Small-sized *Trochammina* assemblages in deep-water Eocene flysch deposits (Outer Carpathians, Poland) and their palaeoecological implications

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ABSTRACT – The global climate change in the early Eocene contributed significantly to the turnover of benthic foraminifera. A major extinction within agglutinated and calcareous forms and the occurrence of opportunistic assemblages resulted. The *Trochammina* material described here belongs to these post-crisis assemblages. Foraminiferal assemblages with numerous *Trochammina* species are identified within deep-water Eocene deposits of the Polish part of the Outer Carpathians. *Trochammina* reach up to 80% of the assemblages, the remainder consists of cosmopolitan agglutinated foraminifera, mainly *Bathysiphon, Recurvoides, Paratrochamminoides* and *Trochamminoides*. The low biodiversity (average number of species 24, of genera 15) and the presence of dwarf forms are the main characteristics of the assemblages. These assemblages occur predominantly in shales with numerous organic traces (lower Hieroglyphic beds), deposited in the Silesian Basin (Outer Carpathians) which was on the northern margin of the western Tethys Ocean during the early Eocene (Ypresian, *c*. 50 Ma). The *Trochammina* biofacies developed in the Silesian Basin after the Paleocene–Eocene Thermal Maximum crisis, and is dominated by opportunistic forms, mainly represented by mobile epifauna and shallow-water infauna, interpreted as a recolonizing assemblage in a low energy environment.

KEYWORDS: agglutinated foraminifera, Trochammina, deep water, palaeoecology, biostratigraphy, early Eocene, Outer Carpathians

INTRODUCTION

Deep-water benthic foraminifera commonly inhabit environments that are dominated by 'flysch' sedimentation, a special type of environment where benthic foraminifera colonize the sea floor at depths of up to several thousand of metres, in radically changing conditions of oxygen and nutrient supply (e.g. Miller & Lohmann, 1982; Schönfeld, 2002; Smith & Gallagher, 2003; Ortiz *et al.* 2011). Water depth affects water column pressure and bottom temperature which are crucial to the benthos, as these parameters limit the development of calcareous-shelled fauna (e.g. Funnell, 1967; Schnitker & Tjalsma, 1980; Corliss & Honjo, 1981; Olszewska, 1981, 1984; van Morkhoven *et al.*, 1986; Tjalsma & Lohmann, 1983; Waśkowska-Oliwa, 2005). The delivery of oxygen and food is dependent on the supply of water and sediment to the basin floor. In deep-sea environments this is controlled primarily by the amount and intensity of gravity currents. Turbidites have a strong influence on the benthic foraminiferal occurrence and distribution (Ortiz *et al.*, 2011). However, these currents can bring materials needed by benthic organisms, and/or may cause a threat for the foraminiferal population and may bury it. The palaeontological record in flysch deposits can be variable, especially in high-energy environments as foraminifera generally prefer low-energy environments, and muddy rather than sandy substrates. Assemblages that are associated with thicker mudstone series are good environmental indicators because they mostly represent the autochthonous assemblage that was living on the sea floor during times when gravity currents had no significant impact. The lower parts of the Hieroglyphic beds represent such a sedimentary setting. Assemblages with a number of small-sized *Trochammina* have previously been identified within these deposits (Waśkowska, 2012).

Assemblages dominated by one or a few species/genera are well known from the flysch depositional environments of the Outer Carpathians. The increased abundance of, for example, *Glomospira, Nothia, Bathysiphon, Paratrochamminoides, Reophax, Recurvoides* and *Praesphaerammina* is well known in Eocene deep-water deposits (e.g. Geroch, 1960; Geroch *et al.* 1967; Jurkiewicz, 1967; Bubik, 1995*b*; Bąk *et al.* 1997; Olszewska, 1997; Waśkowska-Oliwa, 2000; Bąk, 2004; Kender *et al.*, 2005; Waśkowska, 2011*a*). The appearance of such assemblages in deep-water conditions is associated with specific changes in the environment, often of regional or wider significance. Some of these foraminiferal acmes are characteristic of specific time intervals, and are used successfully as stratigraphic indicators in the Carpathian basins and further afield in the western Tethys (Kaminski, 2005).

GEOLOGICAL BACKGROUND

The Outer Carpathians have a nappe structure which was developed in the Miocene. Micropalaeontological research was carried out on Eocene deposits belonging to the Silesian Nappe (Fig. 1a) including the informal subdivision named as Hieroglyphic beds. A formal lithostratigraphy for the studied region has yet to be defined. The deposits analysed in this work are from the Kamesznica region (Janoska section, Beskid Śląski Range) and the Szczyrzyc region (Krzesławice section, Beskid Wyspowy Range) (Fig. 1b, c). Hieroglyphic beds are represented there by thin-bedded flysch shale–sandstone deposits (Burtan, 1974, 1978; Chodyń & Waśkowska-Oliwa, 2006; Waśkowska-Oliwa *et al.* 2008; Doktor *et al.*, 2010). Mudstones are dominant, forming sequences of beds of variable thicknesses from several centimetres to tens of metres, grey, green and bluish in colour. Thin intercalations of variegated shales are observed locally in thicker complexes. The intercalated sandstones are usually siliceous, thin-bedded and fine-grained. Their characteristic feature, which gives the name to the unit, is
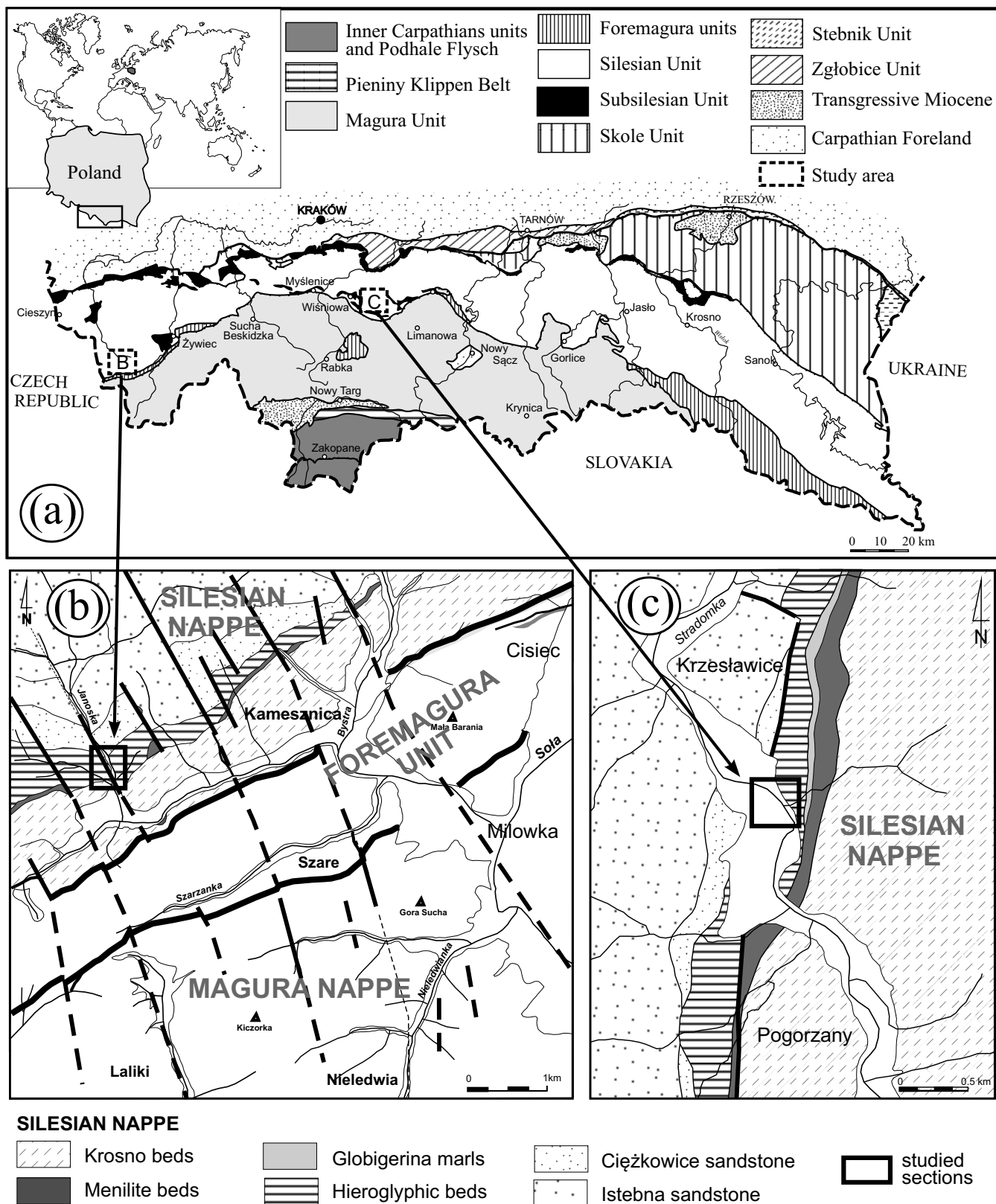
Fig. 1. (**a**) Geological sketch-maps of study areas on the background tectonic map of the Polish Carpathians: (**b**) Kamesznica area, after Burtan *et al.* (1956, modified); (**c**) Krzesławice area, after Chodyń & Waśkowska-Oliwa (2006, modified).

the presence of numerous sedimentary features reminiscent of hieroglyphics. The sampled sections belong to the Hieroglyphic beds where sandstone beds are missing or represent only a minor component of the lithology (Fig. 3).

The studied sediments were deposited in the Outer Carpathians basin, which was a part of the Tethys Ocean and had the features of a deep-sea basin, dominated by flysch-type sedimentation. Its range and inner configuration changed over time. In the Late Cretaceous, interbasinal elevations subdivided the basinal area into smaller sub-basins, one of which was the Silesian Basin (Fig. 2). The Early Paleogene was a time of tectonic reorganization, which occurred as a result of the subsidence of some previously elevated structures (Golonka *et al.*, 2006, 2008, 2011; Golonka, 2011 and papers cited therein). The Miocene tectonic movements that formed the present architecture of the Outer Carpathians led to the uplift and emergence of accumulated deposits in the Carpathian basins and their transformation into nappes. The nappes were superimposed on to one another, and the separation between them more or less coincides with the formation of Late Cretaceous–Early Paleogene basins (Golonka & Waśkowska-Oliwa, 2007).

METHODS AND MATERIALS
Lithostratigraphic position
The small-sized *Trochammina* assemblages are identified in deposits of the Beskid Śląski and Beskid Wyspowy ranges in the Silesian Nappe. In both analysed profiles, spaced 100 km apart, the *Trochammina* assemblages occur in the lower part of the stratigraphic section, overlying the strongly reduced Ciężkowice sandstone (Fig. 3). The lithology of the lower part of the Hieroglyphic beds is similar in the analysed profiles, even though they were located at widely separated areas during the early Eocene. The lower part of the Hieroglyphic beds is developed as a mudstone facies, with an almost total lack of sandstones. The highly bioturbated deposits are grey and green, and contain authogenic pyrite and a large admixture of muscovite. In both sections, intercalations of variegated mudstones are present, which are of smaller proportion than in typical hieroglyphic facies; they are accessory and of limited thickness. Intercalations of the variegated mudstones are concentrated in the lower part of Hieroglyphic beds. The characteristic feature of the western section, the Janoska profile, is the common occurrence of sideritic nodules ranging in size from a few centimetres to tens of centimetres in length, which are not found in Krzesławice. Above the sequence of grey mudstones with numerous *Trochammina*, the lithology of the Hieroglyphic beds changes slightly, with an increase in parallel and/or wavy laminated thin-bedded sandstones with quartz and muscovite.

Lithology
Assemblages with small-sized *Trochammina* have been identified in the sequence (50–100 m) of green-grey mudstone (Fig. 3). The proportion of carbonate is estimated to be on average $1–3 \, g \, kg^{-1}$ and the mudstones are characterized by very low TOC, between 0.03 and 0.04%. The mudstones are heavily bioturbated. A few variegated shale intercalations up to tens of centimetres in thickness occur within the mudstones. Very fine-grained, thin-bedded sandstones are rare, and are found only in the Janoska section. After sample processing, the sand-sized fraction of the residue was found to be relatively small, mostly represented by foraminifera with a dominance of thick- and medium-grained agglutinated forms. The characteristic feature of the mudstone is the increased abundance of muscovite, which occurs frequently as thin petal-like crystal fragments. Muscovite is very common in the flysch sediments; it belongs to a group of mica that is resistant to chemical weathering, and is an allogenic component. Foraminifera, especially the coarse-grained epifaunal forms (i.e. *Bathysiphon* or *Trochammina*), have muscovite clasts incorporated into their tests (Plate 1). Another feature of this deposit is the presence of numerous pyrite grains. They occur most often as authogenic regular crystals of isometric shape and various sizes, and are also found incorporated into agglutinated foraminifera tests.

Methodology
The 30 studied samples were collected from outcrops in the banks of two Carpathian streams: Janoska and Stradomka (Fig. 1b, c). The weight of each sample was about 1 kg. The material was prepared according to a standard micropaleontological preparation procedure, including maceration in a saturated Glauber's salt solution, and washing over a 63 μm sieve. Foraminifera from the residues were picked quantitatively and photographically documented using a binocular microscope and scanning electron microscope. All foraminifera were picked from each sample, except samples with a large number of specimens. Such samples were divided into equal-sized random splits and foraminifera were picked from one part of the residue. The number of foraminifera in the whole sample was estimated on the basis of the random split. The abundance of foraminifera was very varied, from 300 to over 3100 specimens per sample from the Krzesławice section, and from 700 to over 10 000 specimens per sample in the Janoska section. Some foraminifera, such as tubular taxa (e.g. *Bathysiphon, Psammosiphonella, Rhizammina*) and uniserial multichambered taxa (e.g. *Reophax, Subreophax, Hormosina*), were preserved only as fragments, which were counted as individual specimens. *Trochammina* dimensions were measured on specimens from Krzesławice section samples (Table 1). The diameter of rounded-shaped forms or the longer axis in elongated forms were measured using a binocular microscope. A total of 120–300 specimens of *Trochammina* per sample were measured. Measurements were made on samples in which the amount of *Trochammina* exceeds 120 specimens.

The samples are housed in the author's collection in the Department of General Geology and Geotourism at the AGH University of Science and Technology in Kraków.

RESULTS
Biostratigraphy
A typical feature of the small-sized *Trochammina* assemblages is that they are taxonomically poor, with cosmopolitan agglutinated forms which have little biostratigraphical value. Only *Saccamminoides carpathicus* Geroch, an index taxon for the late Ypresian, occurs irregularly in the sampled sections. This species occurs at Janoska in samples 138/18/07, 135/13/07, 130/8/07, 137/17/07 and 129/7/07 (Fig. 3c). At Krzesławice, in sample 71/39/05 (variegated shales), in an assemblage with an increased proportion of *Trochammina*, one specimen was identified as ?*Saccamminoides carpathicus* Geroch. In the same profile, sample 11/38a/09 (collected about 10 m below sample 71/39/05) (Fig. 3b), yielded a specimen of *Reticulophragmium amplectens* (Grzybowski) (Fig. 4). The first appearance of this species in the Carpathians flysch is dated as late Ypresian in age, and it may
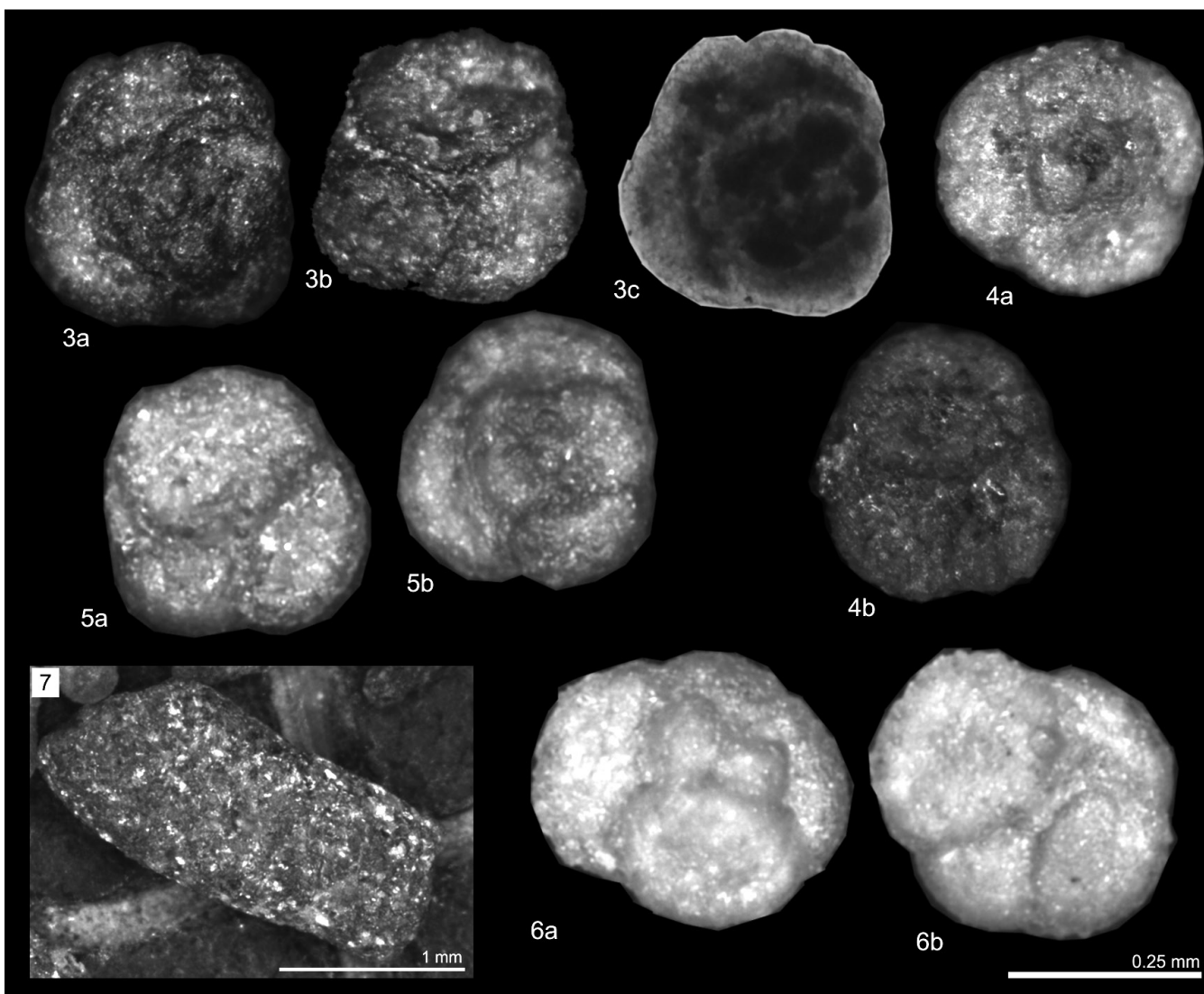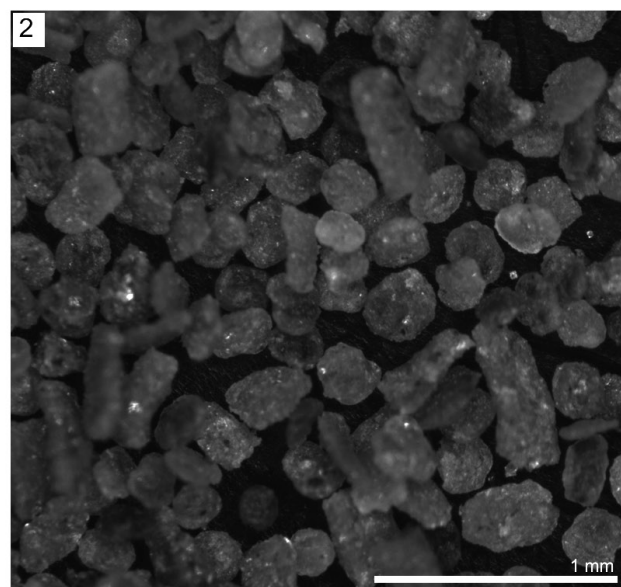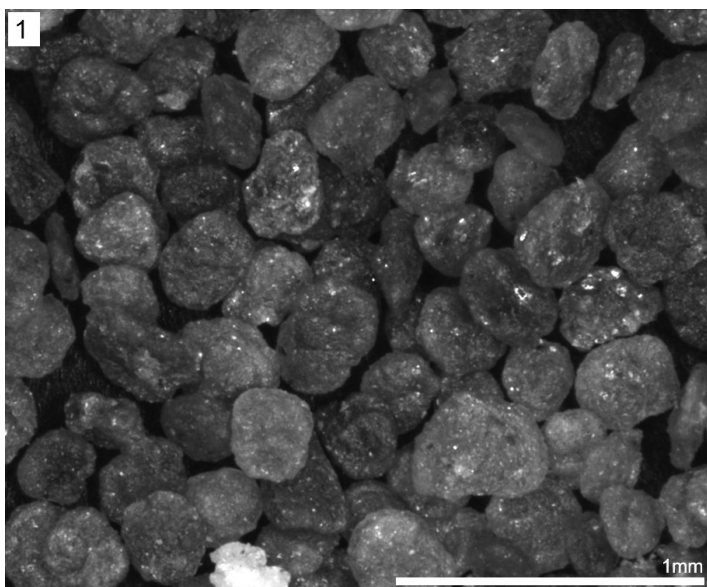
Table 1. Dimensions of *Trochammina* tests in the Krzesławice section (%)

| Sample	Diameter (length) of *Trochammina* specimens (mm)								Number of measured specimens
	>0.2	0.21–0.25	0.26–0.30	0.31–0.35	0.36–0.40	0.41–0.45	0.46–0.50	<0.50	
40/36/5	5.21	7.81	15.63	15.71	22.96	14.00	10.58	8.07	300
93/63//09	2.75	15.17	37.93	30.00	7.93	3.79	1.03	1.37	290
10/37/06	4.93	27.98	36.21	24.69	2.26	2.88	0.61	0.42	300
71/39/05	7.50	25.00	22.50	27.50	12.50	3.75	0.62	0.62	300
93/64/09	—	16.40	33.33	31.74	13.22	3.70	1.05	0.52	200
41/40/06	0.93	40.18	39.25	14.95	4.67	—	—	—	220
95/65/09	3.76	46.77	40.32	7.52	1.07	0.53	—	—	200
90/42/05	—	21.42	17.85	25.89	6.25	24.10	1.78	2.67	120
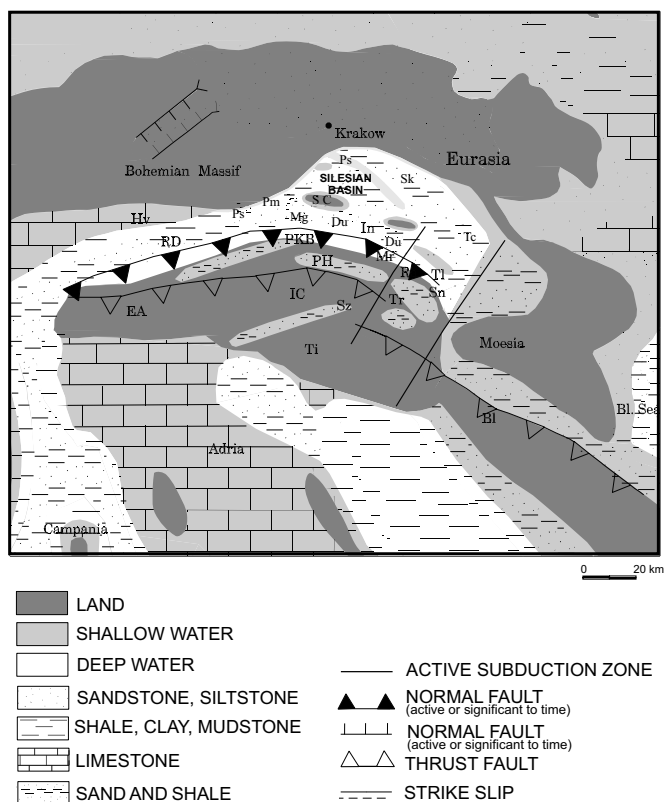
Fig. 2. Palaeogeographical position of the Carpathian Silesian Basin in the Eocene (45 Ma), after Golonka *et al.* (2006, modified). Abbreviations: Bl, Balkan Basin and foldbelt; Du, Dukla Basin; EA, Eastern Alps; Hv, Helvetic shelf; IC, Inner Carpathians; In, Inacovce-Kricevo zone; Mg, Magura Basin; Mr, Marmarosh Massif; PH, Inner Carpathian (Podhale) Basin; PKB, Pieniny Klippen Belt; Pm, Fore-Magura Basin; Ps, Sub-Silesian Ridge and slope zone; Ra, Rakhiv Basin; RD, Rheno Danubian; SC, Silesian Ridge (Cordillera); Sk, Skole Basin; Sn, Sinaia Basin; Sz, Szolnok Basin; Tc, Tarcau Basin; Ti, Tisa plate; Tl, Teleajen Basin; Tr, Transilvanian Basin.

co-occur in a short interval together with *Saccamminoides carpathicus* (Olszewska *et al.*, 1996; Olszewska, 1997; Kaminski & Gradstein, 2005; Waśkowska, 2011*b*). From the deposits with the *Trochammina* biofacies the following taxa were recognized: *Pseudonodosinella elongata* (Grzybowski), *Eratidus gerochii* Kaminski & Gradstein and ?*Eggerelloides* aff. *E. propinqus* (Brady). These taxa appear in the lower Eocene in the Carpathian flysch (e.g. Jurkiewicz, 1967; Morgiel & Szymakowska, 1978; Geroch & Koszarski, 1988; Bubik, 1995*a*, 2006; Kaminski & Gradstein, 2005) and occur only in the Eocene. *Caudammina ovula* (Grzybowski), *Glomospira diffundens* Cushman & Renz, *Caudammina excelsa* (Dylążanka) and *Hormosina velascoensis* (Cushman) occur irregularly as accompanying single taxa. These taxa are common in the uppermost Cretaceous–Paleocene and range to the lower Eocene (Jurkiewicz, 1967; Bąk, 2004; Kaminski & Gradstein, 2005; Waśkowska, 2011*a*, *b*).

The presence of ?*Saccamminoides carpathicus* Geroch in only one sample in the Krzesławice section is a weak biostratigraphical marker and to confirm the biostratigraphical result adjacent levels were sampled. Mudstones lying below the Hieroglyphic beds contain agglutinated foraminifera assemblages of Paleocene age, with numerous *Caudammina, Hormosina* and *Rzehakina*, among which *Rzehakina fissistomata* (Grzybowski) is present (Fig. 4). This species is known in the Carpathians exclusively from the Paleocene (Morgiel & Olszewska, 1981; Geroch & Nowak, 1984; Geroch & Koszarski, 1988; Olszewska, 1997; Bubik *et al.*, 1999; Waśkowska-Oliwa, 2008; and papers cited therein), while deposits about 150 m above contain relatively numerous *Reticulophragmium amplectens* (Grzybowski), indicating a middle Eocene (Lutetian) age. Analysed assemblages with increased numbers of *Trochammina* in the Krzesławice section thus represent the lower Eocene (Ypresian). The biostratigraphical data thus indicate superposition in the studied deposits.

In the Carpathians two lower Eocene foraminiferal biozones are distinguished. The older one – *Glomospira* diverse species (div. sp., with an acme of the genus *Glomospira*) – is characteristic for the lower Ypresian and, following it, the index species
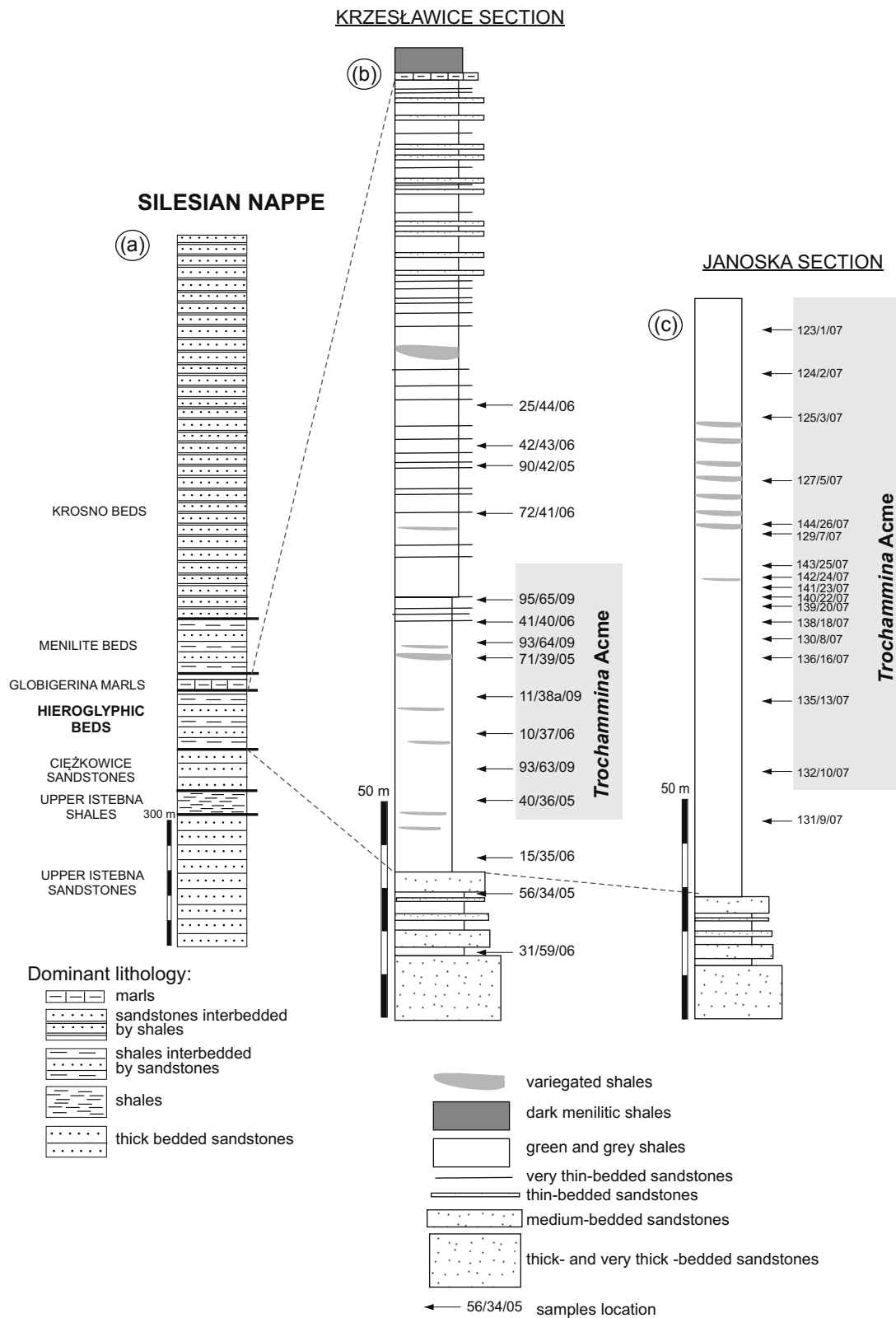
Fig. 3. Lithological logs of analysed profiles of Hieroglyphic beds (**b**, **c**) with sample points and their position in general log of Paleogene deposits of Silesian Nappe (**a**).
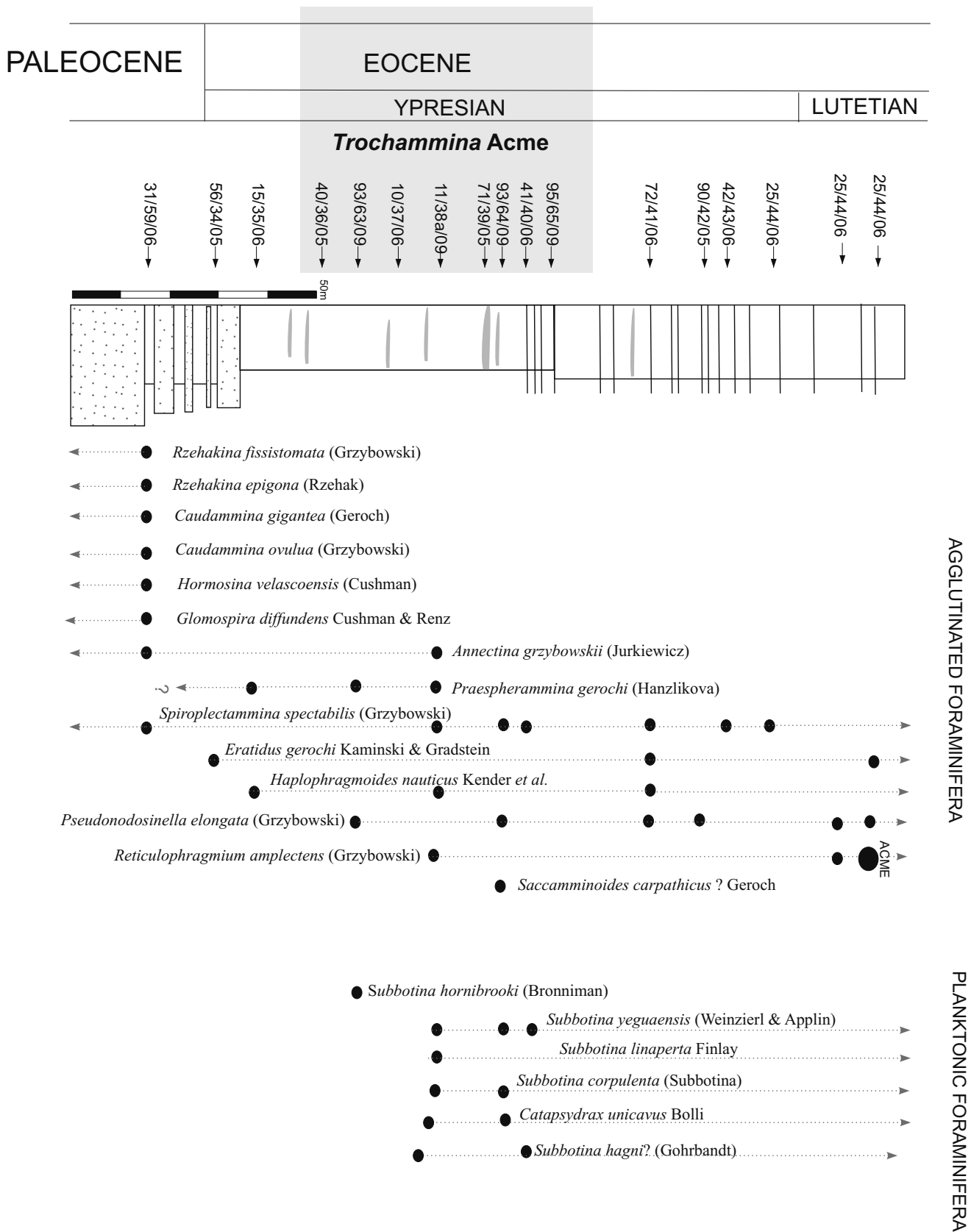
Fig. 4. Distribution of biostratigraphically important taxa against lithological log of lower Hieroglyphic beds in Krzesławice area. Arrows indicate the continuation of species ranges in the lower or higher part of the lithostratigraphic log.
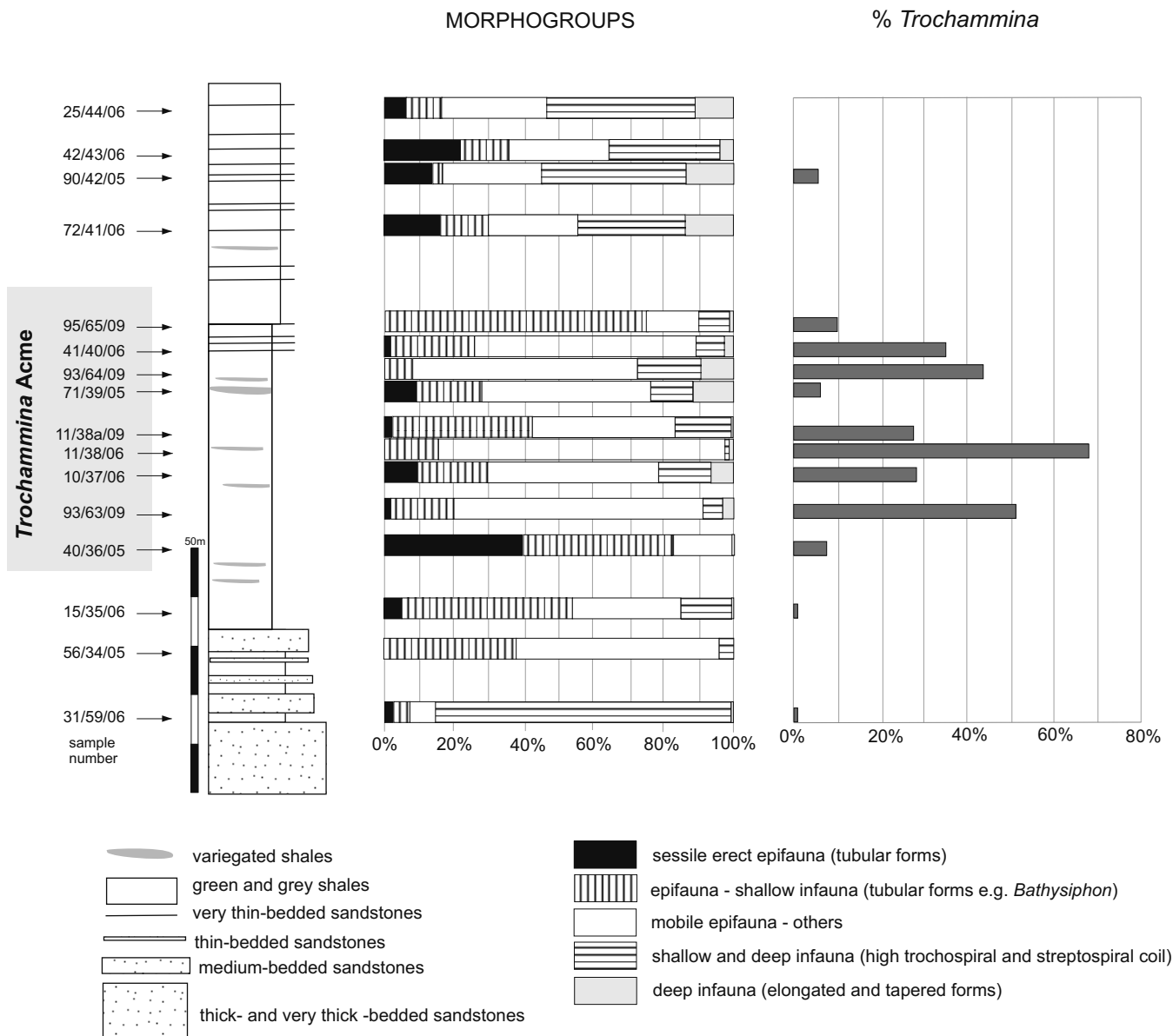
Fig. 5. Distribution of basic morphogroups and *Trochammina* in lower Hieroglyphic beds at Krzesławice section.

Saccamminoides carpathicus Geroch defines the upper Ypresian (*sensu* Morgiel & Olszewska, 1981; Olszewska, 1997). In the analysed sections the *Glomospira* div. sp. biozone is not present. In the depositional environment of the Heiroglyphic beds the assemblages characteristic for the *Glomospira* div. sp. biozone were replaced by the small-sized *Trochammina* assemblages (Plate 2).

In some Krzesławice samples, planktonic foraminifera have been identified as poorly preserved accessory forms (often as internal moulds), i.e. *Subbotina linaperta* Finlay, *Subbotina hagni*? (Gohrbandt), *Subbotina yeguaensis* (Weinzierl & Applin), *Subbotina corpulenta* (Subbotina) and *Catapsydrax unicavus* Bolli (Fig. 4), cosmopolitan taxa known from the Eocene of the Carpathians. They appear in the Ypresian, in the younger part of this interval and survived until the late Eocene (Pearson *et al.*, 2006). In sample 93/64/09 (lower part of deposits with small-sized *Trochammina* assemblages), *Subbotina hornibrooki* (Brönnimann) is present, typi-

cal for the early Ypresian. Slightly higher in the profile *Subbotina linaperta* Finlay and *Subbotina yeguaensis* (Weinzierl & Applin) are present in one sample with the agglutinated species *Reticulophragmium amplectens* (Grzybowski), *Haplophragmoides nauticus* Kender *et al.* and *Annectina grzybowskii* (Jurkiewicz) (Fig. 4). These foraminifera co-occur only in the Ypresian. The stratigraphic range for *Annectina grzybowskii* (Jurkiewicz) is upper Cenomanian to Paleocene (Olszewska *et al.*, 1996; Kaminski & Gradstein, 2005), but this form is identified also in the Eocene in the Carpathians (Hanzlikova & Pesl, 1964; Waśkowska-Oliwa, 2005; Cieszkowski *et al.* 2006; Waśkowska, 2011*b*). All of the aforementioned planktonic species are present below the acme of *Reticulophragmium amplectens* (Grzybowski). Taking into account the taxonomical composition of agglutinated and planktonic foraminifera and their biostratigraphical ranges, the assemblages with numerous small-sized *Trochammina* occurred in the Ypresian.
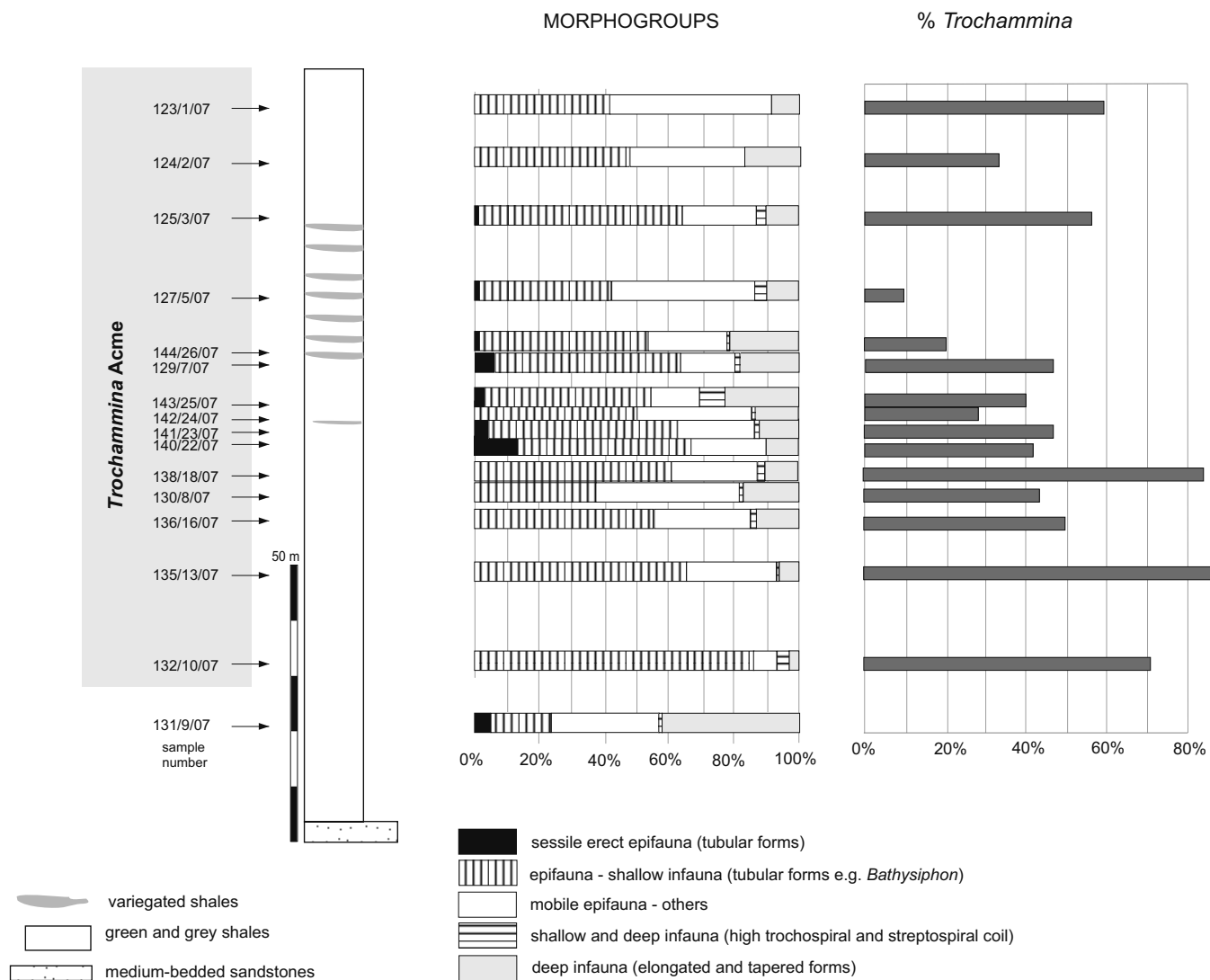
**Fig. 6.** Distribution of basic morphogroups and *Trochammina* in lower Hieroglyphic beds at Janoska.

THE SMALL-SIZED *TROCHAMMINA* ASSEMBLAGE
Assemblage composition, taxonomic diversity

Agglutinated taxa are dominant in the analysed assemblages and calcareous forms are uncommon. Fish teeth are an associated component and are especially prevalent in the Krzesławice section. Agglutinated forms are in a good state of preservation; most of them have diagnostic characteristics, allowing taxonomic determination at the specific or generic level. A typical feature of the assemblages is the presence of coarse- and medium-grained forms (e.g. *Bathysiphon, Trochammina, Reophax, Karrerulina*). Specimens of *Trochammina* accounted for an average of 42% of the assemblages in Krzesławice and 47% of the assemblages in Janoska (Figs 5 and 6). These values should be regarded as minimum values. The real percentage of *Trochammina* could be higher, because taxa such as the tubular foraminifera (numerous in the analysed material) and uniserial multichambered forms occur as fragments and each was counted as an individual specimen, so their actual abundance is certainly overstated. *Trochammina* in the Krzesławice section reach almost 70% and at Janoska more than

80% (Figs 5 and 6), and such assemblages can be called monotaxa associations. Another important large group of microfossils are the tubular forms belonging to the genus *Bathysiphon* (Figs 5 and 6). These are cosmopolitan foraminifera in the Carpathian flysch, and are usually represented by test fragments. Another important group of foraminifera, with proportions of a few to several percent are the genera *Paratrochamminoides* and *Trochamminoides, Recurvoides* and *Thalmannammina*; a small percentage of the assemblage is comprised of *Ammodiscus* and *Glomospira*. Other cosmopolitan foraminifera are poorly represented, for example *Placentammina, Arthrodendron, Haplophragmoides, Karrerulina* and *Pseudonodosinella* (Plates 3 and 4).

Scarce calcareous foraminifera were occasionally found in individual samples from the Krzesławice section (nos 93/63/09, 11/38a/09, 93/64/09, 41/40/09). They consist of single or a few specimens. The state of preservation was poor, most often the shell surface was dissolved, partially or completely, resulting in internal moulds. Planktonic foraminifera are represented primarily by the so-called large *Subbotina* (e.g. *S. yeguaensis* (Weinzel &

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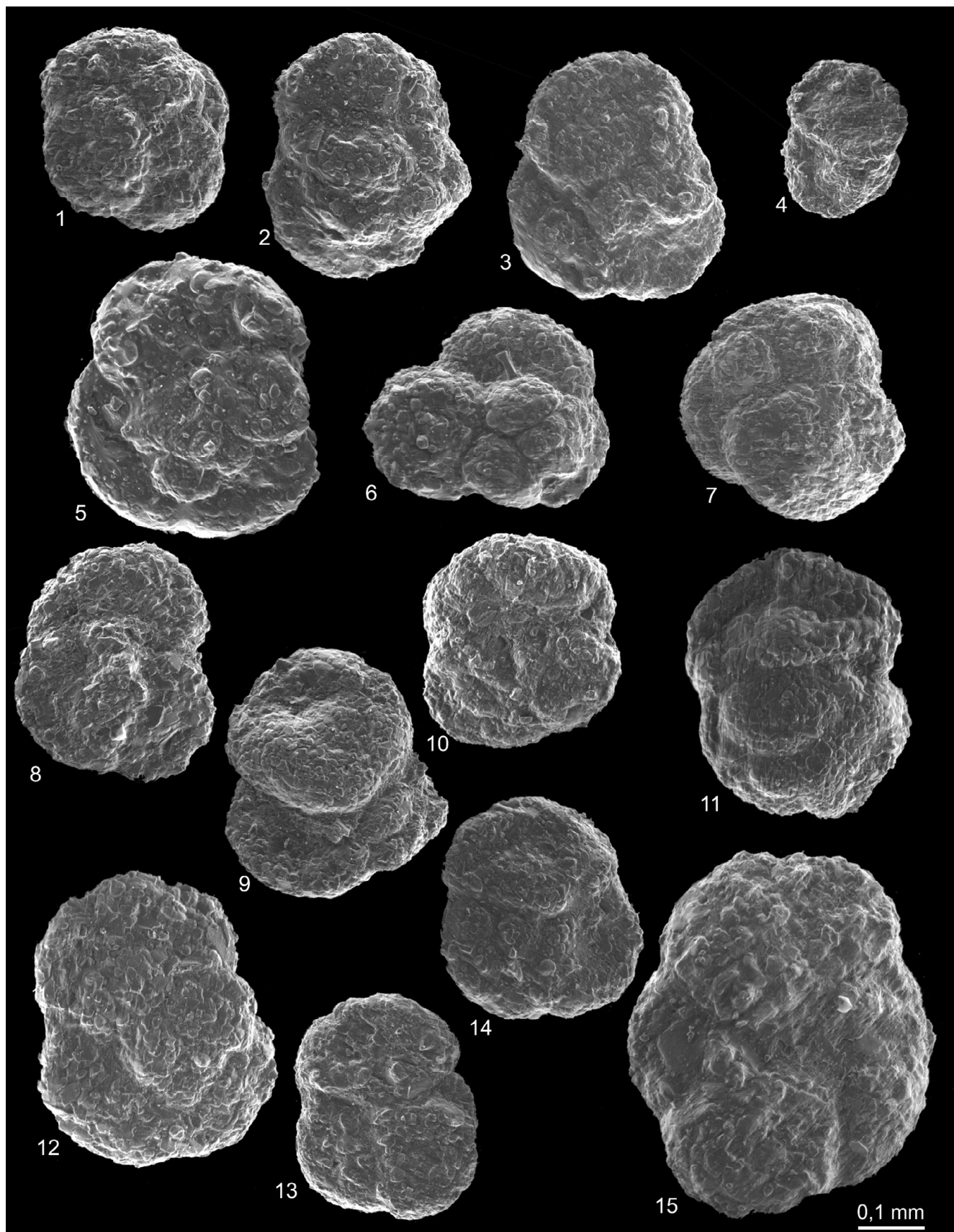
Applin), *S. corpulenta* (Subbotina), *S. hagni*? (Gohrbandt) and *S. linaperta* (Finlay)) (Plate 4). Calcareous forms include *Nuttallides truempyi* (Nuttall) and *Oridorsalis umbonatus* (Reuss). In assemblages with numerous *Trochammina* the average overall generic diversity is 15. Excluding *Trochammina*, the average number of species is 23. In the underlying Paleocene deposits 45 species belonging to 24 genera were found, while in overlying deposits 36 species belonging to 21 genera were recorded. Small-sized *Trochammina* assemblages show a decreasing trend in diversity in comparison with assemblages from surrounding deposits.

Size of foraminiferal tests

Another trend observed in assemblages with numerous *Trochammina* is a decrease in the size of all foraminiferal tests. Assemblages are represented mainly by specimens that measure 0.2–0.4 mm length (or diameter); larger forms are significantly more numerous in deposits underlying and overlying the *Trochammina* assemblages.

Size differences are clearly visible on the tests of specimens of one taxonomic group. The genus *Trochammina* was chosen for measurement in samples from the Krzesławice section.

Dimensions of *Trochammina* specimens within the size range 0.20–0.35 mm are dominant and represent 80–95% of *Trochammina*. Larger forms, with diameter (length) above 0.45 mm are rare or absent; specimens smaller than 0.2 mm are more common. In assemblages from the under- and overlying deposits the forms smaller than 0.35 mm make up to 40% of *Trochammina*, and the most common forms occur in the size range 0.31–0.45 mm, with some specimens exceeding a diameter of 0.5 mm.

Morphogroup distribution

Benthic foraminifera live at the surface of the sea floor and within the upper few centimetres of the sediment. One of the easily identifiable effects of environmental adaptation is test morphology. It is possible to estimate palaeoecological parameters of the assemblage, indicating its depositional environment on the basis of the test shape, as has been previously shown by Jones & Charnock (1985) with later modifications (see Murray *et al.*, 2011 and papers cited therein). This has been successfully used for palaeontological analysis of Mesozoic and Cenozoic palaeoenvironments (Coccioni & Galeotti, 1994; Nagy *et al.*, 1995; Bąk *et al.*, 1997; Peryt *et al.*, 1997; Mancin, 2001; Waśkowska-Oliwa & Leśniak, 2003; Bąk, 2004; Kender *et al.*, 2008; Setoyama *et al.*, 2011).

In the analysed material, an overwhelming dominance of forms connected with the sediment surface (epifauna and *Bathysiphon*) is clear, which can range from 70–98% in assemblages from both profiles (Figs 5 and 6). The largest group consists of mobile foraminifera (predominantly *Trochammina*), colonizing the surface of the sediment, the tests of which are typically flattened, low trochospiral, planoconvex and concavo-convex. Apart from *Trochammina* they are represented by various species of *Ammodiscus, Glomospira, Trochamminoides* and *Paratrochamminoides*. The increase of epifauna is associated with monogeneric *Trochammina* dominance, and with a decrease in the abundance of deep migrating infauna.

The infaunal group that is significantly reduced is the shallow-deep infauna, represented by high-trochospiral and trochospiral forms such as *Recurvoides* and *Thalmannammina*.

An important component of the analysed assemblages is *Bathysiphon*, belonging to the tubular forms, often incorporated into the group of erect epifauna. Research on modern assemblages indicates that *Bathysiphon* can function as an infaunal–epifaunal form, choosing a horizontal or nearly horizontal position in the sediment (Gooday *et al.*, 2002). This form builds very long tubular chambers, attaining a length of a few centimetres, with irregular thickness and constrictions in many places (Małecki, 1973). This type of test morphology is not conducive to continued functioning as erect epifauna. *Bathysiphon* most often inhabits the subsurface parts of the bottom sediment, intensely penetrating them, being able to move quite fast within the sediment (e.g. Gooday *et al.*, 1992; Geslin *et al.*, 2004). It is included here in the deposit feeders (Gooday *et al.*, 2002).

THE ASSEMBLAGE IN VARIEGATED SHALE INTERCALATIONS

Both analysed profiles contain intercalations of variegated shales with a thickness from a few to tens of centimetres. In comparison with the typical grey mudstones with numerous *Trochammina*, the variegated shales are finer-grained, with increased amounts of clay minerals and lesser amounts of muscovite and rare pyrite. In the variegated deposits, the TOC values increase rapidly to 0.03–0.38%, with a concomitant slight increase in the amount of carbonate reaching 6 g kg^{-1}. Foraminiferal assemblages in the variegated shales are represented by sample 71/39/09 of the Krzesławice section, and sample 127/5/07 from Janoska. Samples Janoska 130/8/07 and Janoska 144/26/07 were collected from mixed variegated shale and typical Hieroglyphic beds. The taxonomic composition of assemblages from the variegated shales differs significantly from those characteristic for the small-sized *Trochammina* assemblages from surrounding deposits. The main feature is the small amount of *Trochammina*, which is estimated here as 6.5% in the Krzesławice section, giving a value 8 times lower than average, and 9% in the Janoska section which is 5 times lower than average (Figs 5 and 6). The decrease in *Trochammina* does not affect the solid trend in the distribution of morphogroups and the proportion of the mobile epifauna, which is preserved in the surrounding deposits, because it is compensated by an increase in the number of other foraminifera incorporated into this group, especially with species of *Ammodiscus, Glomospira, Paratrochamminoides* and *Trochamminoides*. The group of deep migrating infauna is here much more numerous and taxonomically diversified.

Explanation of Plate 2. *Trochammina*, SEM images. **fig. 1.** sample Janoska135/13/07, specimen no. t7. **fig. 2.** sample Janoska 135/13/07, specimen no. t11. **fig. 13.** sample Janoska 135/13/07, specimen no. t32. **fig. 14.** sample Janoska 135/13/07, specimen no. t35. **fig. 3.** Janoska 123/10/07, specimen no. t16. **fig. 4.** sample Janoska 123/10/07, specimen no. t20. **fig. 6.** Janoska 123/10/07, specimen no. t24. **fig. 12.** sample Janoska 123/10/07, specimen no. t33. **fig. 5.** sample Krzesławice 40/36/07, specimen no. t7. **fig. 7.** sample Krzesławice 40/36/07, specimen no. t9. **fig. 8.** sample Krzesławice 40/36/07, specimen no. t14. **fig. 9.** sample Krzesławice 40/36/07, specimen no. t19. **fig. 10.** sample Krzesławice 40/36/07, specimen no. t45. **fig. 11.** sample Krzesławice 40/36/07, specimen no. t 56. **fig. 15.** sample Krzesławice 40/36/07, specimen no. t78.
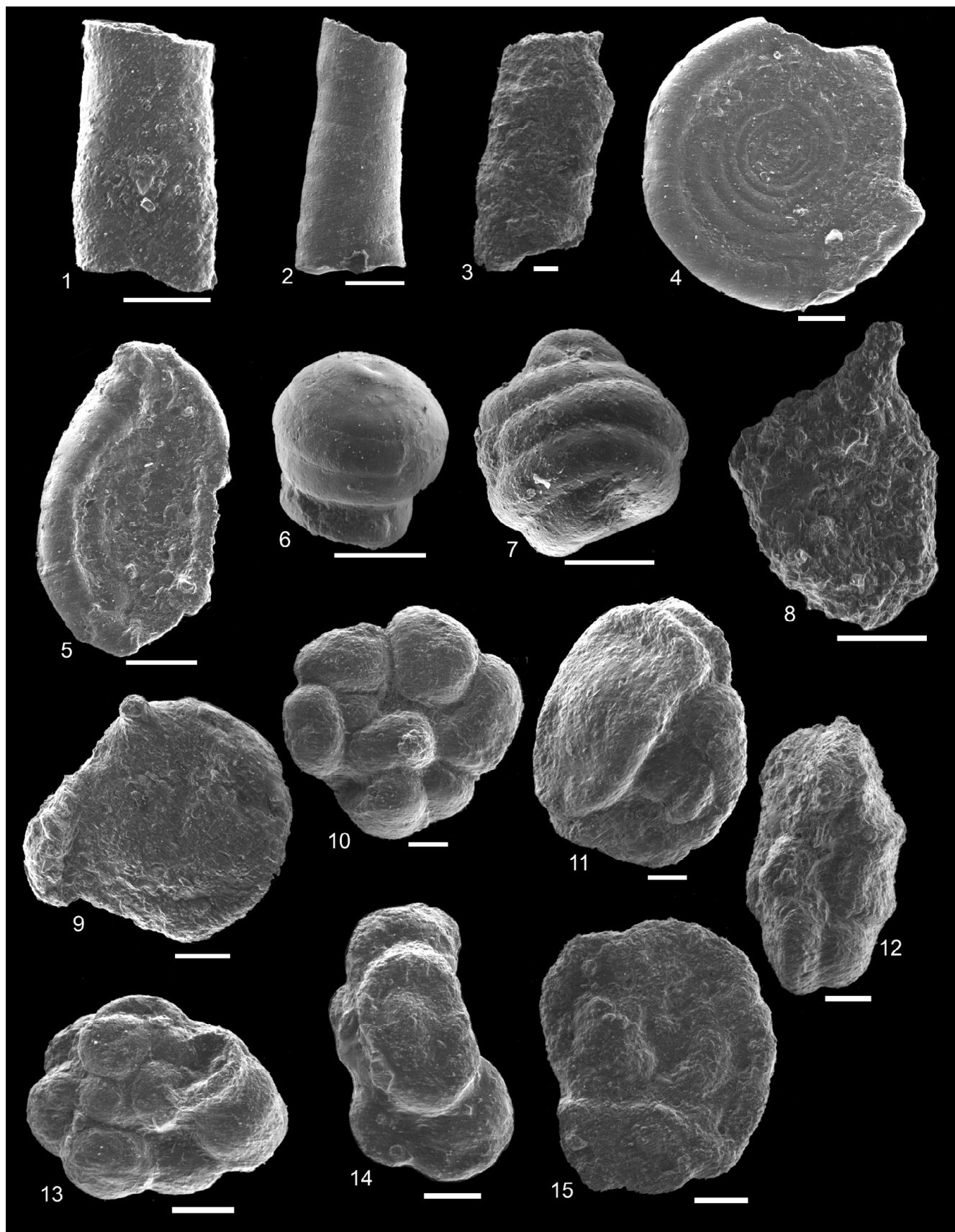
It should also be noted that the variegated shales assemblage is abundant in the Krzesławice section, where the number of specimens in a single sample exceeds 3100, and in the Janoska profile where it exceeds 10 000 foraminifera. These high faunal abundances may be the result of sedimentary condensation, indicating a decrease in the supply of terrigenous material.

In the variegated shales the biodiversity increases. Although, the number of genera is similar, as in the small-sized *Trochammina* assemblages, the number of species is higher and increases to 35 species.

DISCUSSION
Distribution of lower Paleogene *Trochammina* in the Carpathians

In the deep-water setting of the Outer Carpathians, *Trochammina* is frequent in all Paleogene facies, with the following taxa: *Trochammina globigeriniformis* (Parker & Jones), *Trochammina quadriloba* Geroch (*Ammogloborotalia quadriloba*, as re-assigned by Kaminski *et al.*, 2007), *Trochammina altiformis* Cushman & Renz (*Trochamminopsis altiformis* as re-assigned by Kaminski & Gradstein, 2005) and *Trochammina bulloidiformis* (Grzybowski) (Geroch, 1959, 1960; Geroch *et al.* 1967; Jurkiewicz, 1967; Morgiel & Szymakowska, 1978; Malinowska, 1984; Waśkowska-Oliwa, 2005). They are known not only from individual Carpathian basins, but also reported from other regions of Tethys (Kuhnt & Kaminski, 1990; Kuhnt & Collins, 1996; Kaminski & Gradstein, 2005). They are usually recorded in the Carpathian literature as an accessory component of diverse multispecies assemblages. It is also possible that additional undescribed trochamminid species are present in the assemblage, since the taxonomy of this group is still unclear. None of the *Trochammina* species is similar to taxa from modern salt marshes described by Scott & Medioli (1980). The trochamminids are usually present in assemblages from Outer Carpathian deposits, but they occur as single specimens. Large numbers of *Trochammina* species are found in the lower Paleogene deposits of the Eastern Outer Carpathians that are included into the Dukla Nappe. The occurrence of *Trochammina* there is characteristic for late Paleocene and early Eocene age assemblages. A *Recurvoides–Trochammina–Trochamminoides* and *Paratrochamminoides* biofacies has been distinguished in the Paleocene assemblages (Bąk, 2004). However, in the Hieroglyphic beds of the Silesian Nappe, assemblages with numerous *Trochammina* have been indentified (Waśkowska, 2012). This group is dominated by foraminifera with a free test, low trochospiral coiling, evolute, dorsal side flattened and ventral side convex; their chambers increase rapidly in size, with the last whorl containing 4–3.5 chambers, and they have a coarsely agglutinated wall (Plates 1 and 2). Their size is highly variable, from 0.17–0.62 mm. The largest forms are morphologically referred to

Trochammina umiatensis Tappan, whereas the distinguishing features of the small forms are somewhat obscured by the coarsely agglutinated wall. The *Trochammina* specimens illustrated by Bubik (1995b) and Bąk (2004) from deep-water Paleogene deposits of the Carpathians show some resemblance to the fine specimens in the material analysed in this study. Determination of the species-level taxonomy will require further investigation.

Trochammina assemblages and global climatic change

The early Eocene was a time interval associated with the reconstruction of benthic fauna in deep-water basins, especially marked in the Outer Carpathians basins (Bubik, 1995a; Bąk, 2004; Waśkowska-Oliwa, 2005). This trend is global in extent and is associated with changes in palaeoclimate in the late Paleocene, especially connected to the Paleocene–Eocene Thermal Maximum (PETM; Tjalsma & Lohman, 1983; Miller *et al.*, 1987; Kennett & Stott, 1991; Pak & Miller, 1992; Kaiho *et al.*, 1993, 1996; Thomas & Shackleton, 1996; Thomas, 1998; Pardo *et al.*, 1999; Galeotti *et al.*, 2004; Bąk & Barwicz-Piskorz, 2005), which is associated with changes in the carbon cycle (Boersma *et al.*, 1987). As a result, a mass extinction of many species of benthic foraminifera is observed in the deep-sea environment, and the event is identified as the largest global extinction of calcareous benthonic foraminifera (Thomas, 1998; Alegret *et al.*, 2010).

The early Eocene assemblages are known as a new post-crisis fauna; among them there are many opportunistic long-living forms that persisted from the Cretaceous and which managed to survive the late Paleocene crisis (Kaminski *et al.*, 1996). In the Carpathian basins post-crisis assemblages are characteristic because they have low taxonomic diversity with numerous small forms of *Glomospira*, with two species dominating (Jurkiewicz, 1967; Bubik, 1994, 1995b; Bąk *et al.*, 1997; Waśkowska-Oliwa, 2000; Bąk, 2004; Oszczypko *et al.*, 2005; Cieszkowski *et al.*, 2011; Waśkowska, 2011a; Arreguin-Rodriguez *et al.*, 2013). *Glomospira* assemblages are usually found in hemipelagic variegated deep-sea deposits (Morgiel & Olszewska, 1981, 1982; Waśkowska-Oliwa, 2000; Bąk, 2004; Cieszkowski *et al.*, 2004; Bąk & Barwicz-Piskorz, 2005) representing areas of low sedimentation rate (Kaminski *et al.*, 1989). The successive rebuilding of the structure of the benthic foraminiferal assemblage was a gradual and long-term process that lasted until the middle Eocene, when conditions once again became favourable for the development of benthos in low-energy conditions. At this time benthic foraminiferal assemblages reached their maximum diversity, and at the same time the epi- and infaunal niches were evenly inhabited (Kaminski *et al.*, 1999). An interval of restructuring of the benthic assemblage is associated with the later phase of the early Eocene, which is characterized by the presence of *Saccamminoides carpathicus* (Geroch). The reconstruction was not uniform, took place at different rates

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Explanation of Plate. 3. Agglutinated foraminifera from *Trochammina* assemblages, SEM images. **fig. 1.** *Bathysiphon* sp. (sample Janoska 132/10/07, specimen no. 23). **fig. 2.** *Bathysiphon* sp. (sample Janoska 132/10/07, specimen no. 34). **fig. 3.** *Bathysiphon* sp. (Krzesławice 40/36/05, specimen no. b14). **fig. 4.** *Ammodiscus incertus* (d'Orbigny) (Janoska 132/10/07, specimen no. a3). **fig. 5.** *Ammodiscus peruvianus* Berry (Janoska 123/1/07, specimen no. a4). **fig. 6.** *Glomospira charoides* (Jones & Parker) (Janoska 123/1/07, specimen no. g7). **fig. 7.** *Glomospira charoides* (Jones & Parker) (Janoska 123/1/07, specimen no. g15). **fig. 8.** *Saccammina grzybowskii* (Schubert) (Janoska 123/1/07, specimen no. s2). **fig. 9.** *Placentammina placenta* (Grzybowski) (Krzesławice 40/36/05, specimen no. pl2). **fig. 10.** *Paratrochamminoides deflexiformis* (Noth) (Krzesławice 40/36/05, specimen no. pr34). **fig. 13.** *Paratrochamminoides deflexiformis* (Noth) (Krzesławice 40/36/05, specimen no. pr14). fig. 11. *Paratrochamminoides* sp. (Krzesławice 40/36/05, specimen no. pr15). **fig. 12.** *Trochamminoides subcoronatus* (Grzybowski) (Janoska 123/1/09, specimen no. tr10). **fig. 14.** *Trochamminoides subcoronatus* (Grzybowski) (Janoska 123/1/09, specimen no. tr17). fig. 15. *Trochamminoides dubius* (Grzybowski) (Janoska 123/1/07, specimen no. tr19). Scale bars 100 μm.
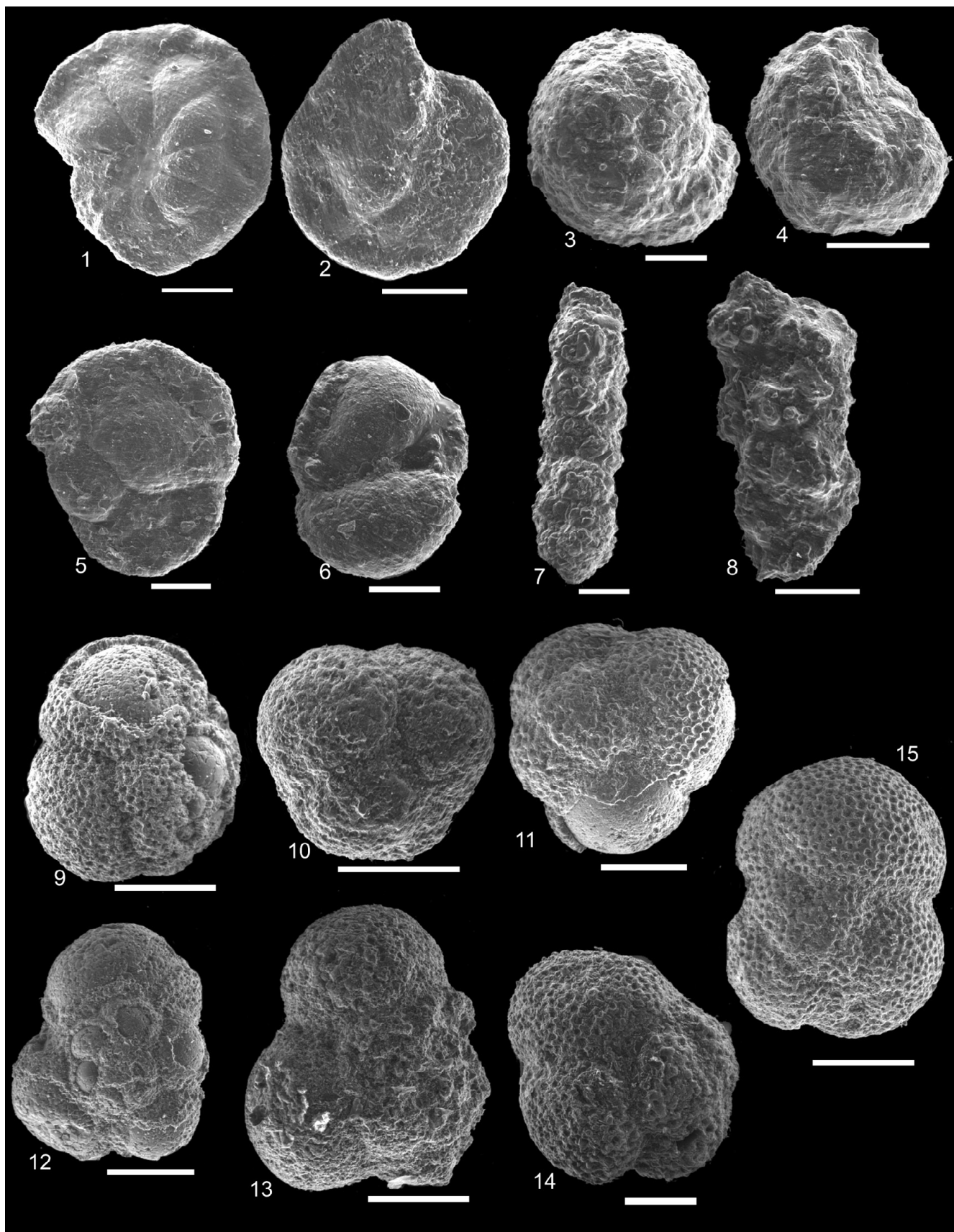
and was dependent on many factors, most of all on the environmental conditions.

In the Silesian Basin, the fauna became differentiated very slowly during the early Eocene. The structure of the *Trochammina* assemblage is very similar to the slightly younger assemblages of the *Glomospira* biofacies, but they differ in the composition of the dominant forms. In the studied material, assemblages characteristic for the *Glomospira* biofacies were not found. Directly above the typical Paleocene assemblages, ones with little distinctive fauna are present, followed by assemblages of the *Trochammina* biofacies. Such a record relates to the grey mudstone deposits. However, within the profile in which the *Trochammina* biofacies is the typical association, intercalations of variegated mudstone appear, in which a sharp increase in *Glomospira* is present and taxonomic diversity is higher. The lack of *Glomospira* biofacies could be an effect of local replacement by the more environmentally tolerant *Trochammina* biofacies in the Silesian Basin.

Opportunistic *Trochammina* assemblages

Trochammina is recorded in the Carpathian basins from the Cretaceous to Oligocene, but it appears rather as an accessory taxon, rarely represented by large numbers of specimens. Increased numbers have been recorded in lower Paleogene from Skole and Dukla basins (Bąk *et al.*, 1997; Bąk, 2004). Numerous reports in the literature refer to the mass appearances of small-sized *Trochammina* in shallow-water environments, where the dominance of this taxon is associated with stressful environmental conditions, such as reduced salinity, oxygen hypoxia, stormy environments, after earthquakes, low or high TOC values (Nagy *et al.*, 1988, 2010; Hollis *et al.*, 1995; Rasmussen *et al.*, 2003; Barbosa *et al.*, 2005; Hawkes *et al.*, 2010; Hromic *et al.*, 2012). It is also common in brackish environments (Jones, 1988; Nagy *et al.*, 1995). *Trochammina* is considered to be an opportunistic form (Scott *et al.*, 1983; Murray, 1991; Nagy *et al.*, 1995), which can create well-functioning associations in marsh environments that are unfavourable for other foraminifera. It is also referred to as an invasive form (McGann *et al.* 2012), rapidly colonizing new environments, adaptable for settling new areas (Alve, 1999). Thus, its mass appearance in deep-sea environments could have been the result of adverse benthic conditions during the Eocene.

Well-developed *Trochammina*-dominated assemblages in the lower Eocene of the Silesian Basin may have filled ecological niches that had been opened up after the Paleocene–Eocene benthic foraminiferal extinction event. *Trochammina* is an epifaunal taxon, functioning on the surface of the sediment, known as an active or passive herbivore. It is common in high-energy environments (Nagy *et al.*, 1995) and includes forms with high ecological tolerance (Nagy *et al.*, 1988).

A significant, stable and relatively numerous component of assemblages with small-sized *Trochammina* is *Bathysiphon*. *Bathysiphon*, next to *Arthrodendron*, belongs to the foraminifera with largest overall dimensions found in the analysed material. *Bathysiphon* builds tubular tests, which are found as fragments in the analysed material. The length of the tests differs – some modern species of *Bathysiphon* are classified as macrofauna, reaching a length of over 10 cm (Gooday *et al.*, 2002). It is difficult to estimate the original amount of *Bathysiphon*, because of the differing shell parameters which can make up these forms. One of the best preserved and more or less complete examples of *Bathysiphon* in the deep-sea Carpathian deposits (locality shore of Rożnowskie Lake – Silesian Nappe, Hieroglyphic beds) reaches a length of about 3 cm (Małecki, 1973). Taking into account the size of the *Bathysiphon* fragments, their number should be much lower. *Bathysiphon*, belonging to simple foraminifera, represents epifauna and shallow infauna. It lives on the surface of the sediment or in the bottom sediment, in an almost horizontal position, frequently moving. This form is a deposit-feeder (Gooday *et al.*, 1992) and it is considered to be the main bioturbating organism in the bottom sediment (Geslin *et al.*, 2004). *Bathysiphon* is cosmopolitan (Kaminski & Gradstein, 2005), is characteristic of deep-water assemblages and is abundantly represented in the Carpathian basins. It has a high ecological tolerance – the highest known among flysch-type foraminifera. Evidence of this is the presence of *Bathysiphon* as the only foraminifera in deposits indicating high energy or dysoxic environments (Ortiz *et al.*, 2011). This type of monotaxa assemblage is very common in the Carpathian flysch. Laboratory tests confirm that *Bathysiphon* is tolerant of low oxygen conditions (Geslin *et al.*, 2004). Taking into account the distribution of morphogroups, assemblages with numerous *Trochammina* are dominated by forms living on the surface of the sediment and its uppermost layer. These forms represent a group of actively moving foraminifera, obtaining their food from the sediment (Jones & Charnock, 1985; Kuhnt *et al.*, 1996).

A special feature of the *Trochammina* biofacies is the dwarfing of the assemblage. It concerns not only *Trochammina*, but also occurs in other forms, i.e. *Ammodiscus, Glomospira, Karrerulina, Trochamminoides, Paratrochamminoides, Recurvoides*, etc.. This trend is observed in assemblages that inhabit environments with rapidly changing environmental parameters (Nagy *et al.*, 2010). The small size is a strategy known also among other primitive organisms when under specific conditions the reproduction rate increases while dimensions decease (Harries *et al.*, 1996; Thomas, 1988; Alegret *et al.*, 2010). The result is a relatively rapid increase in the number of dwarfed forms of the species (Benhard, 1986; Kaiho, 1999) and functioning monotaxa assemblages or assemblages with one species dominant. Such a strategy is used by

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Explanation of Plate. 4. Benthic and planktonic foraminifera from *Trochammina* assemblages, SEM images. **fig. 1.** *Haplophragmoides walteri* (Grzybowski) (sample Krzesławice 11/38a/09, specimen no. h3). **fig. 2.** *Haplophragmoides walteri* (Grzybowski) (Janoska 132/10/07, specimen no. h6). **fig. 3.** *Recurvoides walteri* (Grzybowski) (Janoska 132/1/09, specimen no. r45). **fig. 4.** *Recurvoides walteri* (Grzybowski) (Janoska 132/10/09, specimen no. r23). **fig. 5.** *Cystammina* sp. (Krzesławice 11/38a/09, specimen no. c2). **fig. 6.** *Cystammina* sp. (Krzesławice 11/38a/09, specimen no. c6). **fig. 7.** *Karrerulina conversa* (Grzybowski) (Krzesławice 11/38a/09, specimen no. k2). **fig. 8.** *Karrerulina horrida* (Mjatliuk) (Janoska 123/1/09, specimen no. 13). **fig. 9.** *Subbotina hornibrooki* (Brönniman) (Krzesławice 93/63/09, specimen no. p1). **fig. 10.** *Subbotina hornibrooki* (Brönniman) (Krzesławice 93/63/09, specimen no. p2). **fig. 11.** *Subbotina hornibrooki* (Brönniman) (Krzesławice 93/63/09, specimen no. p3). **fig. 12.** *Subbotina yeguaensis* (Weinzierl & Applin) (Krzesławice 41/40/06, specimen no. p8). **fig. 13.** *Subbotina yeguaensis* (Weinzierl & Applin) (Krzesławice 93/64/09, specimen no. p16). **fig. 14.** *Subbotina corpulenta* (Subbotina) (Krzesłwice 93/64/09, specimen no. p19). **fig. 15.** *Subbotina linaperta* Finlay (Krzesławice 11/38a/09, specimen no. 3). Scale bars 100 μm.

opportunistic forms recolonizing the sea floor (Kitazato, 1995; Nagy *et al.*, 2010; Waśkowska, 2011*a*). These are assemblages of foraminifera characteristic of the first stages of rebuilding the structure of the association after the crisis, i.e. the survival phase. They can exist for a short time (Waśkowska, 2011*a*) or last for a long interval during adverse conditions (Kaiho, 1999). In the early Eocene flysch deposits assemblages of this type are common, where there are mass occurrences of stunted *Glomospira*.

Bathymetry
Small-sized *Trochammina* assemblages developed close to the foraminifera lysocline and local carbonate compensation depth (CCD). Such a bathymetry is indicated by the assemblage structure, dominated by agglutinated foraminifera. Calcareous forms belonging to plankton and benthos are represented irregularly in the assemblages, as a minor component. The surfaces of their tests bear distinctive signs of corrosion, which is the result of partial or complete dissolution, resulting in internal moulds. There are probably a few forms that have been preserved and have not been destroyed at depths corresponding to the CCD.

CONCLUSIONS
Assemblages with numerous small-sized *Trochammina* appeared in the Eocene in the Silesian Basin, where they are characteristic of the lower part of the Hieroglyphic beds. In Krzesławice they occur within a 50 m thickness of mudstone shales, and in Janoska they are present within a sequence of more than 100 m thick developed as grey mudstones with relatively large amounts of muscovite, pyrite and low amounts of TOC.In the studied deposits foraminiferal assemblages are observed that are dominated by opportunistic forms of the genus *Trochammina*, which frequently represents more than 70% of all foraminifera. Their characteristic features are the presence of numerous dwarfed forms, low taxonomic diversity, association with cosmopolitan forms, i.e. *Bathysiphon, Recurvoides, Paratrochamminoides* and *Trochamminoides*, and strong dominance of epifaunal and shallow mobile infaunal morphogroups. These assemblages are developed in deep-water environments, close to the local CCD.

The late Ypresian age of the *Trochammina* biofacies was assessed on the basis of the presence of index taxa for this interval, i.e. *Saccamminoides carpathicus* Geroch, and occasional co-occurring planktonic foraminifera. The *Trochammina* biofacies developed in the Silesian Basin after the Paleocene–Eocene benthic foraminiferal extinction (associated with the PETM), as a recolonizing assemblage. The biofacies remained stable during the early Eocene, in conditions that restricted the development of more complex foraminiferal assemblages.

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