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Foraminiferal palaeodepth indicators from the lower Palaeogene deposits of the Subsilesian Unit (Polish Outer Carpathians)

(Figs 1–10)

Abstract. The presented research results are an attempt at establishing the relative depth of sediment deposition in the Subsilesian zone of the Carpathian basin. To estimate palaeodepth calcareous and agglutinated foraminifera were investigated, taking into account the preservation conditions, life environment, and bathymetrical preferences of individual species of the calcareous benthic forms. Micropalaeontological analysis were carried out on foraminiferal assemblages from the Palaeocene–Middle Eocene deposits of the Lanckorona–Zegocina Tectonic Zone and the Żywiec Tectonic Window (Subsilesian Unit), which are represented by the Szydłowiec sandstones (Palaeocene part), the Czerwin sandstones, the Gorzeń sandstones, the Radziechowy sandstones, the Lipowa beds as well as shales, that occur above or between these sandstones.

The microfauna assemblages indicate that a change in the sedimentation depth of the individual lithosomes is conspicuous in the Early Palaeocene. During the Early Palaeocene the depth was between the CCD and the foraminiferal lysocline (FL); however, during the Late Palaeocene and the Early Eocene a deepening related to the CCD is evident or local shallowing of the CCD. Deposition took place in the lower part of the range between the CCD and FL, achieving the maximum palaeodepth in the latest Palaeocene. The depth changes of the Subsilesian basin zone can be correlated with global trends of the raising level of the World Ocean, and also with a period of increased subsidence of the Carpathian basins.

Key words: palaeobathymetry, CCD, foraminiferal lysocline, Subsilesian Unit, Palaeocene, Eocene, foraminifera.

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INTRODUCTION

The Subsilesian Unit appears in relatively small areas in the Outer Polish Carpathians. Exposures of this unit are concentrated along the northern and southern edge of the Silesian Nappe. The microfaunal analyses were carried out in the southern range, where the Subsilesian Unit is exposed in several tectonic windows within the Silesian Nappe or in the tectonic contact zone of the Silesian and Magura nappes. A number of tectonic windows occur along the axial zone of the anticyclinal structure known as the Lanckorona-Żegocina Zone (Książkiewicz, 1972), which extends from Rajbrot village in the east to the Wadowice region in the west. Farther to the west, the next tectonic window that includes sediments of the Subsilesian Unit is called the Żywiec Tectonic Window (Geroch & Gradziński, 1955; Książkiewicz, 1972; Unrug, 1969). The sediments occurring within the Żywiec tectonic window series represent an age interval from the Lower Cretaceous to the Oligocene (Burtan et al., 1974; Geroch & Gradziński, 1955; Geroch et al., 1967; Książkiewicz, 1951a, b, 1972; Skoczylas-Ciszewska, 1960; Unrug, 1969).

The Subsilesian Unit was distinguished in the Polish Flysch Carpathians as an independent unit by Książkiewicz (1951 a, b) and shortly afterwards a group of geologists and palaeontologists began intensive geological and palaeontological investigations. The numerous descriptive works and papers in which foraminifera were used in order to establish the stratigraphic position, arose then. Among the most important works concerning the Palaeogene deposits of the Subsilesian Unit are: Geroch & Gradziński (1955), Liszkowa (1959), Skoczylas-Ciszewska (1960), Liszkowa & Nowak (1963), Huss (1966), Książkiewicz (1966), Geroch et al. (1967), Jurkiewicz (1967), Jednorowska (1975), Burtan et al. (1974) and Burtan (1978). A number of studies concentrated upon estimates of palaeodepth of the Palaeogene Carpathian basins, e.g.: Koszarski & Żytko (1965), Jurkiewicz (1967), Książkiewicz (1975), Sikora (1976), Geroch et al. (1979), Morgiel & Olszewska (1981), Olszewska (1981, 1984), Kotlarczyk (1991) and Malata (2000). Foraminifera have been used as useful bathymetric indicators most of these studies.

METHODS

The present paper encompasses the micropalaeontological analyses of foraminiferal assemblages from the Palaeocene–Middle Eocene. Micropalaeontological analyses were carried out in the southern range of the Subsilesian Unit outcrops. Eleven strongly tectonized profiles of Lower Palaeogene sediments of the Subsilesian Unit were investigated (Fig. 1). Examined materials were collected from: Pluskawka stream in the Żegocina Zone, Krzyworzeka, Lipnik, Czerwin, Foszczówka streams in the Wiśniowa Tectonic Window, Gościęba, Gorzeć Górny, Dąbrówka streams and Bachowice area in the Lanckorona Zone as well as Leśnianka and Żarnówka streams in the Żywiec Tectonic Window. The samples were collected from shaly sediments from thick sequences. The materials (300 g of dry shales or marls) were prepared by using standard micropalaeontological techniques in order to obtain microfossils. Repeated boiling and drying using Glauber Salt disinte-
grated the samples, which were then washed through a set of sieves (100 and 63 μm screen) and dried. All specimens picked from the dry residue were statistically counted and taxonomically identified. For statistical analyses 5 fragments, which usually occur as crushed (e.g. tubular forms), were considered as a single foraminifer. The detailed data can be found in Waœkowska-Oliwa (2001). The basis of the bathymetrical analysis was the examination of the autochthonous faunas that were adopted from the repeatedly recurrent groups of the agglutinated foraminifera and well-preserved benthic calcareous forms (Figs 3, 4). As a rule, foraminiferal associations did not show signs of redeposition. Samples consisting of a minimum of 150 specimens were taken into account. SEM photos were made at the Scanning Electron Microscopy Laboratory of the Institute of Geological Sciences UJ (Kraków).

**LITHOLOGY**

The development of Lower Palaeogene sediments within the Subsilesian Unit is diverse. It is widely considered that there are mainly marly sediments representing a
shallower facies: the Frydek-type marls or a deeper facies: the Węglówka marls below the Lower Palaeogene deposits (Skoczylas-Ciszewska, 1960; Książkiewicz, 1951a, b, 1956; Geroch & Gradziński, 1955; Liszkowa & Nowak, 1963; Geroch et al., 1967; Unrug, 1969; Burtan et al., 1974; Burtan, 1978). During the Late Cretaceous alongside the marls coarse-grained clastic sediments were deposited. As a result of this sedimentation the Rybie sandstones and conglomerates were deposited within the Żegocina Zone (Skoczylas-Ciszewska, 1960; Unrug, 1969; Jugowiec-Nazarkiewicz & Jankowski, 2001; Gasiński et al., 2001) as well as the Szydłowiec sandstones within the Wiśnowa and Żywiec tectonic windows and the Lanckorona Zone (Książkiewicz, 1951a, b; Geroch & Gradziński, 1955; Geroch et al., 1967; Unrug, 1969, Burtan, 1974, 1978; Burtan et al., 1974) (Fig. 2).

**Żegocina Zone**

The Lower Palaeogene sediments are represented by variegated shales and marls in the Żegocina Zone (Skoczylas-Ciszewska, 1960; Unrug, 1969). Above the Rybie sandstones, there is a complex of green, non-calcareous, marly shales with
rare intercalations of thin bedded, fine-grained, glauconite sandstones. Above the Rybie sandstones, there is a complex of green, non-calcareous, marly shales with rare intercalations of thin bedded, fine-grained, glauconite sandstones. These sandstones are overlain by red or cherry-red marly shales with intercalations of green, brown or grey shales.

The Wiśniowa Tectonic Window

The geological section of the Palaeogene deposits in the Wiśniowa Tectonic Window begins with the Szydłowiec sandstones (Fig. 2). The deposition of these sandstones started in the Late Cretaceous (Burtan, 1974, 1978; Burtan et al., 1974). They are developed as coarse-grained partially conglomeratic, calcareous, thick-bedded, light grey sandstones. They consist of quartz grains, coated fragments of organodetric limestones (mainly bryozoans and algae) and include pieces of coal and calcareous green shales.

Above them there the Czerwin sandstones are developed (Burtan, 1974; 1978; Burtan et al., 1974; Cieszkowski et al., 2001) represented by a complex of sandstones and shales. The calcareous, fine-grained sandstones are thick- and medium-bedded. They consist of quartz grains, glauconite which gives them a green tint, as well as various calcareous clasts. The sandstones can be considered as alloidapic limestones (Cieszkowski et al., 2001). The sandstone layers are intercalated by greenish shales.

The Czerwin sandstones are overlain by a light marly, green shale complex (Cieszkowski et al., 2001) with the rare intercalations of thin-bedded and fine-grained sandstones (Leśniak et al., 2001). They pass up section into a series of green-brown shales called the Lipowa beds (Cieszkowski et al., in print). Those mottled shales are green, green-grey and brown, sporadically red in colour. The sediments include scarce intercalations of thin- and medium-bedded, fine-grained quartz sandstones with isolated beds or ankeritic concretions.

The Lanckorona Zone

The geological profile of the Palaeogene deposits starts in the Lanckorona Zone with the Szydłowiec sandstones (Książkiewicz, 1951a, b) as in the Wiśniowa Tectonic Window. The Gorzeń sandstones occur above them (Książkiewicz, 1951a, b) (Fig. 2). The Gorzeń beds mostly consist of thin- to medium-bedded sandstones with intercalations of shales, but occasionally thick-bedded sandstone layers occur too. The sandstones are siliceous, grey and grey-greenish, graded, fine- or rarely medium-grained. Shales are usually clayey, grey and grey-greenish, more or less bioturbated. Over them occur green and green-brown shales (Liszkowa & Nowak, 1963; Geroch et al., 1967). The shales are marly in the lower part of the section and clayey above. Within the clayey part of the complex, thin-bedded, fine-grained green-brown quartzite sandstones with glauconite occur. The complex of green-brown shales passes upwards into a complex of variegated shales and marls (Książkiewicz, 1951b, Geroch et al., 1967). These are red, cherry red, green or grey shales.
in colour, with rare intercalations of thin-bedded, fine-grained sandstones bearing numerous of trace fossils. In the area where the Palaeocene flysch facies were not developed, clayey-marly sediments were deposited (Książkiewicz, 1956).

The Żywiec Tectonic Window

In the Żywiec Tectonic Window above the Szydłowiec sandstones there is a complex of marly and clayey green shales (Geroch & Gradziński, 1995; Unrug, 1969). This complex grades into a complex of variegated shales, which include intercalations of thin-bedded, fine-grained sandstones (Leśniak & Waśkowska, 2001). These sediments are overlain by the Radziechowy glauconite sandstones (Geroch & Gradziński, 1955; Neścieruk, 1998) (Fig. 2). These beds are developed in the form of sandy-shaley flysch consisting of two facies: sandy and sandy-shaley (Leśniak & Waśkowska-Oliwa, 2001). The thick-, medium- and thin-bedded green sandstones are usually medium- and coarse-grained. The marly shales are green-grey or green-brown in colour. There above them occur the Lipowa beds (Neścieruk, 1998). There are mainly made up of marly, striped and brown-green shales. The shales are occasionally intercalated by grey thin-bedded, fine-grained, sandstones.

All geological sections of the Subsilesian Unit are marked by presence of bentonized tuffite layers that occur within a complex of Lower Eocene shales (Książkiewicz, 1956; Burtan, 1978; Leśniak et al., 2001). These tuffite layers seem to be a correlation horizon (Cieszkowski et al., in print).

BIOSTRATIGRAPHY

The biostratigraphical analyses have been carried out on the strength of the foraminiferal assemblages, which were worked out for the Polish Flysch Carpathians by Olszewska (1997). This zonation is based upon foraminiferal associations which are common within the Carpathian sedimentary basins (i.e., agglutinated foraminifera). The additional advantage of this zonation is the list of the characteristic species for individual assemblages that include planktonic and benthic calcareous taxa, which are common components of the foraminiferal associations from the deposits of the Subsilesian Unit. The assemblages defined by Olszewska (1997) are clearly distinguishable in the micropalaeontological material from the sediments of the Subsilesian Unit. The current foraminiferal investigations introduce small modifications to the individual definitions of the boundaries. The biostratigraphical analysis is here presented only for purpose of this study, however the issue of biostratigraphy of the Subsilesian deposits will be the subject of a separate, more detailed paper.

Rzehakina fissistomata Zone (Interval zone) – the interval between the LO of Rzehakina inclusa (Grzybowski) and the LO of Rzehakina fissistomata (Grzybowski) (Fig. 6: 2) or/and LO of Haplophragmoides mjalltikae (Maslakova). The occurrence of numerous foraminifera representing the genus Glomospira is signifi-
Fig. 3. Proportion of agglutinated and calcareous benthic foraminifera

Fig. 4. Examples of typical generic distribution among calcareous benthic foraminiferal assemblages (a full circle represents 100% of calcareous benthic foraminifera): 1 – Aragonia, 2 – Dentalina, 3 – Eponides, 4 – Ellipsoglandulina, 5 – Globobulimina, 6 – Lenticulina, 7 – Nodosaria, 8 – Osangularia, 9 – Pullenia, 10 – Anomalinoidea, 11 – Gavelinella, 12 – Gyroidinoidea, 13 – Lagena, 14 – Nutallides, 15 – Nutallinella, 16 – Abysammina, 17 – Anomalina, 18 – Clinapertina, 19 – Globocassidulina, 20 – Pleurostomella, 21 – Stilostomella
cant for the upper boundary of this zone. According to Olszewska (1997), the age of this zone is Palaeocene. Taking the taxonomic qualities and quantitative proportions of specimens into consideration the foraminiferal assemblages included in Rzehakina fissistomata Zone form two clearly separate groups with a stratigraphic succession (Wałkowska-Oliwa, 2004). The older association (Pe-1) is characterised by the occurrence of a variety of genera and species of agglutinated and benthic calcareous foraminifera. The presence of relatively large number of specimens of Hormosina and Caudammina is distinctive for this assemblage. Representatives of Hormosina excelsa (Dylążanka) (Fig. 6: 8), Hormosina velascoensis (Cushman) (Fig. 6: 10), Caudammina ovula (Grzybowski) (Fig. 6: 11, 12) and Caudammina ovuloides (Grzybowski) as well as other forms common in Late Cretaceous foraminiferal associations, e.g., Glomospirella grzybowskii (Jurkiewicz) (Fig. 5: 18), Glomospira diffundens Cushman & Renz (Fig. 5: 11), Remesella varians (Glassner) (Fig. 8: 2, 5), Dorothia div. sp. occur within the standard assemblage. Occasionally Chiloguembelina morsei (Kline) (Fig. 10: 15), Subbotina triloculinoides (Plummer) (Fig. 10: 13) are present. The taxonomic composition of the younger association (Pe-2) is somewhat less diverse. The proportions of individual species change and cosmopolitan forms such as: Recurvoides, Paratrochamminoides, and Rhabdammina dominate the foraminiferal assemblages. Typical Late Cretaceous and Early Palaeocene forms are absent or are rarely represented by single specimens. Nuttallides and Abyssammina are common among the group of calcareous bentonic foraminifera, occasionally Acarinina primitiva (Finlay), Acarinina soldadoensis (Bronnimann), Subbotina linaperta (Finlay), Subbotina velascoensis (Cushman), Subbotina triloculinoides (Plummer) occur among the group of planktonic foraminifera.

The older associations (Pe-1) have been recognised within the Szydłowiec sandstones, the Czerwin sandstones and in the lower part of the green shales. The younger associations (Pe-2) have been identified within the upper part of the green shales, the variegated shales of the Żegocina Zone, the sandstones of the Żywicz Tectonic Window, and the Gorzeñ sandstones.

Fig. 5. Agglutinated foraminifera from the lower Palaeogene of the Subsilesian Unit. 1 – Rhabdammina sp., sample nr 273 Czerwin; 2 – Rhabdammina linearis Brady, 363 Lipnik; 3 – Rhabdammina cylindrica Glaessner, 349 Gośćbia; 4 – Rhabdammina sp. with Ammolagen aclavata, Jones & Parker), 311 Czerwin; 5 – Hyperammina elongata Brady, 266 Czerwin; 6 – Nothia excelsa (Grzybowski), 316 Czerwin; 7 – Saccammina placenta (Grzybowski), 261 Czerwin; 8 – Ammodiscus tenuissimus Grzybowski, 249 Gośćbia; 9 – Ammodiscus cretaceus (Reuss), 264 Czerwin; 10 – Ammodiscus cretaceus (Reuss), 312 Czerwin; 11 – Glomospira diffundens (Cushman & Renz), 329 Gośćbia; 12 – Glomospira glomerata (Grzybowski), 314 Czerwin; 13 – Glomospira charoides (Jones & Parker), 273 Czerwin; 14 – Glomospira gordialis (Jones & Parker), 363 Lipnik; 15 – Glomospira charoides (Jones & Parker), 363 Lipnik; 16 – Glomospira irregularis (Grzybowski), 184 Czerwin; 17 – Glomospira serpens (Grzybowski), 231 Czerwin; 18 – Glomospirella grzybowskii (Jurkiewicz), 311 Gościębia; 19 – Glomospirella sp., 261 Czerwin. Scale bar = 100 µm.
Glomospira div. sp. Zone (Acme zone) – the interval of common occurrence of the genus Glomospira, between the LO of Rzehakina fissistomata (Grzybowski) and/or Haplophragmoides mjatliukae (Maslakova) and the FO of Saccamminoides carpathicus Geroch (Fig. 7: 5, 6). Age – the early part of the Early Eocene. The foraminiferal assemblages which have been assigned to this zone were found in the variegated shales of the Żegocina Zone, the Lipowa beds, brown-green shales and the glauconite Radziechowy sandstones.

Saccamminoides carpathicus Zone (Total Range zone) – the interval between the FO and LO of the index taxon. Age – late Early Eocene. This zone includes the foraminiferal associations in the variegated shales of Żegocina Zone, the Lipowa beds, and the green-brown shales.

Reticulophragmium amplectens Zone (Acme zone) – the interval where specimens of the index taxon occur in large numbers, between the LO of Saccamminoides carpathicus Geroch and the FO of Ammodiscus latus (Grzybowski). Age – early part of the Middle Eocene. The foraminiferal assemblages specific for this zone appeared in the Lipowa beds, marls and shales of the Lanckorona Zone.

FORAMINIFERAL INDICATORS OF RELATIVE BATHYMETRY OF THE SUBSILESIAN UNIT

It is possible to assign a relative depth of sedimentation with relation to the depth of the calcium carbonate compensation depth (CCD) and foraminiferal lysocline (FL) on the basis of the analysis of the composition of the foraminiferal assemblages. The CCD is the depth where the amount of delivered calcareous material equals its dissolution (Gradziński et al., 1986) and the FL is usually situated a few hundred meters above it (Kennett, 1982). A sudden increase in the amount of dissolution of calcareous foraminifera begins at the FL depth. In this case there are calcareous benthic foraminifera possessing shells resistant to dissolution within the interval between CCD and FL (Olszewska, 1981). The estimate of the palaeodepth is also possible thanks to findings the ecological conditions of particular species of foraminifera (Schnitker & Tjalsma, 1980; Corliss & Honjo, 1981; Tjalsma & Lohman, 1983; Olszewska, 1984; Morkhoven et al., 1986).

Fig. 6. Agglutinated foraminifera from the lower Palaeogene of the Subsilesian Unit. 1 – Kalamopsis grzybowskii (Dylążanka), sample nr 330 Gośćbia; 2 – Rzehakina fissistomata (Grzybowski), 329 Gośćbia; 3 – Rzehakina epigona (Rzehak), 311 Gośćbia; 4 – Aschemocella carpathica (Neagu), 231 Czerwin; 5 – Reophax pilulifer Brady, 238 Gośćbia; 6 – Reophax scalaris Grzybowski, 402 Lipowa; 7 – Reophax elongatus Grzybowski (281 Czerwin; 8 – Hormosina excelsa (Dylążanka), 329 Gościbia; 9 – Hormosina excelsa (Dylążanka), 351 Gościbia; 10 – Hormosina velascoensis (Cushman), 243 Foszczówka; 11 – Caudammina ovula (Grzybowski), 329 Gościbia; 12 – Caudammina ovula (Grzybowski), 314 Czerwin; 13 – Hormosina sp. 1, 329 Gościbia; 14 – Haplophragmoides walteri (Grzybowski), 273 Czerwin; 15 – Haplophragmoides walteri (Grzybowski), 314 Czerwin; 16 – Paratrochamminoides uviformis (Grzybowski), 363 Lipnik; 17 – Trochamminoides coronatus (Brady), 265 Czerwin; 18 – Paratrochamminoides irregularis (White), 239 Gościbia. Scale bar = 100 µm
The origin of the Szydłowiec sandstones is the result of Late Cretaceous–Early Palaeocene coarse-grained sedimentation in the Subsilesian Unit. From the Early Palaeocene the activity of turbidity density currents started to decline and shaly-sandstone as thin-bedded flysch was deposited. They are the so-called Czerwin sandstones in the Wiśniowa Tectonic Window and the Gorzeń sandstones in the Lanckorona Zone.

The Palaeogene foraminiferal assemblages form the Szydłowiec sandstones are dominated by agglutinated foraminifera, which make up on average from 90% to 98% (Fig. 3), and exceptionally 80% of the association. Planktonic foraminifera are usually absent or only occur occasionally (up to 1%). The calcareous benthic foraminifera are sparse, but appear in the each sample in amounts ranging from 2% to 10% (Fig. 3), and sporadically up to 20%. A similar composition characterises the foraminiferal assemblages occurring within the Czerwin sandstones. They consist nearly entirely of agglutinated taxa (from 89% to 96%) and a accompanied by calcareous benthic foraminifera (from 1% to 14%) (Fig. 3). The presence of the planktonic foraminifera is sporadic, but when they occur they make up a maximum of 5% of the assemblage and are poorly preserved. The calcareous benthic foraminifera from these two lithosomes are represented by: Anomalina, Anomalainoides, Aragonia, Cibicidoides, Dentalina, Eponides, Ellipsoglandulina, Ellipsopolymorpha, Gavelinella, Globobulimina, Gyroidinoides, Guttulina, Lagena, Lenticulina, Nodosaria, Nodosarella, Nuttallides, Osangularia, Pullenia, Stensioeina (Fig. 4). These genera are mostly regarded as deepwater taxa of the bathyal zone (Berggren & Aubert, 1975; Tjalsma & Lohman, 1983; Olszewska, 1984; Morkhoven et al., 1986; Olszewska et al., 1996). Although the calcareous benthos represent such a minor admixture compared with the whole association (merely a few percent), the fact of its great diversity is interesting. As a rule, the individual species occur in amount of a few specimens in each 300 g of dry sediment and are well preserved. Among the agglutinated benthos agglutinated forms with calcareous cement were found, including Dorothia crassa (Marsson) (Fig. 8: 3), Dorothia indentata Cushman & Jarvis (Fig. 8: 4), Dorothia trochoides (Marsson) and Remesella varians (Glaessner) (Fig. 8: 2, 5). The latest mentioned taxon has been identified in relatively large numbers within some samples. The agglutinated benthos is diversified

Fig. 7  Agglutinated foraminifera from the lower Palaeogene of the Subsilesian Unit. 1 – Paratrochamminoides heteromorphus (Grzybowski), sample nr 266 Czerwin; 2 – Lituotuba litiformis (Brady), 268 Czerwin; 3 – Ammosphaeroidina pseudopaciloculata (Mjatliuk), 311 Gościębia; 4 – Praecystammina sveni Gradstein & Kaminski, 203 Czerwin; 5 – Saccamminoides carpathicus Geroch, 273 Czerwin; 6 – Saccamminoides carpathicus Geroch, 312 Czerwin; 7 – Spiroplectammina spectabilis (Grzybowski) (327 Gościębia; 8 – Karrerulina coniformis (Grzybowski), 363 Lipnik; 9 – Karrerulina conversa (Grzybowski), 363 Lipnik; 10 – Gerochammina conversa (Grzybowski), 216 Czerwin; 11 – Recurvoides nucleolus (Grzybowski), 312 Czerwin; 12 – Recurvoides with Ammolagena clavata (Jones & Parker), 427 Lipowa; 13, 14 – Trochammina globigeriniformis (Parker & Jones), 339 Gościębia; 15 – Arenobulimina dorbignyi (Reuss) 349 Gościębia; 16 – Remesella varians (Glaessner). Scale bar = 100 µm
with respect to species. It is represented by about 33–35 species per sample. Foraminiferal assemblages dominated by agglutinated forms with a constant but not large admixture of well-preserved, deepwater calcareous benthos are characteristic for environments above the CCD, but below FL.

The stage of shaly sedimentation started at the beginning of the Late Palaeocene. The foraminiferal assemblages identified within the shale series (the upper part of Pe-1 as well as the lower part of Pe-2 of *Rzehakina fissistomata* Zone), which occur above flysch sediments, resemble a taxonomic composition of the foraminiferal associations represented by the Szydłowiec sandstones and the Czerwin sandstones. A permanent feature of these associations is the occurrence of calcareous benthic foraminifera in variable numbers. This fluctuates between 1% and 3% only sporadically reaching 15% of the association. The calcareous foraminifera consist solely of deepwater taxa. The agglutinated fauna represents on average 96% to 99% of the group (Fig. 3). Planktonic foraminifera are usually absent, and whenever they appear they make up only 1% of the assemblage and are very poorly preserved. The depth represented by this foraminiferal assemblage is typical for the depth range between CCD and FL.

The microfauna occurring in the Palaeocene Gorzeń sandstones is typical for a depth close to CCD. The foraminiferal associations that are represented only by agglutinated taxa – almost exclusively siliceous fauna (agglutinated species with calcareous cement have been found sporadically in the single samples), indicate this type of deposition.

The foraminiferal associations representing the Upper Palaeocene shaly deposits (*Rzehakina fissistomata* Zone) and also the Lower Eocene sediments (*Glomospira* div. sp. Zone and *Saccamminoides carpathicus* Zone) are twofold: they consist of exclusively siliceous-agglutinated taxa or mixed groups of agglutinated-calcareous fauna. Associations including only siliceous-agglutinated foraminifera occur in the Upper Palaeocene sediments more frequently and represent more than 35% of the samples. However, this number is lower and make up 25% of the assemblages in the Lower Eocene deposits. Within the mixed agglutinated-calcareous associations the following average composition of particular foraminiferal groups were found:

- Upper Palaeocene shales – agglutinated benthos: 98–99%, calcareous benthos: 1–2% (exceptionally up to 9%) (Fig. 3);

![Fig. 8. Agglutinated and calcareous benthic foraminifera from the lower Palaeogene of the Subsilesian Unit.](http://example.com)

1 – *Dorothyia bulleta* (Carsey), sample nr 278 Czerwin;
2 – *Remesella varians* (Glaessner), 278 Czerwin;
3 – *Dorothyia crassa* (Marsson), 278 Czerwin;
4 – *Dorothyia intendata* Cushman & Jarvis, 423 Pluskawka;
5 – *Remesella varians* (Glaessner), 332 Gościęba;
6 – *Dentalina gracilis* d’Orbigny, 314 Czerwin;
7 – *Nodosaria* sp. (314 Czerwin;
8 – *Nodosaria velascoensis* Cushman, 314 Czerwin;
9 – *Dentalina catenula* Reuss, 419 Foszczówka;
10 – *Stilostomella* sp., 314 Czerwin;
11 – *Dentalina gracilis d’Orbigny, 419 Foszczówka;
12 – *Stilostomella* sp., 165 Leśnianka;
13 – *Dentalina megapolitana* Reuss, 314 Czerwin;
14 – *Dentalina gracilis d’Orbigny, 314 Czerwin. Scale bar = 100 µm
– sample from the most Lower Eocene shales (*Glomospira* div. sp. Zone) – agglutinated benthos: 94–99%, calcareous benthos 1–6% (exceptionally up to 13%); – Lower Eocene shales (*Saccamminoides carpathicus* Zone) – agglutinated benthos: 90–97%, calcareous benthos 3–10% (exceptionally up to 16%).

The amount of poorly preserved planktonic foraminifera is variable between 0–2% within the analysed sequence of deposits.

The Eocene calcareous benthic taxa are less diversified in comparison to the Early Palaeocene foraminiferal assemblages. Among this foraminiferal group the genera: *Abysammina*, *Eponides*, *Nuttallides*, *Osangularia* and *Quadrimorphina* (Fig. 4) are the most frequent. Definitely the most numerous and characteristic calcareous benthic species is *Nuttallides truempyi* (Nutall) (Fig. 10: 3, 4), a form that is resistant to dissolution. This species is typical of foraminiferal associations occurring in the bathyal zone (Berggren & Aubert, 1976; Tjalsma & Lohman, 1983; Olszewska, 1984; Hulsbos et al., 1989; Morkhoven et al., 1986; Kuhnt & Collins, 1996; Olszewski et al., 1996). Foraminiferal assemblages with the predominant component of calcareous benthic species, containing *Nuttallides truempyi* (Nutall), are described from the depth between FL and CCD (Olszewska, 1981, 1984) in the Polish Outer Carpathians. The studied composition of foraminiferal associations (both qualitative and quantitative) and the preservation state of calcareous fauna indicates just that depth, pointing to the lower part of this range. If coeval mixed agglutinated-calcareous associations occur alternately with associations consisting of only siliceous-agglutinated foraminifera, it can be assumed that they are characteristic of depths close to the CCD. Malata (2001) has determined similar depths for the same type foraminiferal associations coming from the Magura Nappe. The great participation of siliceous-agglutinated assemblages as well as the lowest number of calcareous forms in the mixed foraminiferal groups have been observed within Upper Palaeocene deposits. This suggest either the deposition of the shaly sediments took place at significantly deeper palaeodepths in relation to the others, or the locally CCD was at a shallower depth during the Late Paleocene.

The majority of foraminiferal assemblages from the Lower Eocene glauconite Radziechowy sandstones consist of siliceous-agglutinated taxa (Leśniak & Waszkowska-Oliwa, 2001). These associations are as a rule little taxonomic varied and they include “*Rhabdammina*-fauna” sensu Gradstein & Berggren (1981) and Olszewska (1984), the environment of which is situated below the CCD. However, the calcification of shales separating sandstone beds and the presence of calcareous

Fig. 9. Calcareous benthic foraminifera from the lower Palaeogene of the Subsilesian Unit. 1 – *Ellipsoglandulina obesa* Hanzlikova, 315 Czerwin; 2 – *Ellipsoglandulina velascoensis* (Cushman), 238 Gościębia; 3 – *Nuttallina florea* (White), 330 Gościębia; 4 – *Lenticulina* sp., 184 Czerwin; 5 – *Lenticulina* sp., 420 Foszczyówka; 6 – *Aragonina ouezzaensis* (Rey), 278 Czerwin; 7, 8 – *Globocassidulina inexcelsa* (Franzenau), 314 Czerwin; 9 – *Pullenia coryelli* White, 423 Pluskawka; 10, 11 – *Eponides subcandidulus* (Grzybowski), 231 Czerwin; 12 – *Guttulina* sp., 432 Pluskawka; 13, 14 – *Gyroidimoides globosus* (Hagenow), 429 Pluskawka. Scale bar = 100 µm
benthic and planktonic foraminifera within some samples can imply depths above but very close to the CCD. The glauconite Radziechowy sandstones were formed mainly as a result of deposition from the low and rarely medium concentration density currents (Leœniak & Waœkowska-Oliwa, 2001), which came down from the Baœka Cordillera separating the Silesian and Subsilesian basins (Eliáš, 1998). The model of the submarine cone analysis indicates the deposition of these sandstones in the lower part of the slope and/or in a basin plain (Leœniak & Waœkowska-Oliwa, 2001). Thus, the sedimentary environment of these sandstones was high-energy. For this reason, the fauna of agglutinated foraminifera adapted to such regime, including those species most resistant to change, i.e., primitive species. The composition of this microfauna may not reflect the actual palaeobathymetrical conditions, and associations may chiefly reflect the energy of the sedimentary environment. An influence of the high rate of sedimentation, which prefers the development of agglutinated fauna and a reduction of calcareous foraminifera at the same time, was emphasised by Miller et al. (1982) as well as Kaminski et al. (1989). A similar situation is observed in the Lipowa beds that overlie the Radziechowy sandstones. These deposits represent fine-rhythmical, shaly-sandy flysch in which sandstone layers are placed variously. The foraminiferal assemblages consist of a mixed agglutinated-calcareous fauna, and occur within thick shaly intervals. However, sections including more frequent sandstone layers are characterised by less diverse siliceous-agglutinated foraminiferal fauna (the “Rhabdina fauna”).

The foraminiferal assemblages, representing sediments of the Subsilesian Unit and occurring between FL and CCD, correspond to the Palaeogene associations of group 2 sensu Olszewska (1984) indicating the bathyal zone which can be compared to the Upper Cretaceous “Velasco” type Tethyan associations (Olszewska, 1984).

**DISCUSSION**

The palaeontological record implies that sedimentation took place at different palaeodepths during the Early Palaeogene in the Subsilesian Unit. Foraminiferal assemblages of the Upper Cretaceous marly sediments indicate sedimentation environment above the FL during the Maastrichtian (Liszkowa & Morgiel, 1981; Gasiœski et al., 1999; Cieszkowski et al., 2000; Machaniec & Malata, 2003). Deposition took place in the external shelf – upper slope during the Early Maastrichtian.
FORAMINIFERAL PALAEODEPTH INDICATORS
and in middle part of the slope, partly in the lower continental slope at the end of the Late Maastrictian (Machaniec, 2002). Marly sedimentation was disrupted by the deposition of a shaly-sandy series (the Szydłowiec and Czerwin sandstones) in the Late Cretaceous and Palaeocene. The micropalaeontological indicators suggest deposition of these sediments at a greater depth than the Upper Cretaceous marls, namely between FL and CCD. Only the Gorzeń sandstones (developed in the Lanckorona Zone) could have been deposited close to CCD partially below this boundary. The flysch sedimentation, which is represented by sandy-clayey turbidities, withdrew gradually and during the Late Palaeocene mainly silty turbidities and/or hemipelagic and pelagic sediments formed as shaly series were deposited. At the beginning of the Late Palaeocene the sedimentation clearly took place between the FL and CCD but at significantly deeper palaeodepths than during the Early Palaeocene. However, the depth of sedimentation was greatest and reached a position close to the CCD at the end of the Late Palaeocene as well as during the Early Eocene. The shaly deposits from this interval show the slightest calcification and are devoid of carbonates. The hemipelagic sedimentation was locally interrupted in the Early Eocene, the sandy-shaly series: the Radziechowy sandstones from the Żywiec Tectonic Window were deposited. The estimation of their depositional depth is rather difficult.

Considering the influence of high-energetic environment of sedimentation on the composition of some foraminiferal associations it is suggested that probably the Radziechowy sandstones and overlying Lipowa beds were deposited above the CCD but still close to it.

The Magura, Silesian and Skole basins reached a maximum paleodepth, as well as the Subilesian Zone in the same time interval (Poprawa et al., 2002). The reduction of sediment calcification within deepwater basins was among other things connected with raising sea-level which took place in the World Ocean at the beginning of the Late Palaeocene (Haq et al., 1988; Ross & Ross, 1990; Leszczyński & Malik, 1996). At that time a lowering of the CCD level in the World Ocean is recorded (van Andel, 1975; Kennett, 1982; Gradziński et al., 1986;). For the North Atlantic the depth of this level was assessed at 3000 m in the Late Cretaceous, but in the Early Eocene at 3500 m (van Andel, 1975). The global tendency of lowering the CCD in oceans during the Palaeocene additionally indicates the great depths of the discussed basin. The analysis of the Outer Carpathians sedimentary basins revealed that a stage of increased subsidence caused by the flexural bend of the basement is evident from the end of the Late Cretaceous till the Late Eocene (Poprawa et al., 2002). Such a mechanism of subsidence explains the decrease in activity of source areas among basins (Poprawa et al., 2002) by lower influence of turbidite sedimentation of the Upper Palaeocene series represented by the Szydłowiec, Czerwin and Gorzeń sandstones. The amount of subsidence for the geological profile of the Subsilesian Unit of the Eastern Polish Outer Carpathians is estimated in the range of 1000 m in from the Palaeocene to the Middle Eocene (Poprawa et al., 2002). The decrease of the activity of source areas led to a decline in sedimentation rate as well as facies standardisation manifested in the deposition of deepwater pelagic sedi-
ments and hemipelagic variegated shales (Poprawa et al., 2002) below the CCD within the Skole and Silesian basins (Olszewska & Geroch, 1991; Malata, 2000, 2001). Similar sediments were deposited in a shallower environment just above the CCD or in its range within the Subsilesian basin zone.

**CONCLUSIONS**

The Lower Palaeocene flysch, hemipelagic and pelagic sediments occur within the Lanckorona-Zegocina Zone and the western Żywiec Tectonic Window. They are represented by: the Palaeocene Szydłowiec sandstones (topmost part), the Czernin sandstones and Gorzeń sandstones (foraminiferal *Rzehakina fissistomata* Zone), the Lower Eocene Radziechowy sandstones (*Glomospira* div. sp. Zone) and the Lipowa beds (*Glomospira* div. sp. and *Saccamminoides carpathicus* zones) as well as the shaly-marly complexes of Palaeocene–Middle Eocene age.

The foraminiferal assemblages found within these sediments mainly consist of agglutinated foraminifera. Well-preserved calcareous benthic forms complete their composition. The calcareous benthic foraminifera are mostly bathyal, dissolution-resistant, deepwater species. The planktonic foraminifera are poorly preserved and make up a small percentage of the foraminiferal assemblages. The foraminiferal associations suggest that the relative palaeodepth of sedimentation of the studied deposits took place between the FL and CCD. The change in quantitative proportions of calcareous components in the autochthonous foraminiferal assemblages within individual geological profiles of the Subsilesian Unit indicates a fluctuation of depth during the analysed time interval. The Late Palaeocene and Early Eocene sediments were deposited at deeper palaeodepths related to the CCD with comparison to sediments of the Lower Palaeocene, probably in an environment close to CCD and reached maximum depths in the latest Palaeocene.

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**REFERENCES**


FORAMINIFERAL PALAEODEPTH INDICATORS


APPENDIX

List of foraminifera taxa occurring in discussed deposits in alphabetical order.

Agglutinated foraminifera

Ammobaculites midwayensis Plummer
Ammobaculites wazaczi (Grzybowski)
Ammodiscus cretaceus (Reuss)
Ammodiscus glabratus Cushman & Jarvis
Ammodiscus incertus (d’Orbigny)
Ammodiscus latus Grzybowski
Ammodiscus peruvianus Berry
Ammodiscus planus Loeblich
Ammodiscus tenuissimus Grzybowski
Ammolagena clavata (Jones & Parker)
Ammospheroidina pseudopauciloculata (Mjatliuk)
Arenobulinina dorbignyi (Reuss)
Aschemocella carpathica Neagu
Bathisiphon sp.
Caudammina ovaloides (Grzybowski)
Caudammina ovula (Grzybowski)
Cystammina sveni Gradstein & Kaminski
Dorothia crassa (Marsson)
Dorothia intendata Cushman & Jarvis
Dorothia oyocona (Reuss)
Dorothia retusa (Cushman)
Dorothia trochoides (Marsson)
Gerochammina lenis (Grzybowski)
Gerochammina tenuis (Grzybowski)
Glomospira charoides (Jones & Parker)
Glomospira diffundens Cushman & Renz
Glomospira glomerata (Grzybowski)
Glomospira gordalis (Jones & Parker)
Glomospira irregularis (Grzybowski)
Glomospira serpens (Grzybowski)
Glomospirella biedae Samuel
Glomospirella grzybowski (Jurkiewicz)
Haplophragmoides bulloides (Beisel)
Haplophragmoides kirki Wickenden
Haplophragmoides mjatliukae Maslakova
Haplophragmoides porrectus Maslakova
Haplophragmoides suborbicularis (Grzybowski)
Haplophragmoides walteri (Grzybowski)
Hormosina excelsa (Dyłążanka, 1923)
Hormosina velascoensis (Cushman)
Hyperammina elongata Brady
Hyperammina dilatata Grzybowski
Hyperammina kemillieri Kaminski
Kalanopsis grzybowski (Dyłążanka)
Karrerulina conformis (Grzybowski)
Karrerulina conversa (Grzybowski)
Karrerulina horrida (Mjatliuk)
Lituotuba lituiformis (Brady)
Nothia excelsa (Grzybowski)
Paratrochamminoides contortus (Grzybowski)
Paratrochamminoides deformis (Grzybowski)
Paratrochamminoides draco (Grzybowski)
Paratrochamminoides heteromorphus (Grzybowski)
Paratrochamminoides irregularis (White)
Paratrochamminoides mitratus (Grzybowski)
Paratrochamminoides multilobus (Dylążanka)
Paratrochamminoides olszewskii (Grzybowski)
Paratrochamminoides uviformis (Grzybowski)
Pracystammina globigeraeformis Krasheninnikov
Psamminopella gradsteini Kaminski & Geroch
Psammosphaera fusca Schultze
Recurvoides div. sp.
Remesella varians (Glaessner)
Reophax duplex Grzybowski
Reophax elongatus Grzybowski
Reophax guttifer Brady
Reophax nodulosus Brady
Reophax pilulifer Brady
Reophax scalaris Grzybowski
Reophax trinitanensis (Cushman & Renz)
Reticulophragmium amplexans (Grzybowski)
Rhabdammina cylindrica Glaessner
Rhabdammina discreta Brady
Rhabdammina robusta (Grzybowski)
Rhizammina indivisa Brady
Rzehakina epigona (Rzehak)
Rzehakina fissistomata (Grzybowski)
Rzehakina minima Cushman & Renz
Saccammina grzybowskii (Schubert)
Saccammina placenta (Grzybowski)
Saccamminoides carpaticus Geroch
Spiroplectammina navarroana Cushman
Spiroplectammina spectabilis (Grzybowski)
Subreophax splendidus (Grzybowski)
Textularia sp.
Thalmannammina subturbinata (Grzybowski)
Tritaxia amorpha (Cushman)
Trochammina aliformis Cushman & Renz
Trochammina bulloidiformis (Grzybowski)
Trochammina globigeriniformis (Parker & Jones)
Trochammina quadriloba (Grzybowski)
Trochamminoides coronatus (Brady)
Trochamminoides proteus (Karrer)
Trochamminoides variolarius (Grzybowski)

Calcareous benthic foraminifera

Abysammina poagi Schnitker & Tjalsma
Abysammina quadrata Schnitker & Tjalsma
Anomalina acuta Plummer
FORAMINIFERAL PALAEODEPTH INDICATORS

Anomalina praecuta Vasilenko
Anomalina sp.
Anomalinoideas capitatus (Gümbel)
Anomalinoideas midwayensis (Plummer)
Anomalinoideas rubiginosus (Cushman)
Anomalinoideas semicribratus (Beckman)
Anomalinoideas umbilicata (Brotzen)
Aragonia owezzanensis (Rey)
Aragonia velascoensis (Cushman)
Bulimina sp.
Cibicides sp.
Cibicidoides havanensis (Cushman & Bermudez)
Cibicidoides sp.
Clinapertina complanata Tjalsma & Lohman
Clinapertina subplanispira Tjalsma & Lohman
Dentalina catenula Reuss
Dentalina gracilis d'Orbigny
Dentalina megapolitana Reuss
Dentalina multicostata d'Orbigny
Ellipsopodiumorphina sp.
Ellipsoglandulina cucenicana Olbertz
Ellipsoglandulina obesa Hanzlikova
Ellipsomorphina sp.
Ellipsomorphina velascoensis (Cushman)
Eponides subcandideus (Grzybowski)
Eponides umbonatus (Reuss)
Gavelinella affinis (Hantken)
Gavelinella danica (Brotzen)
Globobulimina sp.
Globocassidulina inexculta (Franzenau)
Guttulina adhaerens (Olszewski)
Guttulina problema d'Orbigny
Gyroidinoideas nitidas (Reuss)
Gyroidina turgida (Hagenow)
Gyroidinoideas girardanus (Reuss)
Gyroidinoideas globosus (Hagenow)
Lagena emaciata Reuss
Lenticulina absisa (Grzybowski)
Marginulinopsis sp.
Nodosarella sp.
Nodosaria limbata d'Orbigny
Nodosaria monile Hagenow
Nodosaria velascoensis Cushman
Nonion havanense Cushman & Bermudez
Nonion sp.
Nuttallides truempyi (Nuttall)
Nuttallinella floraeis (White)
Osangularia plummerae Brotzen
Osangularia velascoensis (Cushman)
Pleurostomella acuta Hantken
Pleurostomella eocena Gümbel
Pleurostomella sp.
Pseudonodosaria cylindracea (Reuss)
Pullenia coryelli White
Quadrimorphina allonorphinooides (Reuss)
Quadrimorphina profunda Schnitker & Tjalsma
Saracenaria sp.
Stensiöina beccariiformis (White)
Stilostomella sp.
Valvulineria alpina Hillebrandt

**Planktonic foraminifera**

Acarinina nitida (Martin)
Acarinina primitiva (Finaly)
Acarinina soldadoensis (Brönnimann)
Acarinina cf. wilcoxensis (Cushman & Ponton)
Chilogümbelnia wilcoxensis (Cushman & Ponton)
Chilogümbelnia morsei (Kline)
Globigerina inscisa Hillebrandt
Globigerina quadrata White
Globigerina turgida Finaly
Globoconusa kostowskii (Brotzen & Pozarska)
Morozovella aequa (Cushman & Renz)
Morozovella subbotinae (Morozowa)
Parasubbotina inaequispira (Subbotina)
Parasubbotina cf. pseudobulloides (Plummer)
Parasubbotina varianta (Subbotina)
Subbotina linaperta (Finaly)
Subbotina triangularis (White)
Subbotina triloculinoides (Plummer)
Subbotina velascoensis (Cushman)
Truncorotalites pseudotopilensis (Subbotina)