

## Fossils from the Silesian-Subsilesian series of the Polish Western Carpathians: the implications for changes in sea level and the marine environment during the Albian–Turonian

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Foraminifera and calcareous nannoplankton, as well as other fossils from the Albian-Turonian deposits of the Western Polish Carpathians, are discussed in relation to changes in depositional environments, which were controlled by geotectonic activity, sea level changes, and anoxic and biotic events. The distribution and diversity of fossils in the deposits studied have been related to global sea level fluctuations or local sea level rise and fall. During the Albian to the Early Cenomanian, and in the Turonian, the local sea level falls led to an increased supply of coarse-grained material rich in siliceous and sometimes calcareous fossils and rock material. This cyclic process has contributed to changes in the marine biota. In the Albian, monospecific foraminiferal assemblages with a surficial infauna which colonized bottom waters after periods of organic influx and oxygen deficiency (OAE1b), evolved into more variable associations including deep infauna which indicate more aerobic conditions. Under these conditions planktonic and calcareous benthic fossils (tintinnids, calcareous nannoplankton, and foraminifera) were also preserved. Their presence was associated with the supply of terrigenous material from shallow-water environments and land, which were eroded during regressions controlled by local tectonic activity. During the Albian-Turonian transition, intense subsidence and volcanic activity associated with a relative sea level rise led to increased productivity of phytoplankton in the area studied. The sea-surface productivity and enhanced upwelling resulted in expanded short-term oxygen minima at the end of the Albian (OAE1d) and the Cenomanian (OAE2). In the latter interval benthic forms became almost extinct while siliceous and calcareous plankton survived. In the Turonian, changes in sea level and sedimentary regime led to re-colonization of the basin bottom.

Key words: Cretaceous, fossils, environments, sea level, Polish Carpathians.

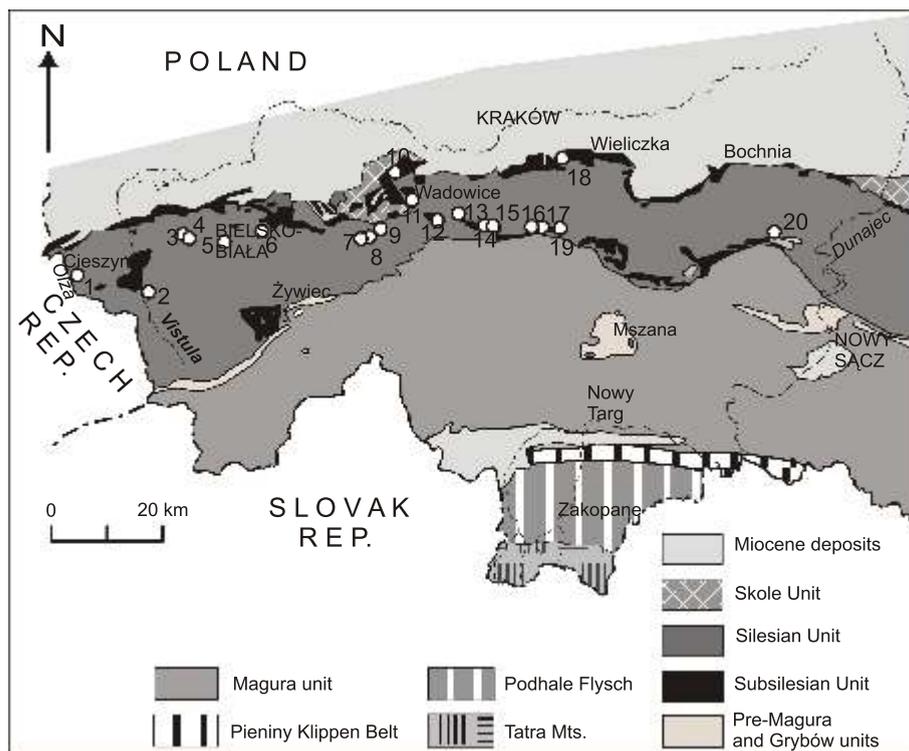
### INTRODUCTION

Collision between the African and European-Asiatic plates led to important changes in global palaeogeography during the mid-Cretaceous (e.g., [Erbacher and Thurow, 1997](#); [Hay et al., 1999](#); [Golonka et al., 2000](#); [Stampfli et al., 2001](#); [Stampfli and Borel, 2002](#); [Cavazza and Wezel, 2003](#)). At that time, the Tethys Ocean was closing and volcanic activity was unusually high. It was responsible for changes in ocean circulation, sea level, the carbon cycle, and sea-surface productivity or preservation conditions ([Bralower and Thierstein, 1984](#); [Haq et al., 1988](#); [Vogt, 1989](#); [Calvert and Pederson, 1992](#); [Erbacher et al., 1999, 2001](#); [Golonka and Krobicki, 2001](#); [Herrle et al., 2003](#)). All these external factors were responsible for the greenhouse conditions in the mid-Cretaceous. At that time massive deposition of organic matter in marine environments resulted in the formation of organic-rich deposits (black shales) ([Schlanger](#)

[and Jenkyns, 1976](#); [Arthur et al., 1990](#)). The widespread distribution of black shales has been regarded as reflecting Oceanic Anoxic Events (OAEs) ([Schlanger and Jenkyns, 1976](#)). Its impact on biotic evolution in the ocean was dependent on how relative sea level coincided with the nutrient supply. The flooding of neighbouring lands and the input of nutrients during a relative rise of sea level led to increased productivity and expansion of the oxygen minima. Under these dysaerobic conditions, deep-dwelling forms became extinct. Shallower dwelling radiolarians and planktonic foraminifera survived ([Leckie, 1987](#); [Erbacher et al., 1999](#); [Robaszyński et al., 2010](#)). The determination of the oxygen minima has been correlated with the uplift of lands and relative sea level falls, corresponding with a decreased nutrient supply, which led to the development of new deep habitats and to the radiation of deep-dwelling forms ([Erbacher and Thurow, 1997](#); [Erbacher et al., 1999](#)).

The above-mentioned model allows for the correlation of micropalaeontological data and different types of organic-rich shale, which reflect the OAEs and sea level fluctuations in the marine environment. It was used to explain the expansion of the oxygen minimum zone (OMZ), which caused the extinction and radiation of foraminifera and radiolarians in the mid-Cretaceous and the Cenomanian-Turonian transition in the North Atlantic and the western Tethys ([Erbacher and Thurow, 1997](#); [Erbacher](#)

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**Fig. 1. Location of outcrops studied in the context of the tectonic units of the Polish Outer Carpathians (modified from [ytko et al., 1989](#))**

1 – Cisownica-3, 2 – Ustro , 3 – Jasienica, 4 – Jaworze, 5 – Lipnik, 6 – Kozy, 7 – Bol cin, 8 – Rzyki, 9 – Kaczyna, 10 – Wo niki, 11 – Klecza, 12 – Barwałd Górny, 13 – Bugaj, 14 – Brody, 15 – Lanckorona, 16 – Bysina, 17 – Barnasiówka, 18 – Lusina, 19 – My lenice, 20 – Rajbrot

[et al., 1999](#)). An attempt to apply this model to reconstructions of the environmental and sea level fluctuations during the Albian–Turonian in the Western Outer Carpathian Basin has been proposed. The northern part of this area included marginal seas, which were especially sensitive to geotectonic instability and changes in sea level during the mid-Cretaceous ([Birkenmajer and Gasi ski, 1992](#); [I czka et al., 1999](#)). In the Subsilesian and Silesian sub-basins the dynamic and rapid deposition of siliciclastic sediments alternated with hemipelagic and pelagic sedimentation of organic-rich shales, which partly correspond to anoxic facies.

The formation of organic-rich siliciclastic deposits, which contain numerous and variable mineralised skeletal parts or components, and also crushed fragments of skeletons belonging to microfossils (foraminifers, radiolarians, sponges, dinocysts), macrofossils (bivalves, belemnites, ammonites) and nanofossils (calcareous nannoplankton), has been analysed in relation to changes in the marine environment, supplies of clastic material, and organic matter in the basin.

## GEOLOGICAL AND BIOSTRATIGRAPHICAL SETTINGS

Rock material was sampled from the Albian–Turonian deposits, including coarse-grained sandstone successions intercalated with shales or separate formations of dark green radiolarian and variegated shales, which occur in the Silesian–Subsilesian zone of the Western Outer Carpathians in Poland.

The deposits described are accessible in profiles located in the Beskid I ski: Cisownica-3, Ustro , Jaworze, Jasienica; the Beskid Mały: Lipnik, Kozy, Bol cin, Rzyki, Kaczyna, Buldonówka; Lanckorona Foothills: Lusina, Wo niki, Klecza, Bugaj, Brody, Barwałd Górny, Lanckorona; the Beskid redni: Bysina, Barnasiówka, Jasienica near My lenice, and also the Beskid Wyspawy: Rajbrot. With the exception of the Wo niki, Barwałd Górny, Lusina, Jasienica near My lenice, and Rajbrot sections that contain the Subsilesian Series, in the exposures listed only deposits of the Silesian Unit occur ([Fig. 1](#)).

In the area studied, located between the Olza and the Dunajec rivers, the deposits sampled belong to the Albian–Turonian Lgota and Gaize beds, the Turonian–lowermost Turonian green radiolarian shales, and the Turonian Godula Beds and variegated marly shales ([I czka et al., 1993](#); [B k et al., 2001](#); [Fig. 2](#)). The so-called Lgota Beds include three lithostratigraphical units. There are coarse-grained sandstones of Early Albian age containing carbonate and magmatic rocks, spicule-rich sandstones intercalated with dark, non-calcareous shales of the Middle–Late Albian age, and spongiolites of Late Albian–Turonian age ([Koszarski and Nowak, 1960](#); [Bieda et al., 1963](#); [Geroch et al., 1967](#)). The lower and uppermost parts of the Lgota Beds occur only in the western part of the study area. Sandstone series intercalated with shales, that are typical of the middle and partly upper part of this lithostratigraphical unit, are exposed in the remaining areas. The Lgota Beds are replaced locally by the Gaize Beds, consisting of sponge spicules in the northern and sporadically in the eastern uplifted parts of the Silesian Basin, which formed as the Subsilesian sub-basin in Cenomanian–Turonian time ([Bieda et al., 1963](#); [Geroch et al.,](#)



ammonites and belemnites) had been reported earlier (Koszarowski et al., 1959; Koszarski and Nowak, 1960).

The oldest foraminiferal assemblage that is dominated by numerous specimens of *Recurvoides pseudononioninoides* Neagu (= *Haplophragmoides* aff. *nonioninoides* sensu Geroch, 1966; Neagu and Platon, 1994) is widely distributed in the lower and middle part of the Lgota Beds of the Silesian and the Subsilesian units (comp. with Geroch, 1966; Szydło, 2008; Figs. 3 and 4). The mass occurrence of this taxon is known from the underlying Verovice Beds and corresponds with the agglutinated foraminiferal zone of *Hpl. nonioninoides*, dated to the Early Albian age (Geroch and Nowak, 1984; Olszewska, 1997; Fig. 2). According to Szydło (2008), the rare taxa belonging to genera *Jaculella*, *Hyperammia*, *Ammodiscus*, *Glomospira*, *Saccammia*, *Caudammia*, *Haplophragmoides*, *Thalmanammia*, *Trochammia*, *Gaudryina*, and *Pseudobolivina* are locally accompanied by the index species in the lower part of the Lgota Beds (Cisownica-3, Jaworze, Lipnik, Kozy; Fig. 3).

In these successions few and poorly preserved radiolarians belonging mainly to the genera *Nasellaria*, *Dictyomitra*, *Stichocapsa*, *Stichocampe*, and sometimes *Spumellaria*, *Cenellipsis*, and *Cenosphaera* are also present (Geroch, 1966; Górka and Geroch, 1989). In these deposits macrofauna also occurs. This is represented by forms belonging to *Inoceramus*, single ammonites referable to *Acanthoplites bigoureti* (Early Albian), and also numerous belemnite rostrae, which are correlated with the mass occurrence zone of *Neohibolites minimus* (Middle Albian; Figs. 3 and 4). In the western part of the Polish Outer Carpathians, this macrofauna is known from the Straconka and Lipnik localities in Beskid Mały (Koszarski and Nowak, 1960; Szymakowska, 1980).

This macrofauna suggests that the lower part of the Lgota Beds was mainly deposited in the Early Albian and partly also in the Middle Albian. At the time, tintinnids (*Colomiella recta*, *C. semiloricata*; Fig. 5A, B) and calcareous dinocysts (*Colomispheera heliosphaera*; Fig. 5C, see Appendix 1\*) locally occur in marls (Jasienica near Mylenice, Subsilesian Unit; Olszewska, 1997; Fig. 4). These deposits were regarded as the Jasienica marls that locally persisted into the latest Turonian (Liszkowa, 1972).

In places, the assemblage with *R. pseudononioninoides* survived until the end of the succession in low frequency (Jaworze, Rzyki, Bysina, Barnasiówka localities; Figs. 3 and 4). In the middle and upper parts of the Lgota Beds, this assemblage is usually replaced by the Late Albian association composed of the species *P. alternans* and *R. imperfectus* and *G. filiformis* (see Appendix 1) in the Lipnik and Kaczyna localities (Fig. 3). The assemblage described also contains numerous specimens of the genera *Plectrorecurvoides* and *Thalmanammia* (Lipnik, Bolcin; Fig. 3). This microfauna corresponds to the *P. alternans* Zone, which is correlated with the Middle Albian–Cenomanian by Geroch and Nowak (1984), or the Late Albian by Olszewska (1997) (Fig. 2). In the latter cases, the upper part of the zone was marked by the first occurrence (FO) of *Bulbobaculites problematicus* towards the end of the Early Cretaceous (Figs. 3 and 4). In Beskid Mały and in the Lanckorona Foothills the Lgota Beds contain arenaceous microfauna, which are represented by the species *Haplophragmoides falcatosuturalis* (Lipnik, Lanckorona – Geroch, 1966; borehole Łodygowice IG-1 – Geroch and Nowak, 1980) and *Arenobulimina chapmani* (Kozy, Fig. 3; Brody, Fig. 4). These Albian forms may still be present in the Cenomanian. Single specimens of calcareous foraminifera of the genera *Lenticulina* and *Pseudonodosaria* locally co-occur with them (Jaworze–Jasienica area and Kozy; Fig. 3).

In the upper part of the Lgota Beds, siliceous microfauna is replaced by calcareous foraminifera, including planktonic and benthic forms. The first simple inflated forms belong to *Hedbergella delrioensis*, *H. infracretacea* and *Heterohelix moremani* (Lipnik, Bolcin, Barnasiówka; Fig. 3) and others are represented by the genus *Rotalipora* (Klecza Dolna, Fig. 4, see Appendix 1). The benthic forms include *Osangularia* (*O. brotzeni*, *O. schloenbachi*), *Lenticulina*, *Gyroidinoides*, *Discorbis*, *Cibicides* (*Cisownica-3*, Lipnik, Bysina, Figs. 3 and 4; cf. with Geroch, 1966). The calcareous foraminifer tests are often small and poorly preserved, showing traces of dissolution and corrosion.

Numerous spicules of sponges and very rare radiolarians (*Spumellaria*) occur next to foraminifera in the deposits discussed. Radiolarians and calcareous foraminifera are preserved usually as moulds composed of pyrite (Geroch, 1966; Bk, 2000).

Additionally, organic-walled dinocysts occur in the Lgota Beds. According to Gedl (2003) these forms, occurring above thick-bedded sandstones, correspond to the *Palaeohystrichophora infusorioides* Zone of Late Albian age and they are correlated with the Albian–Turonian transition (*Epelidophaeridia spinosa* Zone) in the upper part of the Lgota Beds (Gedl, 2003). Generally, palynofacies occurring in the lower part of the Lgota Beds are dominated by forms belonging to *Pterodinium* and by diversified endocysts belonging to the genera *Ovoidinium*, *Odontichitina*, *Muderongia*, *Apteodinium*, *Canningia*, *Cyrculodinium*, *Pseudoceratinium*, and also peridinioids (Lipnik; Gedl, 2001, 2003). Peridinioids also dominate in the upper part of the Lgota Beds. Along with the dominant *Palaeohystrichophora infusorioides* there co-occur numerous black organic objects (phytoclasts) (Lipnik, Rzyki, Barnasiówka; Gedl, 2003). At the top of this succession blooms of *Pseudoceratinium*, *Subtilisphaera*, and *Ovoidinium* are noted (Lipnik, Kozy, Rzyki).

In spicule-rich deposits, which are assigned to the Gaize Beds, the number and diversity of the foraminifera distinctly decrease. The microfauna is represented by calcareous benthic foraminifera of the Albian–Turonian (*Berthelina intermedia*, *B. berthelini*, *Gyroidinoides infracretaceus*, *Valvulinera loetterlei*, *Patellina subcretacea*). Part of them is poorly preserved. These forms belong to the genera *Lagena* and *Cibicides* (Klecza-Babica and Woyniki localities; Fig. 4) or *Guttulina* and *Planularia* (Barwałd; Fig. 4). Planktonic foraminifera belonging to *Rotalipora* co-exist with them (cf. Liszkowa, 1956; Huss, 1957). In these biosiliceous rocks, calcareous nannoplankton have been reported. In the vicinity of Barwałd Górny (Fig. 4), reworked Jurassic species occur (*Watznaueria barnesae*, *Polypodorhabdus escaigii*, *Ellipsogelosphaera britannica*, *Zeugrhabdus erectus*, *Cretarhabdus conicus*, *Stephanolithion atmetos*, *C. crenulatus*, *Lotharingius hauffii*, *Crepidolithus granulatus*, and specimens of *Manivitella pemmatiodea*; Fig. 6, see Appendix 1) known from the Hauterivian; in addition, calcareous benthic foraminifera belonging to the genera *Guttulina*, *Planularia*, and *Lenticulina* are described. Moreover, calcareous nannoplankton including long-lived forms (*Vagalapilla matalosa*, *Watznaueria barnesae*, *Glaukolithus diplogrammus*), and those from the Barremian (*Gl. compactus*) and the Albian–Turonian (*Prediscosphaera columnata*) are reported from Woyniki (Figs. 4 and 6, see Appendix 1). The assemblages described correspond to intervals CC8 and the CC9. In the same sample, agglutinated foraminifera belonging to *B. problematicus*, the FO of which is located in the highest Albian, were found.

In silicified variegated shales and marls, as opposed to spongiolites, there occur not only radiolarians and sponge spicules but also planktonic forms. The dominant component of

\* Supplementary data associated with this article can be found, in the online version, at doi: 10.7306/gq.1206



composition	STUDIED PROFILES FOSSIL MATERIAL	Silesian Unit						Subsilesian Unit						
		Lgota Beds						Variegated shales and marls			Gaize Beds			
		Klecza Dln.-Babica	Bugaj	Brody	Lanckorona	Bysina	Barnasiówka	Klecza - Babica	Lanckorona	Jasienica n. Myślenice	Rajbrot	Woźniki	Lusina	Barwałd Grn.
agglutinated	<i>R. indivisa</i>													
	<i>J. depressa</i>													
	<i>H. gaultina</i>													
	<i>S. placenta</i>													
	<i>A. cretaceus</i>													
	<i>A. tenuissimus</i>													
	<i>G. irregularis</i>													
	<i>G. gaultina</i>													
	<i>K. grzybowski</i>													
	<i>C. ovulum</i>													
	<i>C. silesica</i>													
	<i>Reophax</i> sp.													
	<i>P. troyeri</i>													
	<i>H. kirki</i>													
	<i>R. pseudononioninoides</i>	→ Albian	→ Albian	→ Albian				→ Albian	→ Albian					
	<i>H. walteri</i>													
	<i>R. imperfectus</i>													
	<i>R. godulensis</i>	Cenom.-Turon						Cenom.-Turon	Cenom.-Turon					
	<i>R. variabilis</i>	Cenom.-Turon						Cenom.-Turon	Cenom.-Turon					
	<i>B. problematicus</i>													
	<i>T. neocomiensis</i>	→ Cenoman	→ Cenoman	→ Cenoman				→ Cenoman						
	<i>Ps. variabilis</i>		→ Albian											
	<i>P. alternans</i>													
	<i>P. irregularis</i>													
	<i>T. vocontiana</i>		→ Albian											
	<i>G. filiformis</i>													
	<i>G. oblonga</i>													
	<i>G. tailleuri</i>	Alb.-Turon												
	<i>F. moesiana</i>													
	<i>U. jankoi</i>													
	<i>G. lenis</i>													
	<i>A. chapmani</i>													
	<i>V. lotterlei</i>													
	<i>G. infracretaceus</i>	→ Cenomanian						→ Cenomanian						
	<i>C. aptiensis</i>	→ Albian												
	<i>B. intermedia</i>	→ Albian												
	<i>O. brotzeni</i>													
	<i>P. subcretacea</i>													
	<i>Lagena</i> sp.													
	<i>Cibicides</i> sp.													
<i>Planularia</i> sp.														
<i>Guttulina</i> sp.														
<i>Lenticulina</i> sp.														
<i>H. delrioensis</i>														
<i>H. infracretacea</i>														
<i>H. moremani</i>														
<i>Rotalipora</i>	Cenomanian													
<i>G. cenomana</i>														
calcareous nannoplankton														
tininnids														
calcareous dinocysts														
radiolarians														
sponge spicules														

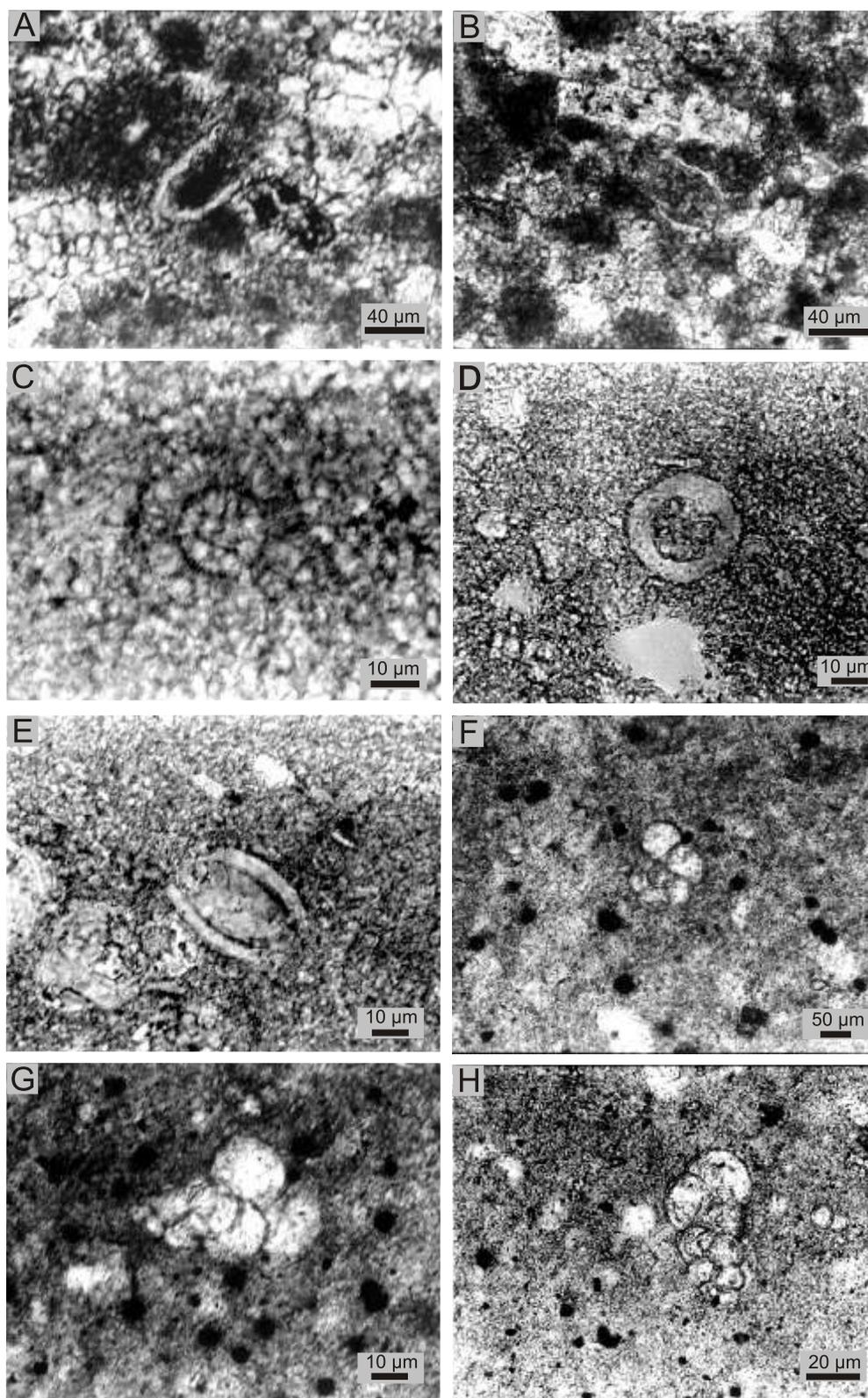
Fig. 4. The distribution and variability of fossil material from the profiles studied of the Subsilesian Unit

Data compiled by the authors of this study, including their own results and the results on radiolarians and dinocysts published by B k (2000) and Gedl (2001, 2003) respectively; for other explanations see Figure 3

planktonic associations is made of spherical skeletons of radiolarians belonging to the genera *Holocryptocanium* and *Hemicryptocapsa* (B k, 2000), as well as smaller conical forms of *Dictyomitra*, which appear rarely in the Lgota Beds of the Silesian Unit (cf. Geroch, 1966; Górka and Geroch, 1989). These forms, belonging to the *Nassellaria* and the *Spumellaria* (*Praeconocaryomma*, *Patellula*), occurred in the Late Cenomanian–Early Turonian (B k, 2000). In Albian–Cenomanian time, dinocysts and planktonic foraminifers co-existed with them. The first are calcareous forms belonging to the species *Orthopithonella sphaerica* and *O. ovalis* (Fig. 5D, E; Rajbrot, Subsilesian Unit; Olszewska, 1997), and organic-walled taxa (Silesian Unit; B k et al., 2000). Foraminiferal plankton, which

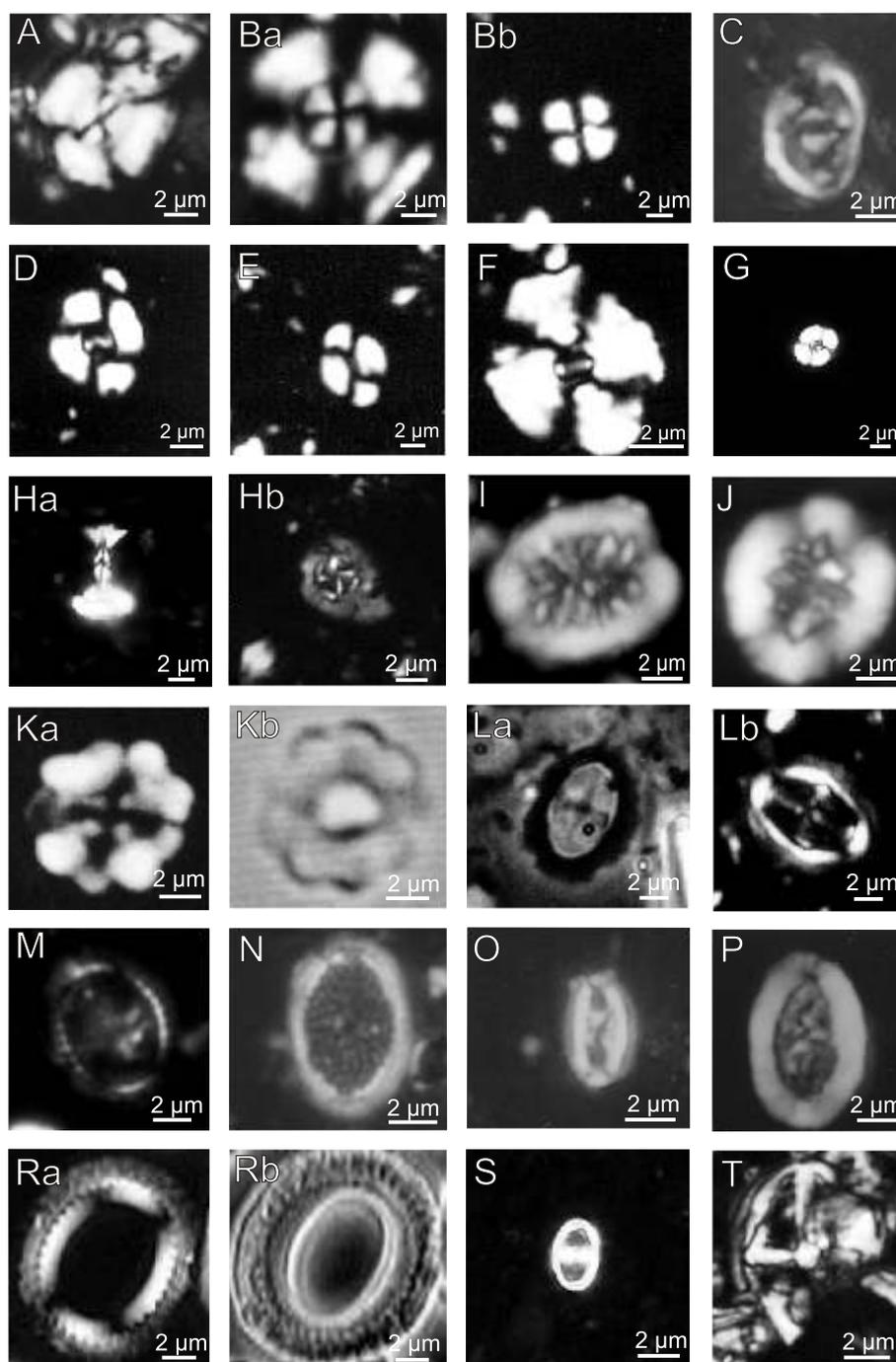
are represented by forms typical of the Cenomanian (*Schackoinea*, *Rotalipora*) and the Cenomanian–Early Turonian (*Praeglobotruncana stephani*), were described in green shales of the Subsilesian Unit occurring between and under radiolarites in W główka (Huss, 1957) and Tuchów, Targanice, and Czaniec Górny (Koszarski et al., 1959) respectively. In the green shales, which include radiolarites, planktonic forms belonging to the genera *Hedbergella*, *Guembeltria*, *Heterohelix* (Fig. 5F–H) were also noted at Rajbrot (cf. Olszewska, 1997).

In the Cenomanian variegated shales of the Silesian Unit, in which siliceous foraminifers are often lacking (Kaczyna; Fig. 3) planktonic foraminifers belonging to the genera *Hedbergella* and *Heterohelix* occur in low numbers (Barnasiówka; Fig. 4). In



**Fig. 5. Calcareous plankton including tintinnids, dinocyst and foraminifers**

Tintinnids: **A** – *Colomiella recta* Bonet, **B** – *C. semiloricata* Trejo (A, B – Jasienica n. Myślenice; Subsilesian Unit); calcareous dinocysts: **C** – *Colomisphaera heliosphaera* (Vogler), Jasienica n. Myślenice (Subsilesian Unit); **D** – *Orthopithonella sphaerica* (Kaufman); **E** – *O. ovalis* (Kaufman) (D, E – Rajbrot; Subsilesian Unit); foraminifers: **F** – *Hedbergella delrioensis* Carsey, **G** – *Guembelitra cenomana* Keller; **H** – *Heterohelix moremani* (Cushman) (F–H – Rajbrot; Subsilesian Unit)



**Fig. 6. Calcareous nannoplankton**

**A** – *Watznaueria barnesae* (Barwałd Górny, Gaize Beds, Subsilesian Unit); **Ba**, **Bb** – *Cyclagelosphaera margerelii* (Buldonówka, Godula Beds, Silesian Unit); **C** – *Glaukolithus compactus* (Wo niki, Gaize Beds, Subsilesian Unit); **D** – *Ellipsagelosphaera lucasii*; **E** – *E. fossacincta*; **F** – *E. britannica*; **G** – *Lotharingius hauffii* (D–G – Barwałd Górny, Gaize Beds, Subsilesian Unit); **Ha**, **Hb** – *Prediscosphaera columnata* (Wo niki, Gaize Beds, Subsilesian Unit); **I** – *Cretarhabdus crenulatus* (Barwałd Górny, Gaize Beds, Subsilesian Unit); **J** – *Cr. conicus*; **Ka**, **Kb** – *Ephrolithus floralis* (J, K – Buldonówka, Godula Beds, Silesian Unit); **La**, **Lb** – *Vagalapilla* sp. (Wo niki, Gaize Beds, Subsilesian Unit); **M** – *Polypodorhabdus escaigii* (Barwałd Górny, Gaize Beds, Subsilesian Unit); **N** – *Ethmorhabdus gallicus* (Buldonówka, Godula Beds, Silesian Unit); **O** – *Stephanolithion atmetos*; **P** – *Crepidolithus granulatus*; **Ra**, **Rb** – *Manivitella pemmatoidea*; **S** – *Zeugrhabdotus erectus* (O–S – Barwałd Górny, Gaize Beds, Subsilesian Unit); **T** – *Vagalapilla matalosa* (Wo niki, Gaize Beds, Subsilesian Unit) (see [Appendix 1](#))

calcareous shales of the same age, agglutinated forms (*Recurvoide sgodulensis*, *R. variabilis*, *Thalmannammina neocomiensis*, *Uvigerinammina praejankoi* or *Bulbobaculites problematicus* – see Appendix 1; Kaczyna, Klecza Dolna) co-exist with single specimens of *Rotalipora* (Rzyki; Figs. 3 and 4). Apart from these, *Falsogaudyrynella moesiana* occurs very rarely (Lanckorona; Fig. 4). Its occurrence determines the age of the variegated shales as being of the earliest Cenomanian.

In the Turonian, these facies were replaced locally by thick-bedded and coarse-grained sandstones, which are typical of the bottom of the Godula Beds (Słomka, 1995). In this part of the succession, macrofauna, including poorly preserved and crushed shells of ammonites and bivalves of the genus *Inoceramus*, occurs locally (Koszarski et al., 1959). In other areas, variegated shales, which occur as intercalations in the glauconitic sandstones, contain rare foraminifers. Single specimens of the planktonic *Marginotruncana coronata*, the FO of which corresponds to the Late Turonian, appear in the Outer Carpathian region (Buldonówka; Fig. 3). In the same sample, mixed and reworked calcareous nannoplankton belonging to the species *W. barnesae*, *E. gallicus*, *Cyclagelosphaera margerelii*, *Cretarhabdus conicus* and *E. floralis* are present (Fig. 6, see Appendix 1). The last form corresponds to the Aptian-Santonian interval (cf. Caron, 1985). In places, the Turonian Godula sandstones are intercalated with variegated shales containing agglutinated foraminifers: *N. excelsa*, *C. ovulum*, *G. lenis* and *U. jankoi* (Fig. 4, see Appendix 1; cf. Geroch et al., 1967).

#### CHANGES IN THE DEPOSITIONAL ENVIRONMENTS

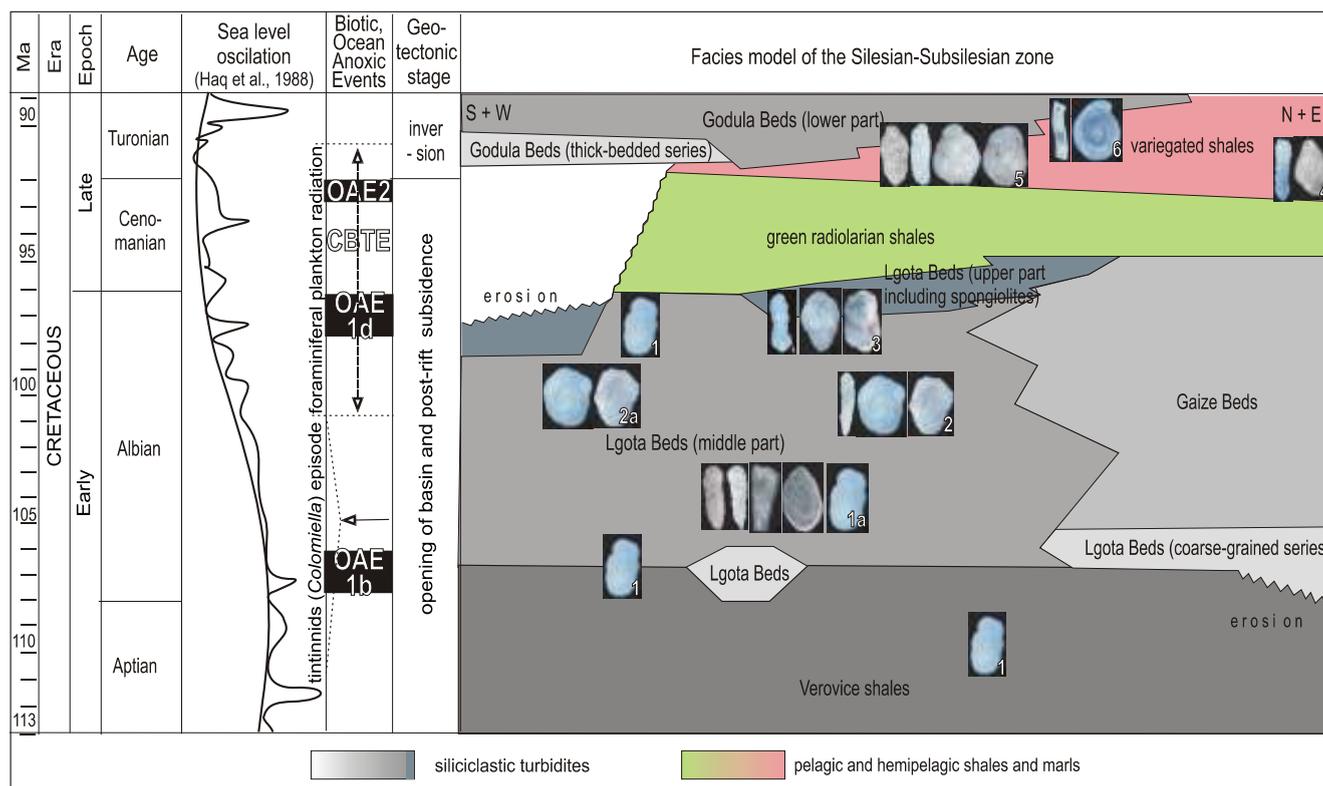
In the Silesian-Subsilesian zone of the Outer Carpathian Basin, biosiliciclastic sedimentation prevailed during the Albian–Turonian. This sedimentary process was clearly related to geotectonic and volcanic activities, which resulted in relative sea level fluctuations and anoxic or biotic events (Ksi kiewicz, 1961, 1975; Gucwa and Wieser, 1980; Olszewska, 1984; Gucwa, 1990; B k et al., 2001, 2005; Olszewska and Malata, 2006; B k, 2007; Szydło, 2008; Olszewska and Szydło, 2012). The availability of oxygen and organic matter content in depositional environments was also controlled by these settings. All these factors had strong influence on the evolution and distribution of biotopes and on fossilisation in the deposits. The fossils, especially calcareous forms, are generally poorly preserved in the deposits studied, and are strongly affected by diagenetic processes. Calcareous fossils include benthic and planktonic foraminifers, as well as nannoplankton, calcareous dinocysts, and the shells of bivalves and ammonites. Calcareous fossils similar to belemnites, siliceous skeletal elements of radiolarians and sponges and also organic dinocysts were reworked and mixed many times before they finally accumulated in the deposits. Calcareous or siliceous skeletons of benthic forms originated in shallow water environments, which were destroyed during the uplift of areas and the sea level falling, especially in the Early Albian and the Early Turonian, and locally in the Late Albian. The occurrence of the organic-walled dinocysts, which are characteristic of low salinity (*Ovoidinium*, *Odontichitina*, *Muderongia*) and terrestrial (peridinioids) environments, coincided with these events during the Albian. These organic-walled cysts had thin and delicate shells devoid of complex appendages (Gedl, 2003). Probably tintinnids belonging to *Colomiella* as index fossils for

the Late Aptian–Early Albian (Longoria, 1973) co-existed with them (Jasienica near My lenice, Subsilesian Unit; Olszewska, 1997; Figs. 3–5 and 7).

This bioclastic material was transported periodically by turbidity currents on slopes. In the initial stages of the process the coarse-grained sandstones of the Lgota, the Gaize, and the Godula beds accumulated. These deposits include the broken and crushed skeletons of benthic (bivalves) and nektonic (belemnites and ammonites) macrofauna, and also crystalline (magmatic, metamorphic) or carbonate blocks characterized by a low degree of weathering (Wieser, 1948; Koszarski and Nowak, 1960; Szymakowska, 1980). In addition, the almost monospecific assemblages of macrofauna contained belemnites, which show evidence of wave action (Lipnik; Koszarski and Nowak, 1960).

The formation of these deposits was related to sudden brief transport of sediments downslope over a short distance (Lee et al., 2007; Szydło, 2011). Calcareous bioclastic material was locally supplied. Individual planktonic forms, accompanied by rare benthic forms, were transported in long-distance suspension currents during the Albian–Turonian transition. In the upper part of the Lgota Beds containing spongiolites (Albian–Turonian), agglutinated microfauna were occasionally replaced by calcareous foraminiferal associations, which consist of opportunistic planktonic (*Hedbergella*, *Heterohelix*) or benthic forms represented by the genera *Osangularia*, *Lenticulina*, *Gyroidinoides*, *Discorbis*, *Cibicides*, and *Dentalina* (Geroch, 1966; B k et al., 2005; Szydło, 2008). These calcareous forms inhabited the near-shore environments, and part of them existed under anaerobic conditions (Bernhard, 1986; Koutsoukos et al., 1990); they are usually preserved as moulds composed of pyrite (Geroch, 1966; B k, 2000). Similar calcareous benthic foraminifers and mostly reworked calcareous nannoplankton, and also planktonic foraminifera and tintinnids, appeared periodically during the deposition of the Gaize Beds in the Albian–Turonian transition and of the Godula Beds in the Early Turonian (Figs. 3, 4 and 7). Massive corroded tests of deep-dwelling planktonic forms (*Rotalipora*) sensitive to environmental changes (Gaize Beds; Liszkowa, 1956) or better preserved, epifaunal benthic forms belong mainly to active deposit feeders (*Berthelina*, *Gyroidinoides*, *Valvulineria*, *Patellina*, *Cibicides*) that are observed in the studied samples of these biosiliceous deposits (Figs. 3 and 4). Benthic foraminifera and calcareous nannoplankton were noted in hemipelagic deposits forming sandstone intercalations, while planktonic foraminifera and tintinnids appeared in hemipelagic and pelagic deposits, which formed as independent lithostratigraphic units. Their relationship was related to short- or long-lasting periods of low tectonic activity and minor eustatic changes, respectively.

During the supply of coarse-grained turbidities into the basin, deep-water circulation was reactivated, the upwelling increased, and the nutrient supplies were more frequent and intense. These factors had an impact on the spread on diverse agglutinated assemblages. In the Albian, assemblages included mainly shallow and surficial epifauna (*Plectrorecurvodes*, *Recurvodes*, *Thalmannammina*) accompanied by a few deep infaunal forms such as *Gaudryina*, *Bulbobaculites*, and *Arenobulimina* (Figs. 3, 4 and 7). In the upper part of the Lgota Beds, bacterial and detritus feeders occurred locally in high numbers (*Haplophragmoides falcatosuturalis*; Geroch, 1966; Geroch and Nowak, 1984; Szydło, 2008). Numerous and diverse agglutinated foraminifera, belonging to shallow or deep infauna, were observed in light grey and green shales of the



**Fig. 7. Faunal changes in agglutinated foraminiferal assemblages in relation to facies models and sea level fluctuations, geotectonic activity, and also oceanic anoxic and biotic events**

Assemblages with: 1 – surficial epifauna (*Recurvoides*), 1a – surficial epifauna (*Recurvoides*), semi-infauna (*Jaculella*) and rare deep infauna (*Gaudryina*, *Pseudobolivina*), 2 – surficial epifauna (*Recurvoides*) and shallow infauna (*Plectrocurvoides*), 3 – numerous mobile (*Haplophragmoides*) and very rare deep (*Bulbobaculites*, *Arenobulimina*) infauna, 4 – very rare deep infauna (*Uvigerinamina*, *Gaudryina*), 5 – surficial infauna (*Recurvoides*) or/and surficial infauna (*Uvigerinamina*, *Gerochammina*), 6 – suspension (*Nothia*) and attached epifauna (*Ammodiscus*)

Lgota Beds as well as in the Cenomanian-Turonian variegated shales, which occur as intercalations in the lower part of the Godula Beds, or constitute a separate lithological unit. Specimens of shallow infauna (*Recurvoides*) are numerous, while mobile (*Haplophragmoides*) and deep infauna (*Uvigerinamina*, *Falsogaudryinella*, *Gaudryina*) rarely occur. The deep infauna (*Gerochammina* and *Uvigerinamina*), including active deposit and bacterial feeders, dominated in variegated shales of the Turonian (Figs. 3, 4 and 7). The accompanying epifaunal suspension feeders (*Nothia*) and forms attached to marine plants (*Ammodiscus*) at that time (Fig. 3). During the homogeneous sedimentation, an impoverished foraminiferal microfauna existed under the conditions of organic influx and oxygen deficiency, which dominated during the relative sea level rise. In the Early Albian, impoverished agglutinated foraminiferal assemblages, similar to those from the Verovice Shales, persisted under dysaerobic conditions (OAE1b) in the separated parts of the basin. The monospecific agglutinated assemblages known as biofacies B (Severin, 1983; Kuhnt and Kaminski, 1990), including mainly surficial infauna (*Recurvoides*), which are accompanied by rare deep infauna (*Gaudryina*, *Pseudobolivina*) or scarce semi-infauna (*Jaculella*) and epifauna (*Glomospira*), appeared in

black organic-rich deposits (lower part of the Lgota Beds; Figs. 3 and 7). In this period, plankton, including calcareous dinocysts and tintiniids (*Colomiella*), probably accumulated in the separated parts of the basin. In the Late Albian and Turonian, intense subsidence and volcanic activity associated with a eustatic sea level rise influenced increased phytoplankton productivity and radiolarian blooms (CBTE). Siliceous plankton productivity and enhanced upwelling led to expanded short-term oxygen minima in the Late Albian (OAE1d) and in the latest Cenomanian (OAE2). In these periods of deficient oxygen levels, agglutinated foraminifers became almost extinct in the bottom waters, while planktonic forms locally survived near the surface (*Hedbergella*, *Heterohelix*, *Guembeltria*) and in surface waters (*Rotalipora*, *Praeglobotruncana*; Caron, 1985; Leckie, 1987; Leckie et al., 2002). The first forms occurred in the upper part of the Lgota Beds, including spongiolites, and the latter were noted in the variegated (green and red) shales belonging to the so-called radiolarian beds (Huss, 1957; Liszkowa, 1956). In these pelagic deposits of the Cenomanian–Turonian, the number of dinocysts specific for open areas (*Pterodinium*) increased (Bk et al., 2000). Forms of this type also occurred periodically in hemipelagic deposits of the Albian (Lgota Beds). This coincided with changes in relative sea level and phytoplankton productivity at the time.

## DISCUSSION

Changes in fossil assemblages are very closely related with sedimentary processes and environmental parameters, which are shaped by geotectonic and volcanic activities and also sea level fluctuations and anoxic and biotic events. Agglutinated foraminifers are regarded as autochthonous microfauna and therefore are closely related to depositional environments (e.g., Haig, 1979; Olszewska, 1984; Jones and Charnock, 1985; Loubere, 1989; Kuhnt et al., 1989, 1992; Szydło, 2008). The simplification of foraminiferal assemblages may mainly be observed under low oxygen conditions and high organic flux. Agglutinated foraminifers existed as bacterial, deposit, and detritus feeders under dysaerobic conditions in the Early Albian (OAE1b) and the Late Albian (OAE1d). In the long perspective, decay of the organic matter contributed to oxygen consumption in the bottom waters and finally led to the disappearance of benthic life. This was intensified by volcanic activity and a maximal deepening of the basin during pelagic sedimentation. The impoverished assemblages could also reflect the short sedimentation periods just after the sudden supply of coarse-grained material into the basin. In the long perspective, the supply of the sandstones contributed to the increase of water circulation and oxygenation of the basin floor. Consequently, these sedimentation episodes favoured numerous and variable deep water morphotypes, which assembled the second ecological type of foraminiferal assemblages.

Faunal changes in the agglutinated microfauna coincided with the supply of calcareous bioclastic material and caused phytoplankton productivity to fluctuate. This event was probably recorded for the first time in the Early Albian. It was correlated with the occurrence of tintinnids (*Colomiella*), which are preserved in marly sediments of the Subsilesian Unit (Olszewska, 1997).

Agglutinated foraminiferal assemblages were periodically replaced by planktonic and calcareous benthic foraminifers during the Albian-Turonian transition. At the time of tectonic instability and dynamic changes in sedimentation, calcareous nannoplankton, including mainly forms which were resistant to dissolution, and limestone of the Stramberk type had been supplied. Carbonate rocks, including calcareous nannoplankton, originated mainly from former Jurassic platforms, which were uplifted and eroded intensely in the separated parts of the basin. These events coincided with the widespread destruction of sponge "reefs", which provided material for forming the biosiliceous deposits (cherty mudstones and spongiolites). In these settings, organic-walled dinocysts of littoral and low salinity environments dominated.

These organic-walled cysts were replaced gradually by forms characteristic of open seas during the Cenomanian. At that time, planktonic siliceous forms (radiolarians) were widespread. The expansion and radiation of the phytoplankton was related to low tectonic activity and low-energy sedimentation. Deposition of this type dominated in the Subsilesian Zone, while the sedimentation of sponge-rich biosiliclastic deposits prevailed in the Silesian Zone. Under these conditions specific planktonic foraminifers survived. Their extinction was caused by the formation of the OMZ in the surface waters during the Late Albian (OAE1d) and the latest Cenomanian (OAE2). Some of these, as eurytopic forms, had a wider ecological tolerance (*Heterohelix*, *Hedbergella*, *Guembelitra*), and other ones,

as stenotopic forms, were very environmentally sensitive (*Rotalipora*, *Praeglobotruncana*; Leckie, 1987; Gasiński, 1997; Hart, 1999; BouDagher-Fadel, 2013). The first were shallow-dwelling forms, while the latter represented deep dwelling microfossils. This sequence of planktonic foraminifers distinctly coincided with the enhanced upwelling that led to the uplift of anoxic waters into the surface at the time.

During the Turonian, the evolution of planktonic foraminifera correlated with dynamic changes in depositional environments, which were induced by the renewed supply of terrigenous material. This material mainly originated from the eastern uplifted parts of the Silesian Basin, formed as the Subsilesian sub-basin, in Cenomanian–Turonian time. The biogenic material, including calcareous skeletal elements of planktonic forms, were locally supplied in that time. These were calcareous nannoplankton of the Jurassic and the Early Cretaceous, and foraminifera of the Turonian–Santonian. Apart from new keeled plankton belonging to *Marginotruncana*, agglutinated benthos that is represented by forms belonging to *Uvigerinammina* and *Gerochammina* occur in foraminiferal assemblages. Faunal changes in foraminiferal associations were correlated with the development of new niches during the sedimentation of variegated calcareous deposition in the Turonian.

## CONCLUSIONS

The sequences of the fossils described were clearly related to sea level changes and also to phytoplankton productivity during the Albian–Turonian. The number, diversity, and preservation of the fossils discussed correspond with oceanic maximum anoxic (OAE1b, OAE1d, OAE2) and biotic (CTBE) events, which can be correlated with geotectonic and volcanic activity in the Outer Carpathian Basin. During and after each type of event there occurred significant faunal changes in foraminiferal assemblages. Usually, the decreased variability and number of the microfauna coincided with dominant siliceous fossils (sponge spicules, radiolarians) during the Late Albian–Cenomanian or the Cenomanian–Turonian. In these intervals, such microfossils were the predominant components of organic-rich deposits (cherty mudstones, spongiolites and radiolarian shales). The spicule-rich deposits included also skeletal elements of macro- and microfossils and also rock clasts from near shore environments and land, which were uplifted and eroded at the time. The accumulation of radiolarian skeletons in large masses coincided with a maximal subsidence and eustatic sea level rise, which previously resulted in radiolarian blooms (CTBE; Thurow, 1988; Baumgartner et al., 1992). Just before and during this event, enhanced volcanic activity and upwelling were associated with an increased surface productivity and the deficiency of oxygen in subsurface waters due to oxidation of organic carbon (Gucwa and Wieser, 1980; Vogt, 1989). This led to expanded and intensified oxygen minima, which coincided with the elimination of life in bottom (agglutinated foraminifers) and then in surface waters (foraminifers, radiolarians and dinocysts). During the Turonian, tectonic reorganization of the basin led to the reactivation of coarse-grained turbidites containing reworked macrofossils and rock blocks similar to those from the Lower Albian thick-bedded deposits, but in low numbers. Finally, coarse-grained deposits were gradually replaced by hemipe-

lagic variegated shales during the Turonian. At that time, diversified agglutinated and single planktonic foraminifera represented mainly by deep-dwelling forms existed in the bottom or subsurface waters.

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