with a burrowed omission surface at their top (unit 8). These are overlain by marls with layers of black flint (unit 9, visible in the ceiling of the underground corridor in Fig. 1c). Units 7 and 8 represent the lower Turonian *Inoceramus labiatus* Zone whereas unit 9 belongs to the middle Turonian *I. lamarcki* Zone (Marcinowski & Walaszczyk, 1985).

#### 4. Materials and methods

In total, 23 productive samples from the Albian–Cenomanian deposits of the Annopol succession were

studied. These samples were collected in the abandoned underground phosphorite mine Jan 1 in Annapol in 2014 (Fig. 1c). Other samples taken from sands forming the lower part of unit 1 at Kopiec proved to be barren, both for micro- and macrofossils. This barren interval of *c.* 1.5 m thickness is not shown in figures.

Sandy samples were washed and sieved into 63–500 µm fractions. More calcareous and lithified samples were disaggregated by using the liquid nitrogen method (Remin *et al.* 2012), cleaned in an ultrasonic bath, dried and sieved into the same fraction (63–500 µm).

Most of the specimens have been determined at species level. All recorded species, 73 in total, are listed in the supplementary online appendix (available at <http://journals.cambridge.org/geo>). Quantitative analyses were based on representative splits (using an Otto microsampler) of 250 or more specimens of benthic and 250 specimens of planktonic foraminifera. For the quantitative analysis, all benthic foraminifera were counted at generic level whereas planktonic foraminifera were counted at specific morphotypes. Seven morphotypes of planktonic foraminifera were distinguished: keeled high-trochospiral (*Dicarinella*, *Rotalipora*, *Thalmaninella*); high-trochospiral with pseudo-keel (*Praeglobotruncana*); high-trochospiral with globular chambers (*Whiteinella*); low-trochospiral with globular chambers (*Hedbergella*); planispiral (*Globigerinelloides*); triserial (*Guembelitra*); and biserial forms (*Heterohelix*).

The counting results were recalculated into the relative abundance of planktonic and benthic foraminifera (P/B ratio), the relative abundance of calcareous and agglutinated forms within benthic foraminiferal assemblages, and the percentages of specific benthic foraminiferal genera and planktonic foraminiferal morphotypes within their relevant assemblages. Planktonic foraminifera were also studied in thin-sections of phosphatic nodules from unit 3. The material is stored in S.J. Thugutt Geological Museum, Faculty of Geology, University of Warsaw.

## 5. Benthic foraminifera

Selected examples of the benthic foraminifera from the Annapol succession are illustrated in Figure 4. The assemblages from the upper part of unit 1 (samples 1–4 in Fig. 5) comprise only agglutinated forms, mainly *Arenobulimina* and *Ataxophragminum*. The relative abundance of specific groups of foraminifera recorded in these assemblages is not presented in Figure 5 since foraminifera are infrequent and the number of specimens is less than 100 per 200 g sample.

The assemblages from samples 5–7 taken from unit 2 (Fig. 5) are also characterized by abundant agglutinated foraminifera; however, calcareous benthic foraminifera appear as an increasingly important element. Calcareous foraminifera are dominated by relatively small and thin-walled representatives of *Orithostella*

(*O. formosa*) and *Lingulogavelinella* (the most numerous are *L. kaptarenkae*, *L. spinosa*, *L. orbiculata* and *L. varsoviensis*). The proportional abundance of calcareous foraminifera in relation to agglutinated forms successively increases upwards in the unit.

Samples 10, 11 and 13–15 from unit 3 (Fig. 5) yield highly diverse assemblages represented by more than 30 species. The most abundant forms belong to the following genera: *Berthelina* (*B. baltica*, *B. belorussica*, *B. intermedia*, *B. cenomanica*, *B. gorzowiensis*); *Cibicides* (*C. gorbenkoi*); *Gavelinella* (*G. schloenbachii*); *Gyroidinoides* (*G. infracretacea*); *Lenticulina* (*L. rotulata*, *L. muensteri*, *L. spp.*); *Lingulogavelinella* (*L. kaptarenkae*, *L. orbiculata*, *L. spinosa*, *L. varsoviensis*); *Orithostella* (*O. formosa*); *Praebulimina* (*P. evexa*, *P. reussi*); *Tappanina* (*T. eouvigeriniformis*); and *Arenobulimina* (*A. advena*, *A. chapmani*, *A. conoidea*, *A. frankei*, *A. obliqua*, *A. polonica*, *A. truncata*, *A. varsoviensis*). There is no domination of any specific taxon in this assemblage. Very similar foraminiferal assemblages occur in the uppermost part of unit 2 (sample 9), in the lower part of unit 4 (samples 16, 17 in Fig. 5) and in burrows descending from unit 4 to unit 3 (sample 12 in Fig. 5) and to the upper part of unit 2 (sample 8 in Fig. 5). The vertical range of these assemblages, which seems to be expanded by burrowing organisms, therefore broadly corresponds to that of the phosphates (Fig. 5).

Benthic foraminifera from samples 18, 20, 21 in unit 4 (Fig. 5) are still dominated by calcareous forms; however, in contrast to the assemblages of unit 3, there is clear domination of a single genus *Berthelina*. This genus encompasses about 40% of the total assemblage and is represented by the following species: *B. baltica*, *B. intermedia*, *B. cenomanica*, *B. gorzowiensis* and *B. belorussica*.

Sample 22 from unit 5 (Fig. 5) strongly resembles those from unit 4 in terms of composition, with the exception that *Orithostella*, a very common taxon in the lower part of the Annapol succession, is entirely absent here. Benthic assemblages from the marly infillings of burrows in unit 4 (sample 19 in Fig. 5) are very similar in composition.

The assemblage from sample 23 of unit 6 (Fig. 5) differs significantly from all the above-mentioned assemblages by the disappearance of many common species (e.g. *Berthelina baltica*, *B. belorussica*, *B. intermedia*, *B. cenomanica*, *B. gorzowiensis*, *Lingulogavelinella kaptarenkae*, *L. orbiculata*, *L. spinosa* and *L. varsoviensis*). It is also characterized by a predominance of a few, newly appearing species such as *Lingulogavelinella globosa* and *Gavelinella berthelini*, which are accompanied by a smaller proportion of other genera, mainly *Lenticulina*, *Gyroidinoides* and *Valvulinera*.

## 6. Planktonic foraminifera

Selected examples of planktonic foraminifera from the Annapol succession are illustrated in Figures 6 and

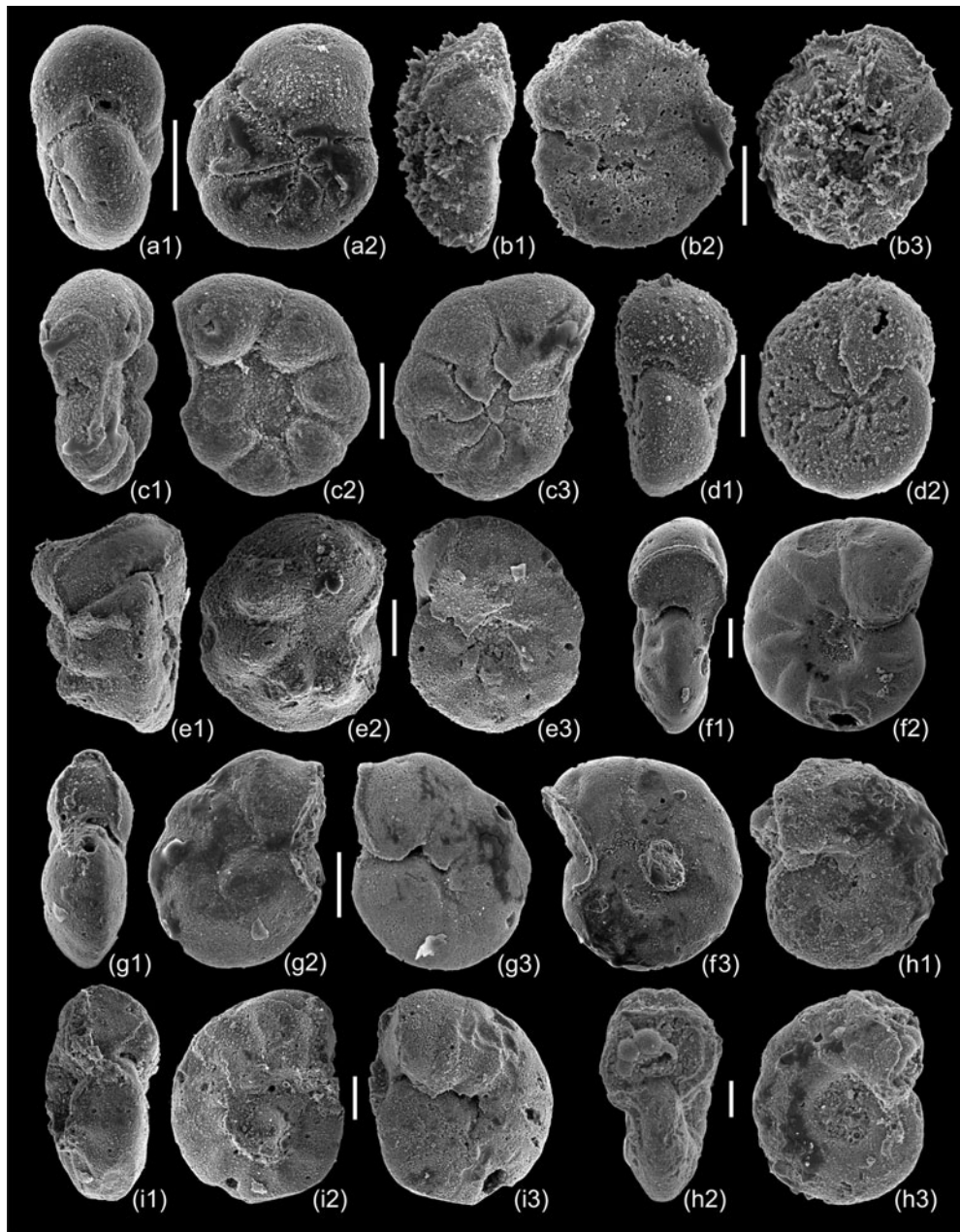


Figure 4. Benthic foraminifera from the Annopol succession. (a1, a2) *Lingulogavelinella orbiculata* (Kusnezova), sample 15, MWGUW ZI/67/01.01. (b1–b3) *Lingulogavelinella spinosa* (Plotnikova), sample 15, MWGUW ZI/67/01.12. (c1–c3) *Lingulogavelinella globosa* (Brotzen), sample 23, MWGUW ZI/67/03.17. (d1, d2) *Lingulogavelinella kaptarenkae* (Plotnikova), sample 13, MWGUW ZI/67/01.05. (e1–e3) *Orithostella formosa* (Brotzen), sample 14, MWGUW ZI/67/01.07. (f1–f3) *Berthelina intermedia* (Berthelin), sample 17, MWGUW ZI/67/01.08. (g1–g3) *Gavelinella berthelini* (Keller), sample 23, MWGUW ZI/67/03.21. (h1–h3) *Berthelina baltica* (Brotzen), sample 16, MWGUW ZI/67/01.44. (i1–i3) *Berthelina cenomanica* (Brotzen), sample 20, MWGUW ZI/67/01.03. Scale bars = 100  $\mu\text{m}$ .

7. These foraminifera are entirely absent from unit 1 (samples 1–4 in Fig. 8). In the lower part of unit 2 (samples 5–7 in Fig. 8), they are more frequent than the benthic foraminifera; the relative proportion of planktonic and benthic foraminifera (P/B ratio) amounts to *c.* 90%. These assemblages are dominated by small and simple forms belonging to two morphogroups: triserial (*Guembelitra cenomana*) and low-trochospiral with globular chambers (*Hedbergella delrioensis*, *H. planispira*, *H. infracretacea* and *Globigerina graysonensis*). Planispiral forms (*Globigerinelloides bentonen-*

*sis*) and serial heterohelicids (*Heterohelix moremani*) form only a few percent of the assemblage, whereas keeled and high-trochospiral forms are absent.

In the uppermost part of unit 2 and in unit 3 (samples 9–15 in Fig. 8) planktonic foraminiferal assemblages are still characterized by very high P/B ratio (about 80%). However, they differ from those from below in terms of specific morphotype ratios. Triserial forms (*Guembelitra*) consist of over a dozen percent of the assemblage and globular hedbergellids comprise *c.* 80%. The

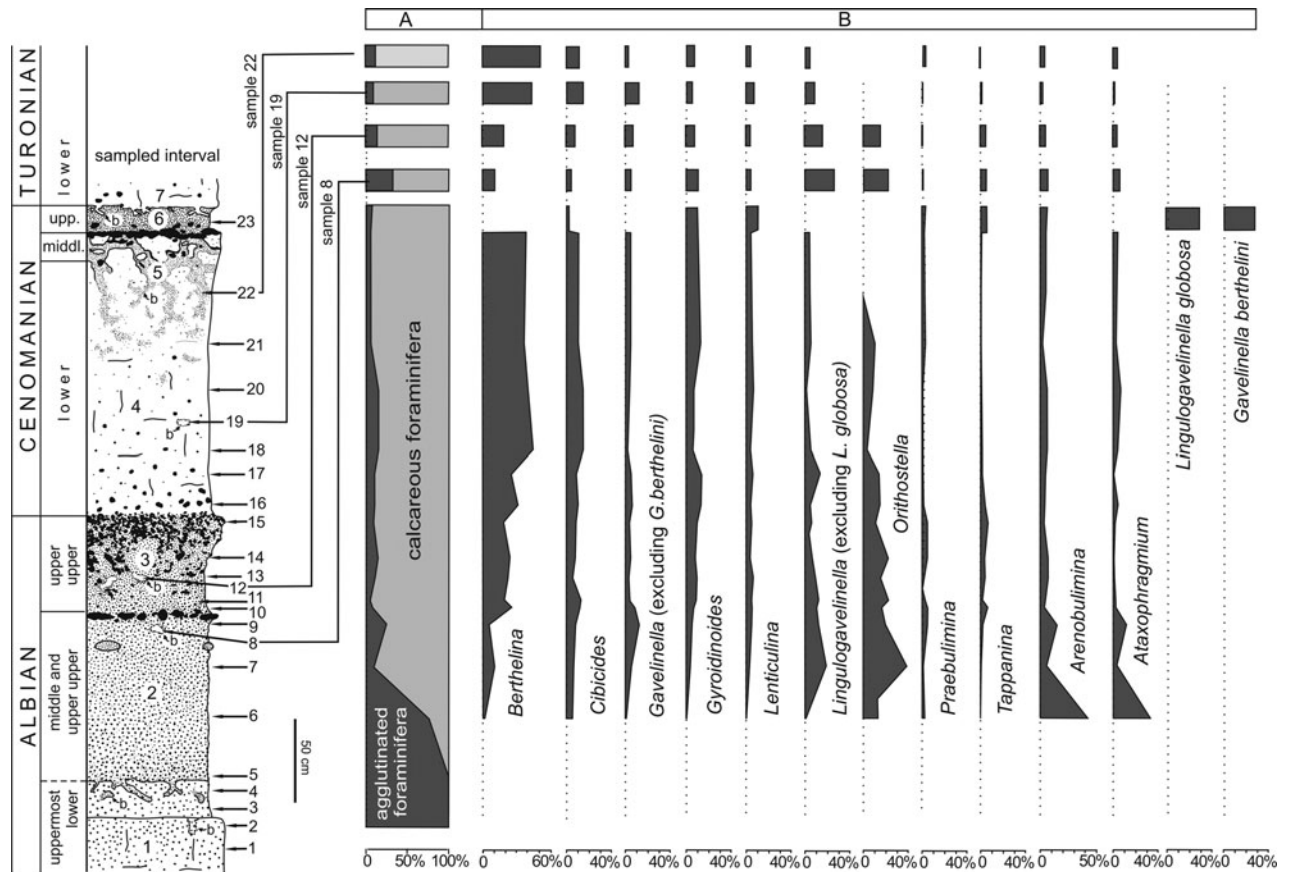


Figure 5. Changes in benthic foraminiferal assemblages in the Albian–Cenomanian interval in the Annapol succession. A – proportions of calcareous and agglutinated forms within benthic foraminiferal assemblages; B – relative abundances of dominant and common species or groups of species; 1–23 – sample position.

complex keeled forms sporadically occur (sample 13); however, they were probably introduced downwards into the older sediments by the activity of burrowing infauna (see discussion in Section 7).

In contrast to the previous assemblages, planktonic foraminiferal assemblages from the lower part of unit 4 (samples 16–17 in Fig. 8) are characterized by the occurrence of more complex morphogroups (single-keeled morphotype (*Thalmaninella*)) and high trochospiral with globular or narrowed chambers (*Whiteinella* and *Praealobotruncana*), still forming just a few percent (1–3%) of the whole assemblage. Very similar planktonic assemblages are recorded in the burrows descending from unit 4 to to unit 3 (sample 12 in Fig. 8) and even to the top part of unit 2 (sample 8 in Fig. 8).

Planktonic foraminiferal assemblages in the higher part of unit 4 (samples 18, 20, 21 in Fig. 8) display a lower P/B ratio which amounts to *c.* 20–30%. These assemblages are characterized by the more frequent occurrence of the complex planktonic forms.

Assemblages of planktonic foraminifera from unit 5 (sample 22 in Fig. 8) are characterized by the appearance of single-keeled *Rotalipora cushmani*. The presence of this taxon is the main difference between unit 5 and the preceding unit.

Planktonic foraminiferal assemblages of marly infillings of burrows within unit 4 (sample 19) dis-

play a very high P/B ratio (about 90%) and more abundant complex forms: single-keeled forms are represented by *Thalmaninella greenhornensis* and *Rotalipora cushmani*; high trochospiral forms with a pseudo-keel are represented by *Praeglobotruncana delrioensis*, *P. gibba* and *P. stephani*; and high trochospiral forms with simple globular chambers are represented by *Whiteinella baltica* and *W. brittonensis*. The assemblages are also characterized by the first appearance of early double-keeled foraminifera of the genus *Dicarinella* (*D. algeriana*, *D. hagni* and *D. imbricata*). All these complex forms constitute *c.* 10% of the material.

Planktonic assemblages from unit 6 (sample 23 in Fig. 8) are characterized by a very high P/B ratio (*c.* 90%) and the frequent occurrence of single-keeled *Rotalipora* (represented only by *R. cushmani*), double-keeled *Dicarinella* (represented by *D. algeriana*, *D. hagni*, *D. imbricata* *D. longoriai*) and the huge complex *Whiteinella* (*W. aprica*, *W. archaeocretacea*, *W. baltica* and *W. brittonensis*) (Fig. 7). They also differ from other assemblages in that they are dominated by high-trochospiral whiteinellids and biserial heterohelicids.

## 7. Stratigraphy

This is based mainly on planktonic foraminifera, which are one of the biostratigraphic tools for the Albian



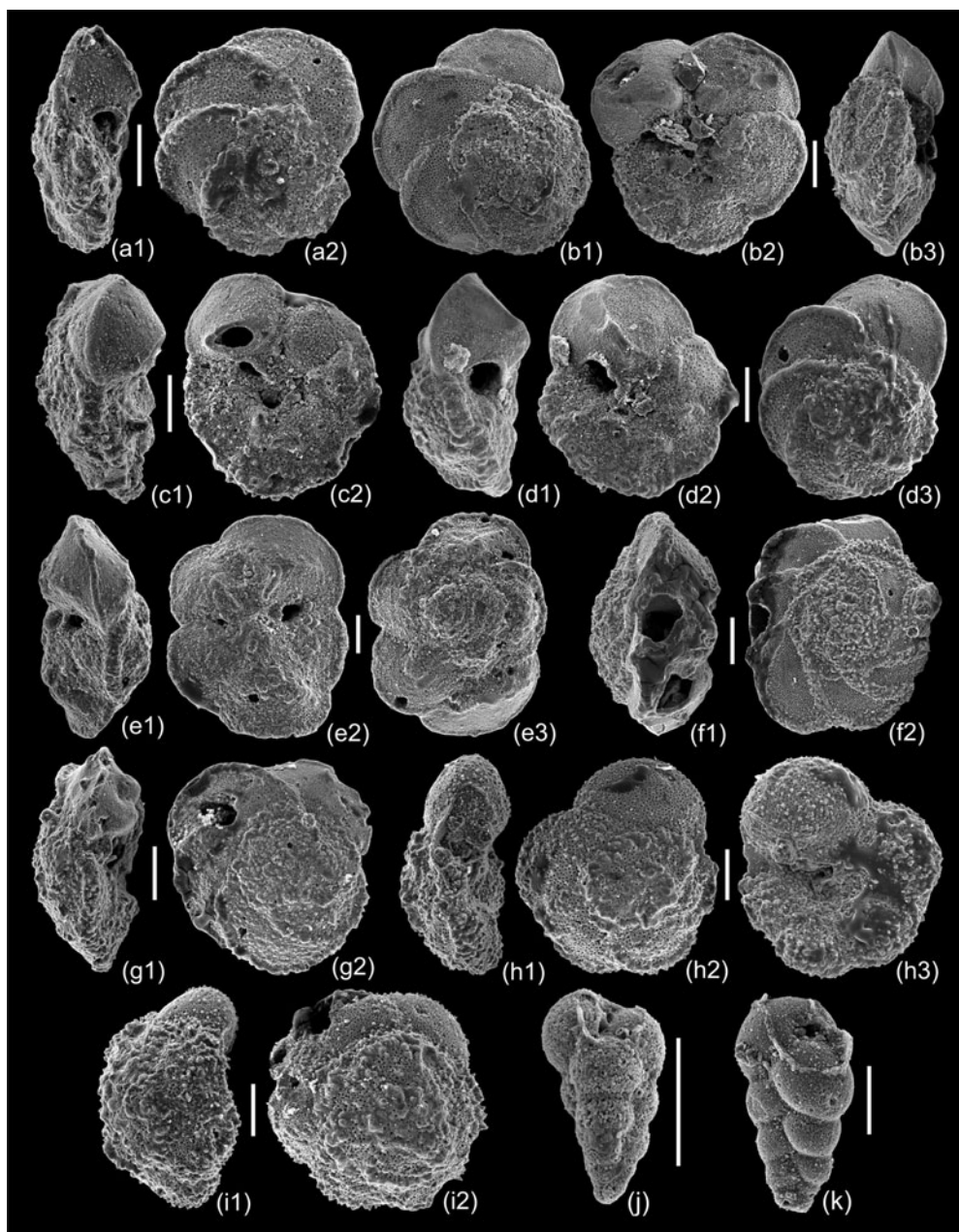


Figure 6. Planktonic foraminifera from the Annopol succession. (a1, a2) *Thalmaninella appenninica* (Renz), sample 16, MWGUW ZI/67/01.48. (b1–b3) *Thalmaninella tehamensis* (Marianos and Zingula), sample 13, MWGUW ZI/67/01.50. (c1, c2) *Thalmaninella gandolfi* (Luterbacher and Premoli-Silva), sample 13, MWGUW ZI/67/03.03. (d1–d3) *Thalmaninella globotruncanoides* (Sigal), sample 16, MWGUW ZI/67/01.08. (e1–e3) *Rotalipora cushmani* (Morrow), sample 23, MWGUW ZI/67/03.09. (f1, f2) *Thalmaninella deckeii* (Franke), sample 22, MWGUW ZI/67/03.016. (g1, g2) *Thalmaninella greenhornensis* (Morrow), sample 19, MWGUW ZI/67/03.22. (h1–h3) *Praeglobotruncana stephani* (Gandolfi), sample 23, MWGUW ZI/67/03.03. (i1, i2) *Praeglobotruncana gibba* (Klaus), sample 19, MWGUW ZI/67/03.15. (j) *Guembeltria cenomana* (Keller), sample 6, MWGUW ZI/67/02.06. (k) *Heterohelix moremani* (Cushman), sample 9, MWGUW ZI/67/01.57. Scale bars = 100  $\mu\text{m}$ .

and Cenomanian stages (Robaszynski & Caron, 1979, 1995; Caron, 1985; Robaszynski *et al.* 1993).

Units 1 and 2 yielded no planktonic foraminifera which could be safely interpreted as *in situ* forms. Well-preserved planktonic forms occur higher in the section and include index species used for standard planktonic foraminiferal zonation (Robaszynski & Caron, 1995), allowing for the correlation of the studied strata with global reference sections. Ranges of the stratigraphically important foraminifera from the

Albian–Cenomanian interval at Annopol are presented in Figure 9.

Sample 13, taken from the middle part of unit 3, yielded the stratigraphically important planktonic foraminifera *Thalmaninella tehamensis*, *T. appenninica*, *T. globotruncanoides* and *T. gandolfi*. The global Boundary Stratotype Section and Point (GSSP) for the base of the Cenomanian Stage was defined (Gale *et al.* 1996; Kennedy *et al.* 2004) at Mont Risou, France, at the level of the first appearance of a

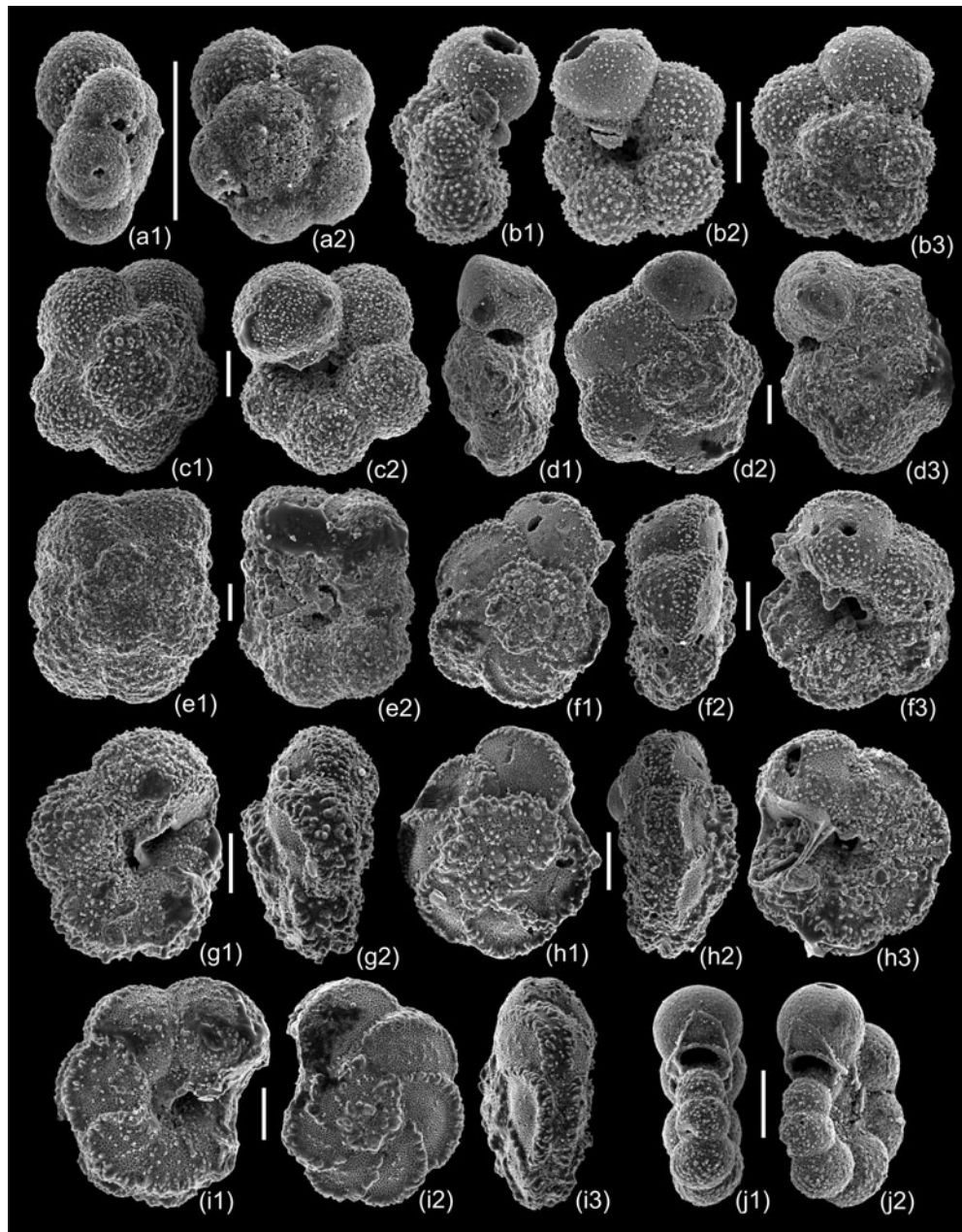


Figure 7. Planctonic foraminifera from the Annopol succession. (a1, a2) *Hedbergella infracretacea* (Glaessner), sample 7, MWGUW ZI/67/02.02. (b1–b3) *Hedbergella delrioensis* (Carsey), sample 13, MWGUW ZI/67/01.37. (c1, c2) *Whiteinella brittonensis* (Loeblich & Tappan), sample 23, MWGUW ZI/67/03.19. (d1–d3) *Whiteinella archaeocretacea* Pessagno, sample 23, MWGUW ZI/67/03.20. (e1, e2) *Whiteinella aprica* (Loeblich & Tappan), sample 23, MWGUW ZI/67/03.01. (f1–f3) *Dicarinella hagni* (Scheibnerova), sample 19, MWGUW ZI/67/03.27. (g1, g2) *Dicarinella* sp., sample 19, MWGUW ZI/67/03.28. (h1–h3) *Dicarinella imbricata* (Mornod), sample 23, MWGUW ZI/67/03.29. (i1–i3) *Dicarinella algeriana* (Caron), sample 23, MWGUW ZI/67/03.24. (j1, j2) *Globigerinelloides bentonensis* (Morrow), sample 9, MWGUW ZI/67/01.36. Scale bars = 100  $\mu$ m.

planktonic foraminifer *Thalmaninella globotruncanoids* (*T. brotzeni* is a synonym). This level is placed slightly lower than the lowest occurrence of *Mantelliceras mantelli*, the basal Cenomanian ammonoid marker (Kennedy *et al.* 2004). According to the current definition of the GSSP, the occurrence of *T. globotruncanoids* in unit 3 would indicate that at least part of this unit already represents the lower Cenomanian Substage (*Thalmaninella globotruncanoids* Zone; see Table 1). There are, however, some important reasons to believe that whole of unit 3 is still of late Albian age and

that the younger foraminifera were introduced here by burrowing animals, as suggested earlier by Walaszczyk (1987). Firstly, several burrows filled with Cenomanian marl identical to that of unit 4 are present in unit 3 and even in the upper part of unit 2 (sample 8, 12; Fig. 2c, d). Marly infills of these burrows yielded the *T. appenninica* and *T. globotruncanoides* and it is possible that these taxa have also been locally introduced by burrowers into the sediment which forms our sample 13, albeit in the latter case burrowers did not leave distinct tunnels. The chaotic and patchy distribution of

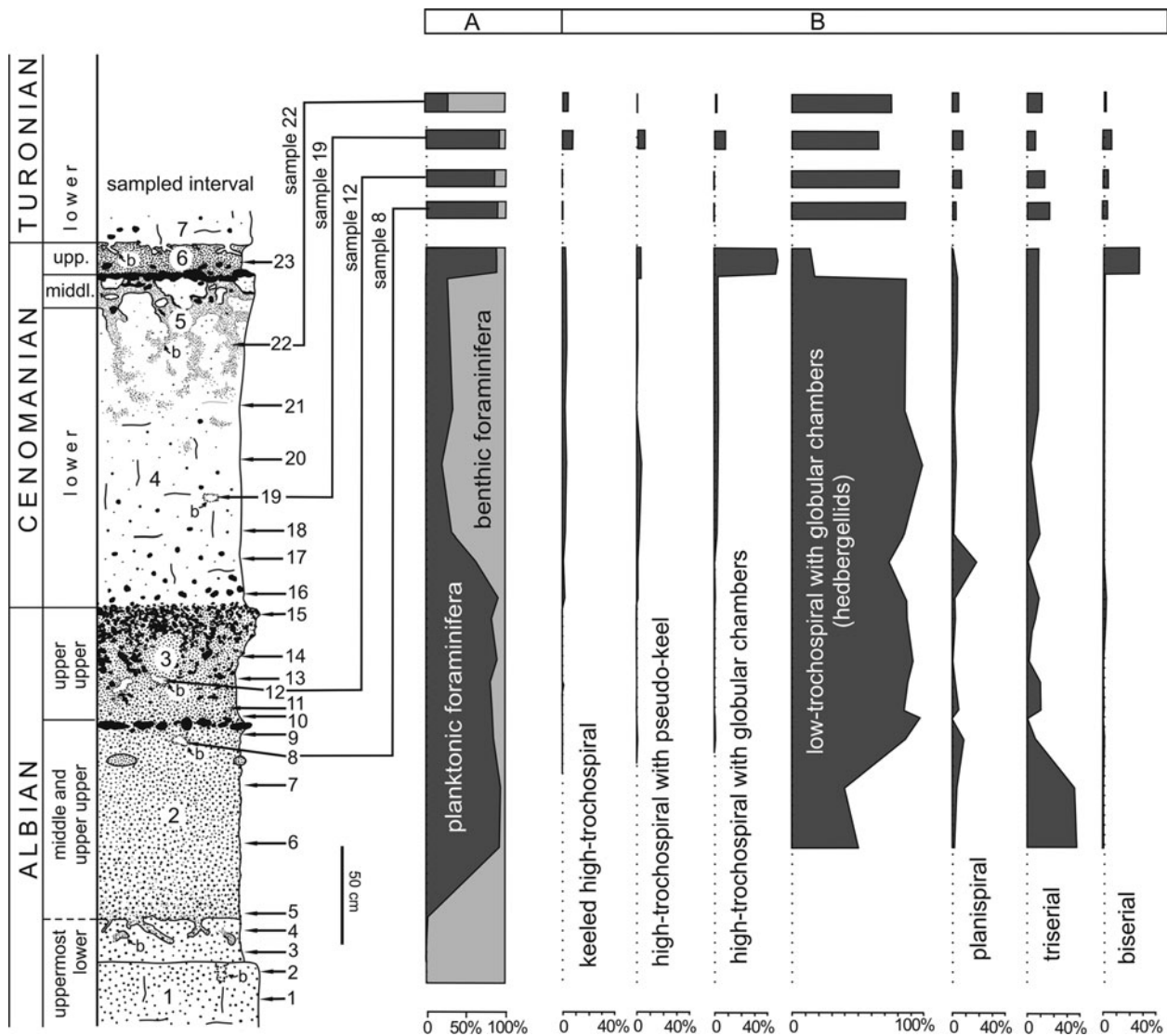


Figure 8. Changes in planktonic foraminiferal assemblages in the Albian–Cenomanian interval in the Annapol succession. A – relative abundances of planktonic and benthic foraminifera within foraminiferal assemblages; B – relative abundances of the seven morphotypes of planktonic foraminifera within planktonic foraminiferal assemblages.

phosphates does suggest strong bioturbation of that level (Fig. 2a, b). Moreover, there are no Cenomanian ammonites in unit 3; all the ammonites present indicate a late Albian age (Machalski & Kennedy, 2013).

Unit 4 yielded the biostratigraphically important *Praeglobotruncana stephani*, *Thalmaninella appenninica*, *T. globotruncanoides* which confirm the lower Cenomanian position of this unit as indicated by macrofossils (the *Thalmaninella globotruncanoides* Zone of Peryt, 1983a, b; see also Walaszczyk, 1987). The early Cenomanian age is supported by the occurrence of benthic foraminifer *Orithostella formosa* (*Orithostella jarzevae* is a synonym), regarded as a marker for the lower Cenomanian deposits in western Europe (Hart et al. 1989). The last appearance of *O. jarzevae* in southern England is recorded in the middle of the lower Cenomanian deposits within the *Mantelliceras saxbii* Subzone (Table 1). The disappearance of this taxon in the lower Cenomanian succession was also noted in western Ukraine (Z. Dubicka, unpubl. PhD thesis, Pol-

ish Academy of Sciences, 2012). At Annapol it occurs close to the top of unit 4 (Fig. 9), adding to our doubts about the presence of the *M. dixonii* Zone in that interval.

Marly fills of burrows in the lower part of unit 4 (sample 19), interpreted as remnants of a lost sedimentary unit, yield the following stratigraphically important planktonic species: *Praeglobotruncana gibba*, *P. stephani*, *Thalmaninella greenhornensis*, *Rotalipora cushmani*, *Whiteinella baltica* and *W. brittonensis*. Early dicarinelids without fully developed keel structures are also present. These are *Dicarinella algeriana*, *D. hagni*, *D. imbricata* and species of the benthic *Berthelina intermedia* group (*B. intermedia*, *B. baltica* and *B. cenomanica*). All these taxa indicate the lower part of the upper Cenomanian Substage, namely the upper part of *R. cushmani* Zone. Based on comparison with the foraminiferal assemblages recorded from the southern England (Paul et al. 1999), these infillings correspond to an upper Cenomanian interval ranging

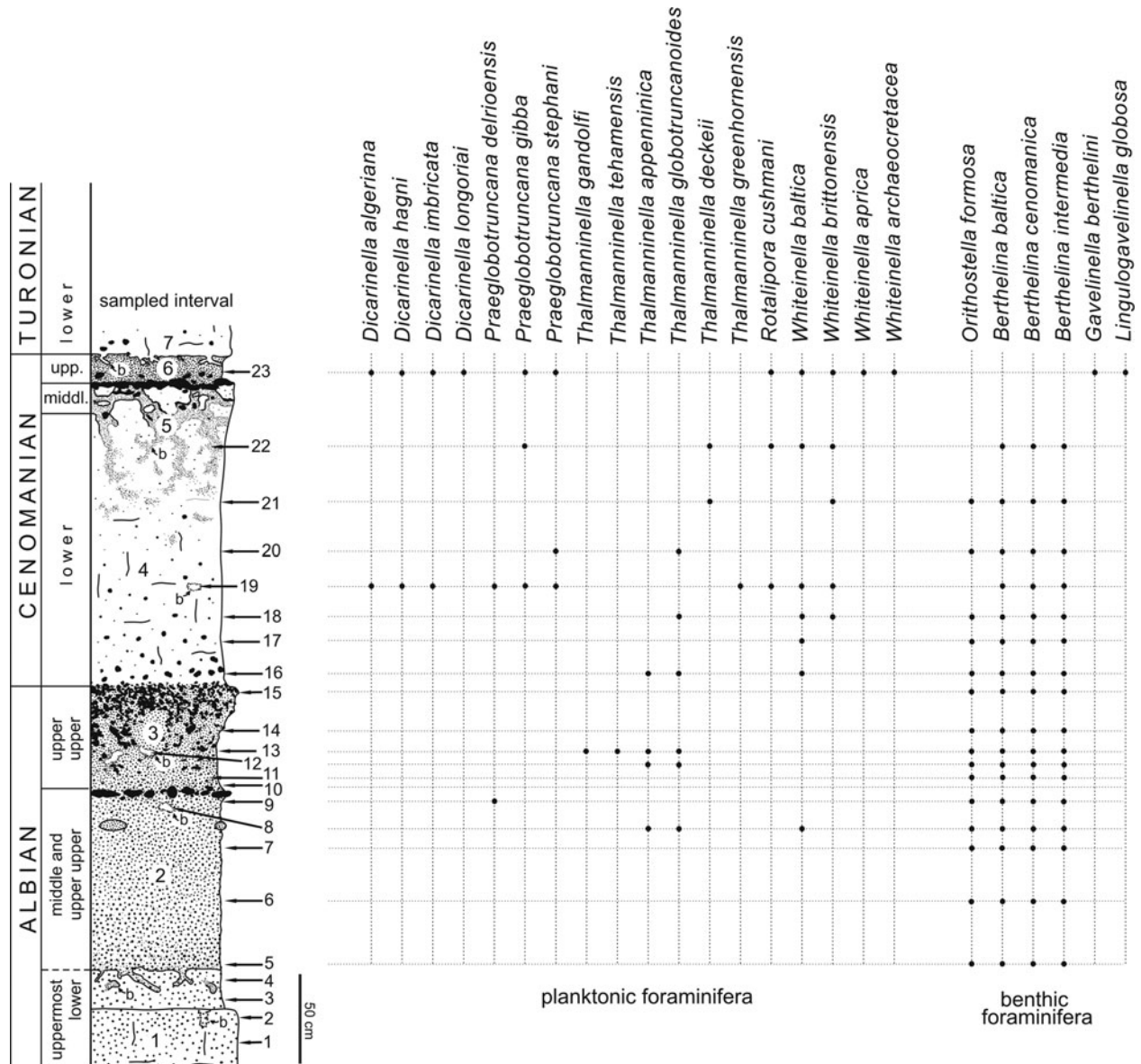


Figure 9. Stratigraphical distribution of selected planktonic and benthic foraminifera in the Annopol succession.

from the Grey Chalk Formation (*Calycoeceras guerangeri* Zone and the 'pre-excursion phase of  $\delta^{13}C'$ ) to the lowermost Plenus Marl (bed 1a) (*Metoicoceras geslinianum* Zone) of the global reference section for the Cenomanian–Turonian interval in Eastbourne, Sussex, SE England.

Unit 5 is characterized by the co-occurrence of *Praeglobotruncana gibba*, *Rotalipora cushmani* and *Thalmanninella deckeii* indicating the middle Cenomanian unit (Caron, 1985; Robaszynski *et al.* 1993), in concert with ammonite dating and the foraminiferal data presented by Marcinowski and Walaszczyk (1985) and Walaszczyk (1987). There is no evidence for the presence of the *Thalmanninella reicheli* Zone (Table 1) in the section, in agreement with Peryt (1983a, b). As the ammonites of the equivalent *Cunningtoniceras inerme* Zone (Table 1) are also missing, this suggests another significant gap in the succession.

Unit 6 yields important *Dicarinella* (*D. algeriana*, *D. hagni* and *D. imbricata*) and *Praeglobotruncana*

(*Praeglobotruncana gibba* and *P. stephani*), a single species of one-keeled forms (*Rotalipora cushmani*) as well as abundant large whiteinellids (*Whiteinella baltica*, *W. brittonensis*, *W. aprica* and *W. archaeocretacea*). Benthic foraminifera are characterized by the absence of the *Berthelina intermedia* group and by the occurrence of *Lingulogavelinella globosa* and *Gavelinella berthelini*. These taxa indicate the uppermost part of the *Rotalipora cushmani* Zone (Table 1) and correspond to the interval from bed 2 to bed 4 in the Plenus Marl (*Metoicoceras geslinianum* ammonite Zone) as exposed in the Eastbourne succession (Paul *et al.* 1999; Pearce, Jarvis & Tocher, 2009).

## 8. Palaeoenvironment

Foraminifera are very useful proxies for palaeoenvironmental studies, based on the correlation between their test shape, composition and environmental requirements (Corliss, 1985; Murray, 2006). Almost

the entire Annapol succession contains mineral-walled foraminifera, ascribed to the agglutinated and/or calcareous foraminifera. No foraminifera are recorded from sands representing the lower part of unit 1.

Mineral-walled foraminifera are characteristic of marine or brackish environments. Today, the transition from marine to freshwater environments is marked by an almost total disappearance of foraminifera, except for the organic-walled Allogromiida (Sen Gupta, 2002). Accordingly, the barren sands near the base of the Annapol mid-Cretaceous succession could even represent a non-marine environment.

The upper part of unit 1 contains mineral-walled foraminifera, which are represented exclusively by agglutinated taxa. Present-day benthic assemblages from very shallow, sandy-bottom environments are typified by an abundance of agglutinated taxa, which show a preference for sands and silts (Abou Ouf, 1992). For example, the foraminiferal assemblages collected at the depth interval 5–50 m off the sandy coast of the Sea of Japan are dominated by agglutinated *Ammobaculites*, *Eggerellina* and *Textularia* (Matoba, 1976). Likewise, the assemblages from the sandy facies off the Washington continental shelf are dominated by agglutinated *Eggerellina* and *Spiroplectammina* (Snyder, Hale & Kontrovitz, 1990). In recent nearshore environments, planktonic foraminifera may be entirely absent (Wang, Zhang & Min, 1985). Extremely shallow-marine conditions, probably a near-sandy-beach setting, are therefore postulated here for the interval discussed. This is supported by the presence of *Ophiomorpha* burrows in sandstones in the middle part of unit 1 (Fig. 1a). These burrows, produced by the calianassid shrimps, point to deposition of sands in an extremely shallow-marine, marginal environment (compare Radwański *et al.* 2012).

Planktonic as well as calcareous benthic foraminifera appear in the upper part of unit 2, indicating a sea-level rise. However, planktonic foraminifera are represented only by shallow-water dwellers: low-trochospiral hedbergellids, biserial heterohelicids and triserial guembelitrids (see Bé, 1977; Caron & Homewood, 1983; Leckie, 1987). The benthic foraminifera are characterized by a high proportion of agglutinated forms and small, thin-walled, low-diversity calcareous taxa. This still points to a very shallow shelf environment (a few dozen metres deep). A very high P/B ratio is measured for the samples from the upper part of unit 2 (samples 6, 7 and 9), which is usually characteristic of a much deeper shelf environment; however, these results are from a relatively low presence of benthic foraminifera. The successive increase in the relative abundance of calcareous benthic foraminifera through unit 2 suggests a slight, progressive sea-level rise.

In the uppermost part of unit 2 and unit 3 (the Phosphorite Bed of other authors), the most shallow-dwelling planktonic foraminifera (triserial *Guembelitria*) decrease in abundance in relation to the deeper *Hedbergella*. A decrease in the abundance of benthic agglutinated forms is also noted. These changes indic-

ate a transgressive pulse. The high diversity of benthic foraminifera suggests substantially higher food availability in comparison to the preceding units. A very high P/B ratio suggests a bloom of planktonic foraminifera, dominated by small, globular hedbergellids. The latter are interpreted as r-strategists, thriving in nutrient-rich waters (Premoli Silva & Sliter, 1999; Petrizzo, 2002). Walaszczyk (1987) interpreted the rise in frequency of hedbergellids as a result of high organic production in the surface waters. Accordingly, foraminiferal assemblages from the Phosphorite Bed, both planktonic and benthic, are interpreted here as the high productivity assemblages *sensu* Gooday (2003). These are characteristic of environments with a high and relatively continuous input of organic matter, supplied from intense primary production associated with upwelling, hydrographic fronts or major river discharges (Gooday, 2003). Summarizing, benthic and planktonic foraminifera suggest a high rate of primary production combined with sea-level rise for this part of the succession.

In units 4 and 5, deep-dwelling *Thalmanninella*, *Praeglobotruncana* and *Whiteinella* become common (their sporadic occurrence in the lower levels is ascribed to burrowing activity of macrobenthic organisms; see above). This change is most likely a consequence of a further transgressive pulse. However, these complex foraminifera are still infrequent. Additionally, a relatively low P/B ratio (20–30%) points to a moderate water depth (as for the Cretaceous epicontinental seas). Benthic foraminifera are here dominated by huge, calcareous, epifaunal forms (*Berthelina*), regarded as typical of oxic environments (Kaiho, 1994, 1999). The contribution of agglutinated and infaunal taxa is much smaller. Accordingly, these sediments were probably deposited in mesotrophic and well-oxygenated bottom water conditions with a moderate input of terrigenous material (see Jorissen, Stigter & Widmark, 1995).

Marly infillings of burrows in the lower part of unit 4 (sample 19) display a significant increase in the relative abundance of deep-dwelling planktonic foraminifera and a much higher P/B ratio (around 80%) in relation to the older units 4 and 5. These changes probably indicate that a pronounced sea-level rise occurred during the late part of the late Cenomanian Age (upper part of *R. cushmani* Zone).

Foraminiferal assemblages from unit 6 show a very high P/B ratio with abundant deep-dwelling forms, interpreted by Walaszczyk (1987) as a result of another, major transgressive pulse. This very high P/B ratio is additionally caused by the radical decrease in number and diversity of benthic foraminifera (Walaszczyk, 1987). Among the latter, the disappearance of the *Berthelina intermedia* group and appearance of a low-diversity assemblage dominated by *Gavelinella berthelini* and *Lingulogavelinella globosa* are observed. This foraminiferal crisis is linked with the Cenomanian–Turonian Boundary Event as recorded in southern England (Jarvis *et al.* 1988; Hart, Dodsworth & Duane, 1993; Paul *et al.* 1999), SE France (Tronchetti &

Grosheny, 1991), Poland (Leary & Peryt, 1991; Peryt & Wyrwicka, 1991, 1993; Peryt *et al.* 1994) and western Ukraine (Z. Dubicka, unpubl. PhD thesis, Polish Academy of Sciences, 2012).

The spreading of the oxygen-minimum bottom waters was commonly invoked as a major cause of extinction of Cenomanian benthic foraminifera (Jarvis *et al.* 1988; Peryt & Wyrwicka, 1991; Tronchetti & Grosheny, 1991; Hart, Dodsworth & Duane, 1993; Peryt *et al.* 1994). Based on the assumption that the oxygen-minimum zone occurred at the sea bottom during the Oceanic Anoxic Event 2 (OAE2), benthic species and morphotypes which survived this event were considered to be resistant to oxygen-depleted environments and even regarded as their potential indicators. However, Gale *et al.* (2000) argued that there is no evidence for the development of the oxygen-minimum bottom waters on the European shelf during the Cenomanian–Turonian transition.

According to Gale *et al.* (2000), a major latest Cenomanian sea-level rise resulted in the spread of oligotrophic, stratified oceanic water onto the shelves. Similarly, Pearce, Jarvis & Tocher (2009) argued that marine productivity collapsed during the latest Cenomanian Age, based on the dinoflagellate evidence. Our data from Annapol support these interpretations. The benthic foraminiferal assemblage from unit 6 is of low abundance and diversity, being dominated by *Lingulogavelinella globosa* and *Gavelinella berthelini*. These taxa possess huge (>300 µm), rounded, biconvex, low-trochospiral calcareous tests and are commonly regarded as epifaunal (Corliss & Chen, 1988; Nagy *et al.* 1995). According to Kaiho (1994, 1999), Jorissen, Stigter & Widmark (1995), van der Zwaan *et al.* (1999) and Dubicka & Peryt (2012), benthic foraminiferal assemblages of low abundance and diversity, dominated by calcareous epifaunal morphotypes, indicate a well-oxygenated oligotrophic environment on the seafloor.

## 9. Sea-level changes

Walaszczyk (1987, fig. 4) first published a bathymetric diagram for the Annapol succession, based on the foraminiferal assemblages. His graph reveals a deepening-upwards trend, punctuated by breaks corresponding to the sedimentary discontinuities. This author explained the facies development of the Annapol succession in terms of eustasy rather than local tectonic movements suggested earlier by Cieśliński (1976) and Marcinowski & Radwański (1983).

We support the general conclusions of Walaszczyk (1987) and concur with the eustatic interpretation of the succession (Fig. 10a, b). Proceeding one step further, we attempt here to assess how many of the global mid-Cretaceous sea-level changes can be seen at Annapol. We have chosen a classic graph of the Cretaceous sea-level changes for the British region (Hancock, 1990, fig. 11) for comparison with the bathymetric patterns which can be deduced from the Annapol succession.

The relevant interval of the British graph is reproduced here in Figure 10b (note that it preserves original zonation used by that author, which is different in some detail from that used here; see Table 1).

The British curve, thought to reflect a global eustatic pattern, is based on a simple concept of peaks of transgression and troughs of regression (Hancock, 1990, fig. 2; Hancock, 2004). The basic idea behind this concept is that levels of nodular chalks and hardgrounds (in the Chalk) and courses of the phosphatic nodules (in the Gault) define the regressive troughs, whereas the mid-points between these levels reflect transgressive peaks (Hancock, 1990). In practice, the situation is not so simple due to erosion which commonly removed much of the transgressive record during the subsequent regressive phases, particularly in marginal environments. At Annapol for example, only the lowermost parts of the successive units seem to be preserved due to severe erosion during successive sea-level drops. The reader is referred to Ernst *et al.* (1996, fig. 4) for a translation of Hancock's nomenclature into that of the standard sequence stratigraphy and to Haq (2014) for the most recent overview of the Cretaceous sequence stratigraphy and eustasy.

The lowest level at Annapol which can be confidently correlated with the British graph is a discontinuity between units 2 and 3 (marked D2/3 in Fig. 10a). The phosphatic layer at the top of unit 2 contains a mixture of ammonites indicating condensation of several Albian ammonite zones, ranging from *Hoplites dentatus* Zone to *Mortoniceras fallax* Zone (Table 1). The latter, being the youngest, dates the phosphatic layer (Kennedy & Machalski, 2015). Nodules yielding these ammonites are probably reworked from several originally separate levels, possibly reflecting several regressive troughs in the middle–lower upper Albian part of the British curve (Fig. 10b). The phosphatic bed at the top of unit 2 corresponds to a regressive trough at the base of the classic *Stoliczkaia dispar* Zone (Hancock, 1990, fig. 11; Fig. 10b). Reworked phosphatic lags at this position are widespread in Europe (Amédéo, 2002). In terms of sequence stratigraphy, the discontinuity between units 2 and 3 at Annapol (D2/3 in Fig. 10a) corresponds to sequence boundary KA17 of Haq (2014, figs 1, 2). Unit 3 contains late late Albian ammonites, indicative of the *M. perinflatum* Zone; it is therefore a level within the classic upper upper Albian *Stoliczkaia* (*Stoliczkaia* in current nomenclature) *dispar* Zone (Machalski & Kennedy, 2013). This is the *Vraconien sensu* Amédéo (2002). The foraminifera indicate a transgressive pulse and, indeed, equivalents of this unit occasionally overlap the Jurassic substrate in some localities close to the study area (Pożaryski, 1947). On the other hand, phosphates forming the upper part of unit 3 originated in regressive conditions during at least two phases of intraformational reworking or winnowing of fine matrix and concentration of the phosphatic material on the sea bottom (Machalski & Olszewska-Nejbert, 2016). This transgressive–regressive situation is compatible with a stillstand during most of the

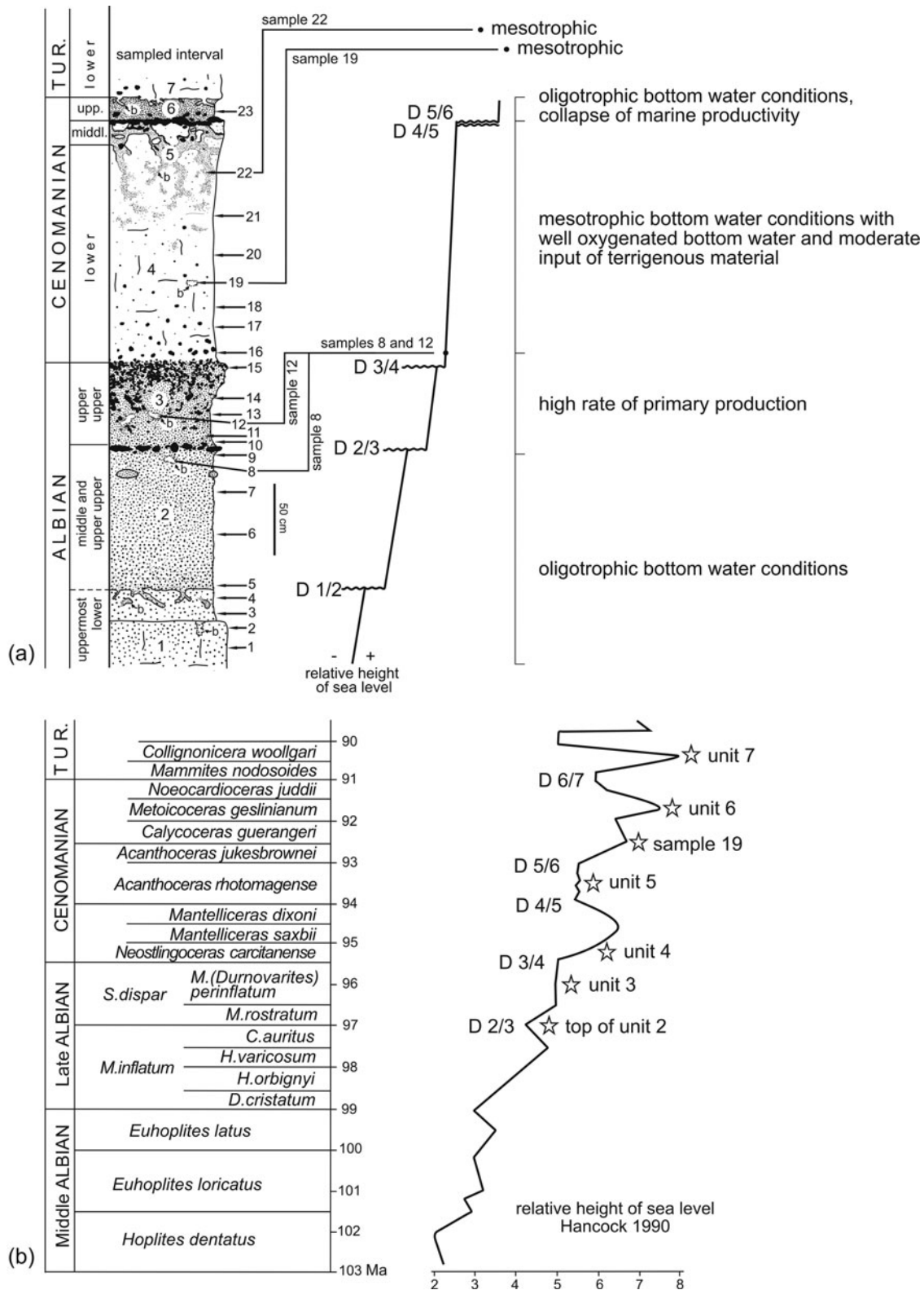


Figure 10. Interpretation of the Annapol succession in terms of sedimentary cycles, bathymetry and biological productivity. Inserted to the left is a fragment of the graph showing sea-level fluctuations for British region (taken from Hancock, 1990, fig. 11) with our correlation of the patterns seen at Annapol. TUR – Turonian; D – sedimentary discontinuities.

*Stoliczkaia dispar* Zone marked on the Hancock graph (Fig. 10b).

Another correlation point is discontinuity D3/4 (Fig. 10a). This is the most prominent stratigraphic boundary in the Annapol succession, separating the

Lower and Upper Cretaceous strata. No ammonites indicative of the uppermost Albian – lowermost Cenomanian *Praeschloenbachia briacensis* Zone are recorded here. The hiatus at the Albian–Cenomanian boundary therefore embraces this zone, a situation

analogous to condensed sections elsewhere (see Machalski & Kennedy, 2013). This gap would clearly correspond to the turning point between the stillstand phase for the *Stoliczkaia dispar* Zone and the beginning of the Cenomanian transgression, marked by Hancock (Fig. 10b). Discontinuity D3/4 at Annopol (Fig. 10a) may be correlated with sequence boundary KA18 of Haq (2014).

Unit 4 begins the Cenomanian sedimentation and is clearly transgressive, starting with a basal layer of phosphates and fossils (the *Neohibolites ultimus/Aucellina* Event of Ernst, Schmid & Seibertz, 1983; see also Wilmsen, 2003, 2013). This unit contains lower Cenomanian ammonites and foraminifera. We have doubts about the presence of the *Mantelliceras dixonii* Zone fossils at Annopol (see Section 7). The presence of an exclusively *M. mantelli* Zone benthic foraminifer near the top of unit 4 (see Section 7) suggests that only this ammonite zone of the lower Cenomanian Substage is present at Annopol. In any case, unit 4 matches well the ascending fragment of the early Cenomanian transgressive peak in the British graph (Fig. 10b).

The next tie-points at Annopol for their correlation with the British graph are two closely spaced discontinuities (D4/5 and D5/6 in Fig. 10a), coalescing into a prominent composite hardground discussed by Marcinowski & Walaszczyk (1985, fig. 2). A strongly reduced unit 5 is sandwiched between these discontinuities, being practically restricted to the burrow infillings in unit 4 (Fig. 10a). There is a mixture of *Turrilites costatus* and *T. acutus* phosphatised ammonites at this level (in addition to the lower Cenomanian forms, also in phosphate preservation) and the foraminifera point to the *Rotalipora cushmani* Zone. The *Cunningtoniceras inerme* and its equivalent *Thalmaninella reicheli* Zone as well as the *Acanthoceras jukesbrownei* Zone are missing. These missing zones define a minimal extent of gaps embracing unit 5, corresponding to surfaces D 4/5 and D5/6, respectively. These gaps seem to reflect the regressive troughs, whereas the whole unit 5 with its *remanié* phosphatic fossil assemblages corresponds, albeit in a highly residual form, to the whole middle Cenomanian eustatic low, as seen on the Hancock graph (Fig. 10b; see Hancock, 2004, fig. 2, for detailed presentation and dating of the mid-Cretaceous low).

The middle Cenomanian developments at Annopol are reminiscent of those in the marginal parts of the Anglo-Paris basin. The classic Rouen Fossil Bed replete with phosphatised ammonite moulds may serve here as a close analogue (Juignet & Kennedy, 1976; Hancock, 2004). Local discontinuities D4/5 and D5/6 at Annopol may be tentatively correlated with the Rouen No. 1 Hardground and Rouen No. 2. Hardground of the above-mentioned authors, respectively. According to Hancock (2004), these two hardgrounds correspond in turn to the *Primus* Event and the Mid-Cenomanian Event of Sussex and the Münsterland (note however that his event definitions do not entirely correspond to those of Ernst, Schmid & Seibertz,

1983 and Wilmsen, 2003, 2013). Also, a glauconite-stained 'Hg grün' in the Hannover area, for which Ernst, Schmid & Seibertz (1983) coined the term 'Mid-Cenomanian Event', seems to be a closely correlative horizon. All abovementioned levels in Normandy and Germany are associated with the acmes of the irregular echinoid *Holaster subglobosus*, as is seen at Annopol (see Section 3). In view of the foraminiferal-based correlation of unit 6 with an interval within the Plenus Marl (*Metoicoceras geslinianum* ammonite Zone) in Eastbourne succession, it seems also probable that an equivalent of the so-called Sub-Plenus Erosion Surface (e.g. Hancock, 1990) may also have merged into the topmost surface of the complex Annopol hardground. If the above correlations are correct, discontinuities D4/5 and D5/6 of the Annopol succession (Fig. 10a) may correspond to sequence boundaries KCe3 and KCe4 of Haq (2014, fig. 2), respectively (with a possibility that his KCe5 is superimposed on KCe4 at Annopol).

The next elements for correlation of the Annopol succession with the British graph are provided with sample 19, representing a lost early late Cenomanian unit and unit 6, dated for the later part of the late Cenomanian (see Section 7). Both these units yield deep-dwelling planktonic foraminifera and are regarded as residual records of the two last transgressive peaks on the Cenomanian portion of the British graph (Fig. 10b). The hardground between the Cenomanian unit 6 and the lower Turonian unit 7 at Annopol (D6/7 in Fig. 10a) may correspond to a regressive trough at the Cenomanian–Turonian boundary (sequence boundary KTu1 of Haq, 2014).

## 10. Concluding remarks

We have studied the foraminiferal assemblages from the Albian and Cenomanian interval of a condensed mid-Cretaceous succession at Annopol, Poland. The focus of our study was to provide a stratigraphic and palaeoenvironmental background for future studies of this important Fossil-Lagerstätte in Poland.

In agreement with Walaszczyk (1987), the foraminiferal record at Annopol turns out to be strongly influenced by burrowing animals. This influence is both negative and positive. A negative aspect is exemplified by the piping down of the younger foraminifera through burrows into older deposits, disturbing the stratigraphic order of the foraminiferal assemblages. The most important effect is seen in the Albian phosphorite horizon in the middle of the succession which contains the Cenomanian index planktonic foraminifera, most probably introduced here by the activity of burrowers. A positive effect over the foraminiferal record was recognized in another interval, namely in the lower part of the lower Cenomanian Substage. The foraminifera recovered from burrows there provide the sole piece of evidence of a lower upper Cenomanian unit missing from the succession.

Despite the abovementioned distortions, vertical changes in foraminiferal assemblages at Annopol



allowed for a relatively precise ‘reading’ of this succession in terms of bathymetry and biological productivity. An overall bathymetric trend for the Annopol succession is deepening upwards, reflecting a stepwise progress of the mid-Cretaceous transgression onto this part of Europe (Marcinowski & Radwański, 1983). Environments varied as far as the biologic productivity is concerned, the highest rate of primary production being deduced for the Albian phosphorite level.

In the last part of the paper (Section 9), we attempted to assess how much of the global mid-Cretaceous sea-level changes can be seen at a section such as that at Annopol. Based on the integration of the foraminiferal and ammonite data with sedimentological observations we compared the patterns deduced for the Annopol succession with the Albian–Cenomanian portion of the British sea-level curve constructed by Hancock (1990). We paid special attention to the sedimentary discontinuities and associated stratigraphic gaps, which may be successfully used for correlations in such marginal successions (the Hiatus stratigraphy or Lücken-stratigraphie of Ernst *et al.* 1996). Somewhat unexpectedly, we found that all major elements of the relevant portion of the British curve, that is, all transgressive peaks and regressive troughs or lows, are recorded in the Annopol succession, although in a residual form.

In summary, the present study has demonstrated that even extremely condensed marine deposits, such as those from the mid-Cretaceous deposits of Annopol, may provide a foraminiferal record of better quality, stratigraphic order and palaeoecologic resolution than conventionally anticipated.

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#### Declaration of interests.

There are no conflicts of interests.

#### Supplementary material

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#### References

- ABOU OUF, M. 1992. Foraminiferal distribution in recent sediments of Jizan Shelf, Red Sea, Saudi Arabia. *Journal of King Abdulaziz University (Marine Sciences)* **3**, 25–38.
- AMÉDRO, F. 2002. Plaidoyer pour un étage Vraconnien entre l’Albien sensu stricto et le Cénomaniien (système Crétacé). *Academie Royale de Belgique, Classe des Sciences* **4**, 1–128.
- BARDET, N., FISCHER, V. & MACHALSKI, M. 2016. Large predatory marine reptiles from the Albian–Cenomanian of Annopol, Poland. *Geological Magazine* **153**, 1–16.
- BÉ, A. W. H. 1977. An ecological, zoogeographic and taxonomic review of recent Planktonic Foraminifera. In *Oceanic Micropaleontology* (ed. A. T. S. Ramsey), pp. 1–100. London: Academic Press.
- CARON, M. 1985. Cretaceous planktic foraminifera. In *Plankton Stratigraphy* (eds H. M. Bolli, J. B. Saunders & K. P. Nielsen), pp. 17–86. Cambridge: Cambridge University Press.
- CARON, M., DALL’AGNOLO, S., ACCARIE, H., BARRERA, E., KAUFFMAN, E. G., AMÉDRO, F., & ROBASZYSKI, F. 2006. High-resolution stratigraphy of the Cenomanian/Turonian boundary interval at Pueblo (USA) and Wadi Bahloul (Tunisia): stable isotope and bio-events correlation. *Geobios* **39**, 171–200.
- CARON, M. & HOMEWOOD, P. 1983. Evolution of early planktonic foraminifers. *Marine Micropaleontology* **7**, 453–62.
- CARTER, D. J. & HART, M. B. 1977. Aspects of mid-Cretaceous stratigraphical micropaleontology. *Bulletin of the British Museum (Natural History), Geology* **29**, 1–135.
- CIEŚLIŃSKI, S. 1959. The Albian and Cenomanian in the northern periphery of the Holy Cross Mountains (stratigraphy based on cephalopods). *Prace Instytutu Geologicznego* **28**, 1–95 (in Polish, with English summary).
- CIEŚLIŃSKI, S. 1976. Development of the Danish–Polish Furrow in the Góry Świętokrzyskie Region in the Albian, Cenomanian and Lower Turonian. *Biuletyn Instytutu Geologicznego* **295**, 249–71 (in Polish, with English summary).
- CIEŚLIŃSKI, S. 1987. Albian and Cenomanian inoceramids in Poland and their stratigraphic significance. *Biuletyn Instytutu Geologicznego* **354**, 11–62 (in Polish, English summary).
- COCCIONI, R. & GALEOTTI, S. 1993. Orbitally induced cycles in benthonic foraminiferal morphogroups and trophic structures distribution patterns from the Late Albian “Amadeus Segment” (Central Italy). *Journal of Micropaleontology* **12**, 227–39.
- COCCIONI, R., GALEOTTI, S. & GRAVILI, M. 1995. Latest Albian–earliest Turonian deep-water agglutinated Foraminifera in the Bottaccione section Gubbio, Italy; biostratigraphic and palaeoecologic implications. *Revista Espanola de Paleontologia*, Volumen Homenaje al Dr. Guillermo Colom, 135–52.
- CORLISS, B. H. 1985. Microhabitats of benthic foraminifera within deep-sea sediments. *Nature* **314**, 435–8.
- CORLISS, B. H. & CHEN, C. 1988. Morphotype patterns of Norwegian Sea deep-sea benthic foraminifera and ecological implications. *Geology* **16**, 716–9.
- DALBY, A. P., PATTERSON, R. T. & HAGGART, J. W. 2009. Distribution of Albian–Cenomanian foraminifera from Queen Charlotte Islands, British Columbia, Canada. Constraints on the timing of the northward movement of the Wrangellia Terrane. *Journal of Foraminiferal Research* **39**, 231–45.
- DUBICKA, Z. & PERYT, D. 2012. Foraminifers and stable isotope record of the Dubivtsi chalk (upper Turonian, Western Ukraine): palaeoenvironmental implications. *Geological Quarterly* **56**, 199–214.
- EICHER, D. L. & WORSTELL, P. 1970. Cenomanian and Turonian foraminifera from the Great Plains, United States. *Micropaleontology* **16**, 269–324.

- ERNST, G., NIEBUHR, B., WIESE, F. & WILMSEN, M. 1996. Facies development, basin dynamics, event correlation and sedimentary cycles in the Upper Cretaceous of selected areas of Germany and Spain. In *Global and Regional Controls on Biogenic Sedimentation. II. Cretaceous Sedimentation* (eds J. Reitner, F. Neuweiler & F. Gunkel). *Research Reports. Göttinger Arbeiten zur Geologie und Paläontologie* **3**, 87–100.
- ERNST, G., SCHMID, F. & SEIBERTZ, E. 1983. Event-Stratigraphie im Cenoman und Turon von NW-Deutschland. *Zitteliana* **10**, 531–54.
- FRIEDRICH, O., ERBACHER, J. & MUTTERLOSE, J. 2006. Paleoenvironmental changes across the Cenomanian/Turonian boundary event (oceanic anoxic Event 2) as indicated by benthic foraminifera from the Demerara Rise (ODP Leg 207). *Revue de Micropaléontologie* **49**, 121–39.
- GALE, A. S., KENNEDY, W. J., BURNETT, J. A., CARON, M. & KIDD, B. E. 1996. The late Albian to Early Cenomanian succession at Mont Risou near Rosans (Drome, SE France): an integrated study (ammonites, inoceramids, planktonic foraminifera, nannofossils, oxygen and carbon isotopes). *Cretaceous Research* **17**, 515–606.
- GALE, A. S., SMITH, A. B., MONKS, N. E. A., YOUNG, J. A., HOWARD, A., WRAY, D. S. & HUGGETT, J. M. 2000. Marine biodiversity through the Late Cenomanian–Early Turonian: palaeoceanographic controls and sequence stratigraphic biases. *Journal of the Geological Society of London* **157**, 745–57.
- GAWOR-BIEDOWA, E. 1972. The Albian, Cenomanian and Turonian foraminifers of Poland and their stratigraphic importance. *Acta Palaeontologica Polonica* **17**, 3–174.
- GEBHARDT, H., WOLFGANG, K. & HOLBOURN, A. 2004. Foraminiferal response to sea level change, organic flux and oxygen deficiency in the Cenomanian of the Tarfaya Basin, southern Morocco. *Marine Micropaleontology* **53**, 133–57.
- GOODAY, A. J. 2003. Benthic foraminifera (Protista) as tools in deep-water paleoceanography: environmental influences on faunal characteristics. *Advances in Marine Biology* **46**, 3–90.
- HANCOCK, J. M. 1990. Sea-level-changes in the British region during the Late Cretaceous. *Proceedings of the Geologists' Association* **100** (for 1989), 565–94.
- HANCOCK, J. 2004. The mid-Cenomanian eustatic low. *Acta Geologica Polonica* **54**, 611–27.
- HAQ, B. U. 2014. Cretaceous eustasy revisited. *Global and Planetary Change* **113**, 44–58.
- HART, M. B., BAILEY, H. W., CRITTENDEN, S., FLETCHER, B. N., PRICE, R. J. & ŚWIECICKI, A. 1989. Cretaceous. In *Stratigraphical Atlas of Fossils Foraminifera* (eds D. G. Jenkins & J. W. Murray), pp. 273–371. Chichester: Ellis Horwood Limited.
- HART, M. B., DODSWORTH, P. & DUANE, A. M. 1993. The late Cenomanian Event in eastern England. *Cretaceous Research* **14**, 495–508.
- JARVIS, I., CARSON, G. A., COOPER, M. K. E., HART, M. B., LEARY, P. N., TOCHER, B. A., HORNE, D. & ROSENFELD, A. 1988. Microfossil assemblages and the Cenomanian-Turonian (Late Cretaceous) oceanic anoxic event. *Cretaceous Research* **9**, 3–103.
- JORISSEN, F. J., STIGTER, H. C. & WIDMARK, J. G. W. 1995. A conceptual model explaining benthic foraminiferal microhabitats. *Marine Micropaleontology* **26**, 3–15.
- JUIGNET, P. 1980. Transgressions-régressions, variations eustatiques et influences tectoniques de l'Aptien au Maastrichtien dans le Bassin de Paris occidental et sur la bordure du Massif Armoricaïn. *Cretaceous Research* **1**, 341–57.
- JUIGNET, P. & KENNEDY, W. J. 1976. Faunes d'ammonites et biostratigraphie comparée du Cenomanian du nord-ouest de la France (Normandie) et du sud de l'Angleterre. *Bulletin Trimestriel de la Société Géologique de Normandie et des Amis du Muséum du Havre* **63**, 1–193.
- KAIHO, K. 1994. Benthic foraminiferal dissolved-oxygen index and dissolved-oxygen levels in the modern ocean. *Geology* **22**, 719–22.
- KAIHO, K. 1999. Effect of organic flux and dissolved oxygen on the benthic foraminiferal index (BFIO). *Marine Micropaleontology* **37**, 67–76.
- KAPUŚCINSKA, A. & MACHALSKI, M. 2015. Upper Albian chelonioid turtles from Poland. *Geobios* **48**, 385–95.
- KELLER, G., HAN, Q., ADATTE, T. & BURNS, S. J. 2001. Palaeoenvironment of the Cenomanian-Turonian transition at Eastbourne, England. *Cretaceous Research* **22**, 391–422.
- KENNEDY, W. J. 2013. On variation in *Schloenbachia varians* (J. Sowerby, 1817) from the Lower Cenomanian of western Kazakhstan. *Acta Geologica Polonica* **63**, 443–68.
- KENNEDY, W. J. & GALE, A. S. 2006. The Cenomanian Stage. *Proceedings of the Geologists' Association* **117**, 187–205.
- KENNEDY, W. J., GALE, A. S., LEES, J. A. & CARON, M. 2004. The Global Boundary Stratotype Section and Point (GSSP) for the base of Cenomanian Stage, Mont Risou, Hautes-Alpes, France. *Episodes* **27**, 21–32.
- KENNEDY, W. J. & MACHALSKI, M. 2015. A late Albian ammonite assemblage from the mid-Cretaceous succession at Annapol, Poland. *Acta Geologica Polonica* **65**(4). doi: [10.1515/agp-2015-0021](https://doi.org/10.1515/agp-2015-0021).
- KOCHHANN, K. G. D., KOUTSOUKOS, E. A. M. & FAUTH, G. 2014. Aptian–Albian benthic foraminifera from DSDP Site 364 (offshore Angola): a paleoenvironmental and paleobiogeographic appraisal. *Cretaceous Research* **48**, 1–11.
- KOUTSOUKOS, E. A. M. & HART, M. B. 1990. Cretaceous foraminiferal morphogroup distribution patterns, paleocommunities and trophic structures: a case study from the Sergipe Basin, Brazil. *Transactions of the Royal Society of Edinburgh, Earth Sciences* **81**, 221–46.
- KUHNT, W., LUDERER, F., NEDERBRAGT, S., THUROW, J. & WAGNER, T. 2005. Orbital-scale record of the late Cenomanian-Turonian oceanic anoxic event (OAE-2) in the Tarfaya Basin (Morocco). *International Journal of Earth Sciences* **94**, 147–59.
- LEARY, P. N. & PERYT, D. 1991. The late Cenomanian oceanic anoxic event in the western Anglo-Paris Basin and southeast Poland; survival strategies of and recolonisation by benthic foraminifera. *Historical Biology* **5**, 321–38.
- LECKIE, R. M. 1987. Paleocology of mid-Cretaceous planktonic foraminifera: a comparison of open ocean and epicontinental sea assemblages. *Micropaleontology* **33**, 164–76.
- MACHALSKI, M. & KENNEDY, W. J. 2013. Oyster-bioimmured ammonites from the Upper Albian of Annapol, Poland: stratigraphic and palaeobiogeographic implications. *Acta Geologica Polonica* **63**, 545–54.
- MACHALSKI, M., KOMOROWSKI, A. & HARASIMIUK, M. 2009. Nowe perspektywy poszukiwań morskich kręgowców kredowych w nieczynnej kopalni fosforytów w Annapolu nad Wisłą. *Przegląd Geologiczny* **57**, 638–41.

- MACHALSKI, M. & MARTILL, D. M. 2013. First pterosaur remains from the Cretaceous of Poland. *Annales Societatis Geologorum Poloniae* **83**, 99–104.
- MACHALSKI, M. & OLSZEWSKA-NEJBERT, D. 2016. A new mode of ammonite preservation – implications for dating of condensed phosphorite deposits. *Lethaia* **49**, 61–72.
- MARCINOWSKI, R. 1980. Cenomanian ammonites from German Democratic Republic, Poland, and the Soviet Union. *Acta Geologica Polonica* **30**, 215–325.
- MARCINOWSKI, R. & RADWAŃSKI, A. 1983. The mid-Cretaceous transgression onto the Central Polish Uplands (marginal part of the Central European Basin). *Zitteliana* **10**, 65–96.
- MARCINOWSKI, R. & RADWAŃSKI, A. 1989. A biostratigraphic approach to the mid-Cretaceous transgressive sequence of the central Polish Uplands. *Cretaceous Research* **10**, 153–72.
- MARCINOWSKI, R. & WALASZCZYK, I. 1985. Middle Cretaceous deposits and biostratigraphy of the Annapol section, Central Polish Uplands. *Österreichische Akademie der Wissenschaft, Schriftenreihe der Erdwissenschaftlichen Kommissionen* **7**, 27–41.
- MARCINOWSKI, R. & WIEDMANN, J. 1985. The Albian ammonite fauna of Poland and its palaeogeographical significance. *Acta Geologica Polonica* **35**, 199–219.
- MARCINOWSKI, R. & WIEDMANN, J. 1990. The Albian ammonites of Poland. *Palaeontologia Polonica* **50**, 1–94.
- MATOBA, Y. 1976. Foraminifera from off Noshiro, Japan, and postmortem destruction of tests in the Japan Sea. In *Progress in Micropaleontology: Selected Papers in Honor of Prof. Kiyoshi Asano* (eds Y. Takayanagi & T. Saito), pp. 169–89. New York: Micropaleontological Press, Special Publications.
- MURRAY, J. W. 2006. *Ecology and Applications of Benthic Foraminifera*. Cambridge: Cambridge University Press, 426 pp.
- NAGY, J., GRADSTEIN, F. M., KAMINSKI, M. A. & HOLBOURN, A. 1995. Foraminiferal morphogroups, paleoenvironments and new taxa from Jurassic and Cretaceous strata of Thakkola, Nepal. *Grzybowski Foundation Special Publications* **3**, 181–209.
- OGG, J. G. & HINNOV, L. A. 2012. *Cretaceous*. In *The Geologic Time Scale* (eds F. M. Gradstein, J. G. Ogg, M. D. Schmitz & G. M. Ogg), pp. 793–853. Amsterdam: Elsevier.
- PAUL, C. R. C., LAMOLDA, M. A., MITCHELL, S. F., VAZIRI, M. R., GOROSTIDI, A. & MARSHALL, J. D. 1999. The Cenomanian–Turonian boundary at Eastbourne (Sussex, UK): a proposed European reference section. *Palaeogeography Palaeoclimatology Palaeoecology* **150**, 83–121.
- PEARCE, M. A., JARVIS, I. & TOCHER, B. A. 2009. The Cenomanian – Turonian boundary event, OAE2 and paleoenvironmental change in epicontinental seas: new insights from the dinocyst record. *Palaeogeography Palaeoclimatology Palaeoecology* **280**, 207–34.
- PERYT, D. 1983a. Mid-Cretaceous microbiostratigraphy and foraminifers of the NE margins of the Świętokrzyskie (Holy Cross) Mts., Poland. *Acta Palaeontologica Polonica* **28**(3–4), 417–66.
- PERYT, D. 1983b. Planktonic foraminiferal zonation of Mid-Cretaceous of the Annapol Anticline (Central Poland). *Zitteliana* **10**, 575–83.
- PERYT, D. & WYRWICKA, K. 1991. The Cenomanian–Turonian Anoxic Event in SE Poland. *Cretaceous Research* **12**, 65–80.
- PERYT, D. & WYRWICKA, K. 1993. The Cenomanian/Turonian boundary event in Central Poland. *Palaeogeography Palaeoclimatology Palaeoecology* **104**, 185–97.
- PERYT, D., WYRWICKA, K., ORTH, C., ATTREP, M. & QUINTANA, L. 1994. Foraminiferal changes and geochemical profiles across the Cenomanian/Turonian boundary in central and southeast Poland. *Terra Nova* **6**, 158–65.
- PETRIZZO, M. R. 2002. Palaeoceanographic and palaeoclimatic inferences from Late Cretaceous planktonic foraminiferal assemblages from the Exmouth Plateau (ODP Sites 762 and 763, eastern Indian Ocean). *Marine Micropaleontology* **45**, 117–50.
- POPOV, E. V. & MACHALSKI, M. 2014. Late Albian chimaeroid fishes (Holocephali, Chimaeroidei) from Annapol, Poland. *Cretaceous Research* **47**, 1–18.
- POŻARYSKI, W. 1947. A phosphate deposit of the north-eastern margin of the Holy Cross Mountains. *Biuletyn Państwowego Instytutu Geologicznego* **27**, 1–56 (in Polish, English summary).
- PREMOLI SILVA, I. & SLITER, W. V. 1999. Cretaceous paleoceanography: evidence from planktonic foraminiferal evolution. In *Evolution of the Cretaceous Ocean–Climate System* (eds E. Barrera & C. C. Johnson), pp. 301–28. Geological Society of America, Special Paper no. 332.
- PRICE, R. J. 1977. Evolutionary interpretation of the Foraminiferida *Arenobulimina*, *Gavelinella*, and *Hedbergella* in the Albian of northern-west Europe. *Palaeontology* **20**, 503–27.
- RADWAŃSKI, A., WYSOCKA, A. & GÓRKA, A. 2012. Miocene burrows of the ghost crab *Ocypode* and their environmental significance (Mykolaiv Sands, Fore-Carpathian Basin, Ukraine). *Acta Geologica Polonica* **62**, 217–29.
- REMIN, Z., DUBICKA, Z., KOZŁOWSKA, A. & KUCHTA, B. 2012. A new method of rock disintegration and foraminiferal extraction with the use of liquid nitrogen [LN 2]. Do conventional methods lead to biased paleoecological and paleoenvironmental interpretations? *Marine Micropaleontology* **86–87**, 11–14.
- ROBASZYŃSKI, F. & CARON, M. (eds) 1979. *Atlas of Mid Cretaceous Planktonic Foraminifera (Boreal Sea & Tethys)*, Part 1–2. Éditions du Centre National de la Recherche Scientifique, Paris, European Working Group on Planktonic Foraminifera, Cahiers de Micropaléontologie.
- ROBASZYŃSKI, F. & CARON, M. 1995. Foraminifères planctoniques du Crétacé: commentaire de la zonation Europe – Méditerranée. *Bulletin de la Société Géologique de France* **166**, 681–92.
- ROBASZYŃSKI, F., CARON, M., AMEDRO, F., DUPUIS, C., HARDENBOL, J., GONZALES DONOSO, J. M., LINARES, D. & GARTNER, S. 1993. Le Cénomanien de la région de Kalaat Senan (Tunise centrale): Litho-biostratigraphie et interprétation séquentielle. *Revue de Paléobiologie* **12**, 351–505.
- ROBASZYŃSKI, F., GALE, A., JUIGNET, P., AMEDRO, F. & HARDENBOL, J. 1998. Sequence stratigraphy in the Upper Cretaceous series of the Anglo-Paris Basin: exemplified by the Cenomanian stage. In *Mesozoic and Cenozoic Sequence Stratigraphy of European Basins* (eds P. de Graciansky, J. Hardenbol, T. Jaquin & P. R. Vail), pp. 363–85. SEPM, Special Publication no. 60.
- SAMSONOWICZ, J. 1925. Esquisse géologique des environs de Rachów sur la Vistule et les transgressions de l'Albien et du Cénomanien dans les sillons nord-européen. *Spra-*

- wozdana Państwowego Instytutu Geologicznego 3, 45–118 (in Polish, French summary).
- SAMSONOWICZ, J. 1934. Explication de la feuille Opatów (zone 45, colonne 33). Service Géologique de Pologne, Warszawa, Carte Géologique Générale de la Pologne au 100.000-e, 1–97.
- SEN GUPTA, B. K. 2002. *Modern Foraminifera*. Dordrecht: Kluwer Academic Publishers, 371 pp.
- SIGAL, J. 1977. Essai de zonation du Cretace mediterraneen l'aide des foraminifres planctoniques. *Géologie Méditerranéenne* 4, 99–108.
- SNYDER, W. S., HALE, R. H. & KONTROVITZ, M. 1990. Distributional patterns of modern benthic foraminifera on the Washington continental shelf. *Micropaleontology* 36, 245–58.
- TRONCHETTI, G. & GROSHENY, D. 1991. Les assemblages de Foraminifères benthiques au passage Cénomanien-Turonien à Vergons, S-E France. *Geobios* 24, 13–31.
- VAN DER ZWAAN, G.J., DUIJNSTEE, I.A.P., DEN DULK, M., ERNST, S.R., JANNINK, N.T. & KOUWENHOVEN, T.J. 1999. Benthic foraminifers: proxies or problems? A review of paleoecological concepts. *Earth Science Reviews* 46, 213–36.
- WALASZCZYK, I. 1987. Mid-Cretaceous events at the marginal part of the Central European Basin (Annopol-on-Vistula section, Central Poland). *Acta Geologica Polonica* 37, 61–74.
- WANG, C. S., HU, X. M., JANSA, L., WAN, X. Q. & TAO, R. 2001. The Cenomanian-Turonian anoxic event in southern Tibet. *Cretaceous Research* 22, 481–90.
- WANG, P., ZHANG, J. & MIN, Q. 1985. Distribution of foraminifera in surface sediments of the East China Sea. In *Marine Micropaleontology of China* (ed P. Wang), pp. 34–69. China Ocean Press, Beijing.
- WILMSEN, M. 2003. Sequence stratigraphy and palaeoceanography of the Cenomanian Stage in northern Germany. *Cretaceous Research* 24, 525–68.
- WILMSEN, M. 2013. Origin and significance of Late Cretaceous bioevents: examples from Cenomanian. *Acta Palaeontologica Polonica* 57, 759–71.