Comparison of deep-water agglutinated foraminifera from the hemipelagic variegated shales (Lower Turonian–Lower Santonian) and the turbiditic Godula beds (Upper Santonian–Campanian) in the Lanckorona-Wadowice area (Silesian Unit, Outer Carpathians, Poland) (Figs 1–7)

Abstract. Deep-water agglutinated foraminifera (DWAF) have been studied from variegated shales and Godula beds exposed in the vicinity of Kalwaria Zebrzydowska (Silesian Nappe, Outer Carpathians, Poland). Following the standard foraminiferal zonation scheme of Geroch & Nowak (1984), the studied variegated shales can be correlated with the *Uvigerinammina jankoi* Zone (Lower Turonian–Lower Santonian). The Godula beds can be correlated to the *Caudammina gigantea* Zone (Upper Santonian–Campanian). Foraminiferal assemblages from the variegated shales are dominated by infaunal and semi-infaunal forms. Their occurrence suggests aerobic bottom water conditions associated with low organic matter availability during the deposition of this unit. Such conditions are presumably related to slow sedimentation rate in low energy, well-oxygenated and oligotrophic bottom environment. In contrast, foraminiferal assemblages from the Godula beds are dominated by epifaunal forms, which collected food from the sediment/water interface. It may suggest that sedimentation took place under relatively higher energy conditions with a higher organic matter flux.

Key words: biostratigraphy, palaeoecology, agglutinated foraminifera, morphogroup analysis, variegated shales, turbidities, Carpathians.

INTRODUCTION

The variegated shales and the Godula beds were deposited in the Silesian basin in deep-water conditions below the CCD. The sedimentation of the variegated...
shales began during the Early Turonian. These sediments consist of red shales with subordinate green shale intercalations. Thin-bedded very fine-grained glauconitic sandstones occur infrequently in this lithostratigraphic unit. The variegated shales are interpreted as deep-sea hemipelagic sediments deposited by the settling of individual grain particles resedimented from proximal areas by bottom currents and/or from highly dispersed turbiditic currents (Leszczyński & Uchman, 1991). The Godula beds consist of turbiditic glauconitic sandstones interlayered with grey-greenish shales and, in the upper part, by red shales. This lithostratigraphic unit overlies the Barnasiówka Radiolarian Shale Formation or the variegated shales and underlies the Istebna sandstones. Sedimentation of the Godula beds took place within a shifting system of submarine fans (Słomka, 1995). The thickness of these sediments decrease eastwards where hemipelagic sedimentation prevail over turbiditic one. This is recorded by the alternation of the thick-bedded facies of the Godula beds with the hemipelagic facies of the variegated shales.

This paper compares of deep-water agglutinated foraminifera from the variegated shales and the Godula beds of the Silesian succession exposed in the Lanckorona-Wadowice area (Outer Carpathians). The aim of the present study is reconstruction of bottom water conditions during sedimentation of these two different facies.

**GEOLOGICAL SETTING**

The Silesian Nappe east of the Skawa dislocation divides in two variously developed parts separated by the Lanckorona tectonic zone: the northern one consisting of Upper Cretaceous strata and the southern part consisting mainly of Oligocene and Lower Miocene Krosno beds (Książkiewicz, 1951, 1977). The Lanckorona-Wadowice area is situated in the northern zone. The Upper Cretaceous sediments of this area consist of the upper part of the Lgota beds, the Barnasiówka Radiolarian Shale Formation, the variegated shales, the Godula beds and the Istebna sandstones (Fig. 1).

The oldest sediments, the upper part of the Barnasiówka Radiolarian Shale Formation (see Bąk et al., 2001), consists of thin-bedded glauconitic siliceous sandstones and light-greenish and green non-calcareous shales with pseudomorphs after carbonates such rodochrosite (Wieser, 1985). This lithostratigraphic unit is overlain by the variegated shales consisting of brick-redish claystones and a subordinate series of green non-calcareous shales, intercalated with thin black manganiferous shales (tuffites?), very thin layers of light-green bentonite and thin-bedded glauconitic sandstones. The Godula beds are characterized by a higher number of glauconitic sandstones and mainly greenish-grey colour of mudstones. Infrequent intercalations of thin red shales occur in the upper part of the Godula beds. The thickness of the variegated shales in the study area is about 150–250 meters (Książkiewicz, 1951) and that of the Godula beds reaches from 200 to 600 meters (Słomka, 1995). The youngest deposits exposed in this area are the Istebna sandstones.
MATERIAL AND METHODS

The studied section crops out in a small creek and its tributary at Klasztorna Góra hill south of Kalwaria Zebrzydowska (Figs 1, 2). The upper part of the Barnasiówka Radiolarian Shale Formation, the variegated shales, the Godula beds and the lower part of the Istebna sandstones are exposed there. Thirty samples have been collected from red and green shales of the variegated shales and with uppermost turbiditic sequences and grey-greenish and red shales of the Godula beds. Their position is shown in Fig. 3. Samples about 0.5 kg each have been processed the following standard method based on solution of Glauber’s salt, warming/freezing cycles and final washing through sieves with a 63 µm mesh diameter.

A total of 300 specimens of foraminifera have been picked out from each sample and mounted on cardboard microscope slides. For morphogroup analysis of fragments of tubular species and multi-chambered, uniserial forms (Reophax, Caudamina) were counted individually and then their number was recalculated taking into account dimensions of unchanged forms (Bak, 2004).

Scanning electron microscope photomicrographs have been taken in the Laboratory of Field Emission Scanning Electron Microscopy and Microanalysis in the Institute of Geological Sciences of the Jagiellonian University.

RESULTS

The studied samples contain deep-water agglutinated foraminifera (Figs 4, 5). Two qualitatively and quantitatively different assemblages have been found. The
one from the variegated shales consists of long-ranging fine-grained small dimension species representing the following genera: *Rhabdammina*, *Hyperammina*, *Rhizammina*, *Glomospira*, *Ammodiscus*, *Trochammina*, and *Recurvoides*. *Uvigerinammina* and *Gerochammina* occur there as well (see in details in Fig. 4). Unidentified specimens of radiolarians and sponge spicules have been found in the investigated variegated shales.

The foraminiferal assemblage from the Godula Beds is composed mainly of coarse-grained large-sized forms: *Rhabdammina*, *Nothia*, *Psammospheara*, *Reophax*. Additionally *Caudammina gigantea* (Geroch) and *Caudammina ovulum* (Grzybowski) occur frequently. Single specimens of *Hormosina crassa* (Geroch) have been observed too. Other forms like *Bathysiphon*, *Ammodiscus*, *Glomospira*, *Trochammina*, *Trochaminoides*, and *Paratrochaminoides* are less frequent.

**BIOSTRATIGRAPHY**

**Interpretation**

Following the standard foraminiferal zonation scheme of Geroch & Nowak (1984), the studied variegated shales can be correlated with the *Uvigerinammina jankoi* Zone. The Godula beds can be correlated to the *Caudammina gigantea* Zone.

The age of the younger foraminiferal assemblage with *Caudammina gigantea*
(Geroch) can be estimated as the Late Santonian–Campanian. This is based on the co-occurrence of the index species, which is known to appear throughout the Late Santonian–Early Campanian (Olszewska, 1997) and Hormosina crassa (Geroch), the stratigraphic range of which is Barremian–Cenomanian (Geroch & Nowak, 1984), respectively up to the Early Senonian according to Morgiel & Olszewska (1981). However, some authors report the occurrence of Caudammina gigantea (Geroch) from younger strata, i.e., Lower Campanian–Maastrichtian (Geroch & Nowak, 1984).

The precise dating of the first appearance of Caudammina gigantea (Geroch) is important for the age-assessment of the top of older Uvigerinammina jankoi Zone.
Fig. 4. Occurrence of deep-water agglutinated foraminifera in the investigated samples. P: 1 specimen, R: 2–4, F: 5–9, C: 10–49, A: ≥ 50 specimens
Fig. 5. Microfauna from variegated shales and Godula beds. 1 – Rhabdammina sp., Pg-3/03; 2 – Nothia sp. – Kz-7/03; 3 – Bathysiphon microrhaphidus (Samuel) – Kz-8/03; 4 – Hyperammina elongata (Brady), Kz-8/03; 5 – Kalamopsis grzybowskii (Dylązanka) – Pg-3/03; 6 – Hormosina velascoensis (Cushman) – Pg-3/03; 7, 8 – Hormosina crassa (Geroch) – Kz-10/03; Pg-2/03; 9, 10 – Caudammina gigantea (Geroch) – Kz-1/03, Kz-6/03; 11 – Reophax duplex (Grzybowski), Kz-6/03; 12 – Psammosphaera fusca (Schultze) – Kz-7/03; 13 – Ammodiscus cretaceous (Reuss) – Kz-10/03; 14 – Rzehakina minima (Cushman & Renz) – Kz-6/03; 15 – Paratrochamminoides olszewskii (Grzybowski), Kz-10/03; 16 – Trochammina globigeriformis (Jones & Parker) – Kz-10/03; 17 – Rhizammina sp. – Pg-3/04; 18 – Gerochammina sp., Pg-5/03; 19 – Uvigerinammina jankoi (Majzon), Pg-3/04; 20 – U. jankoi (Majzon) – Pg-8/03; 21 – Haplophragmoides maja (Maslakova) – Pg-8/03; 22 – Recurvirodes sp., Pg-9/03; 23 – Radiolaria – Pg-5/03; 24 – Radiolaria – Pg-9/03; 25 – Sponge spicule – Pg-5/03; 26 – Sponge spicule – Pg-9/03; 27 – Sponge spicule – Pg-5/03; scale bar 100 µm
Its base can be estimated as not older than the Early Turonian because the first appearance of *Uvigerinammina jankoi* (Majzon) is known from this period (Geroch, 1957; Geroch & Nowak, 1984; Kuhnt, 1992; Bąk, 1998). Thus, the age of the lower part of the variegated shales in the studied section is Lower Turonian–Lower Santonian, whereas the age of overlying Godula beds is the Upper Santonian–Campanian.

**Discussion of biostratigraphy**

The age of the variegated shales and the Godula beds have been studied earlier. For the first time the age of the Godula Beds was described by Hohenegger (1861) as Albian on the base of *Desmoceras dupiniannum* (d’Orb.). The same age of the variegated shales has been estimated as Albian on the basis of species of *Ticinella* (Hanzlíková *et al.*, 1954; see Fig. 6).

Contemporary investigations prove that the age of the lower part of the variegated shales is estimated as Lower Turonian (Bąk *et al.*, 2001). The age of the Godula beds was described by B. Olszewska (in Słomka, 1995). The lower part of the Godula beds is not older than Turonian and is clearly diachronic in different parts of the Outer Carpathian. At the studied section the age of the Godula beds is estimated as Upper Santonian–Campanian. It could indicate that the sedimentation of the Godula beds began during the late Early Senonian. It is relevant with development of the variegated shales at this area.

**PALAEOECOLOGY**

**Morphogroups**

Fossil deep-water agglutinated foraminifera can be used as a tool for reconstruction of sedimentary environments and documenting palaeoceanographic changes in the past. Their palaeoecological habitats are interpreted from comparison with morphologically similar recent living forms, which mode of live is well known. Taking into account shape of test and chamber arrangement, five morphogroups characterizing various life strategies have been distinguished (Corliss, 1985; Jones & Charnock, 1985; Kaiho, 1991; Nagy, 1992; Tyszka, 1994; Nagy *et al.*, 1995; Kaminski *et al.*, 1995; Kuhnt *et al.*, 1996; Bąk *et al.*, 1997, Bąk, 2004).

**Morphogroup A1** comprises tubular, branched forms like *Bathysiphon, Rhabdammina, Hyperammina*, and *Rhizammina*. *Nothia* have been classified in to this morphogroup but their feeding strategy is not clear. Other authors classified this forms to morphogroup A2 (i.e., Geroch & Kaminski, 1992). These forms are suspension feeders, which tend to live as erect epifauna, building a pseudopodial net above the sediment/water interface in order to reach food. Frequent occurrence of suspension feeders in sediment reflects moderate to low levels of organic flux to the sea bottom and their size may be used to estimate changes in palaeoproductivity (Kaminski & Kuhnt, 1995; Gasiński, 1998). The number of specimens and size of their tests increases with higher flux of organic matter to the bottom.
Morphogroup A2 consists of flattened, planispiral coiled and irregular forms such as *Ammodiscus*, *Glomospira*, *Trochamminoides*, *Paratrochamminoides* and *Rzehakina*. Foraminifera representing this morphogroup have various feeding strategy. Some forms like modern *Ammodiscus* are mobile epifaunal detritivores (Nagy et al., 1995), some living species of *Glomospira* live at the surface of the sediment or within its topmost 1.5 cm (Mackensen & Douglas, 1989). The forms belonging to this morphogroup characterize higher energy environments also with increased influence of turbidity currents (Kaminski & Kuhnt, 1989).

Morphogroup A3 comprises plano-convex and concavo-convex forms such as *Trochammina*, *Saccammina* and *Psammosphaera*. They live at the bottom surface with the aperture directed into sediment (Nagy et al., 1995). They also can attach to invertebrate shells (Mackensen & Douglas, 1989) or tube forms like *Rhabdammina* (Nagy et al., 1995). These forms live as epifaunal detritivores and herbivores.
Morphogroup A4 includes rounded forms like *Recurvoides* and *Haplophragmoides*. They are detritivores and live as shallow infauna, 1–4 cm below the sediment surface.

Morphogroup A5 consists of elongated subcylindrical or tapered forms: *Karrellina*, *Gerochammina*, *Spiroplectammina*, *Hormosina*, *Uvigerinammina*, and *Reophax*. They all are detritivores and could be found even more than 10 cm below the sediment surface like Recent *Reophax* (Kaminski *et al.*, 1988; Hunt & Corliss, 1993; Mackensen & Douglas, 1989). The forms with this feeding strategy occur in well-oxygenated, oligotrophic waters. But on the other hand, they may also occur under strongly dysoxic conditions where anaerobic degradation of organic matter may provide an additional food source around the redox front (Jorissen *et al.*, 1995).

The proportions of agglutinated foraminiferal morphogroups are related to the environmental conditions prevailing in the bottom waters and within the topmost part of the sediment. Changes of these proportions may reflect changes in organic flux into bottom (Gooday, 1988, 1994), bottom water oxygenation (Kaiho, 1994; Kaminski *et al.*, 1995) and the energy of bottom currents (Schröder *et al.*, 1988; Kuhnt *et al.*, 2000).

**Interpretation of environmental conditions**

The foraminiferal assemblage from the variegated shales is dominated by infaunal forms (morphogroups A4 and A5 – 48%) and forms representing morphogroup A3 – 33%. The suspension feeding forms (morphogroup A1) comprise 10% of the assemblage (Fig. 7).

Thus, these are mainly small dimension fine-grained foraminifera preferring an infaunal life strategy. Their dominance, together with red colour of sediment, suggest aerobic bottom water conditions associated with low organic matter availability. Such conditions are related to slow sedimentation in a low energy, well-oxygenated and oligotrophic environment. Under low organic matter flux rate the redox boundary layer is in the lower limit of benthic activity in sediment and it provides optimal conditions for epi faunal and shallow to deep infaunal forms (Kuhnt *et al.*, 1996). In contrast, under high organic matter flux rate the redox boundary layer is close to the sediment-water interface and prevents deep infaunal form expansion. This scenario seems to refer to the sedimentary environment of the shales of the Godula beds, which contain foraminifera representing mainly tubular suspension feeding forms – 45% (morphogroup A1; Fig. 7). The remaining part of epifaunal forms amount to 32% of the whole benthos. Infaunal forms (morphogroup A5) comprise only 16% of foraminiferal assemblage from the Godula beds. Such an assemblage, composed predominantly of coarse-grained large-sized foraminifera, suggests a higher flux of organic matter. The occurrence of relatively frequent epifaunal forms that collected food from the bottom sediment may suggest that sedimentation took place under high energy conditions. Low amounts (16%) of infaunal forms in the greenish coloured shales of the Godula beds indicate low oxygen.
concentration at the pore waters, depleted presumably due to bacterial decay of organic matter supplied by diluted turbiditic currents.

**Discussion**

The colour of the sediment depend on several factors: the chemical and mineral composition of the sediment, oxygenation of the seafloor, frequency of turbidite sedimentation, thickness and shape of beds, degree and pattern bioturbations. They all are strictly connected to one other (Leszczyński & Uchman, 1991). The red colour is result from high ratios \( \text{Fe}^{3+}/\text{Fe}^{2+} \) and the green colour with low ratios (Dominik, 1977; Potter et al., 1980). The \( \text{Fe}^{3+}/\text{Fe}^{2+} \) ratio is strongly dependant upon the oxidation state of the sediment. The flux of organic matter is to a large extent responsible for the green coloured shales.

According to the results of this investigation, the morphogroups of the agglutinated foraminifera confirm that the green colour is connected with a higher content
of organic matter, which is expressed by the number of epifaunal forms that collect food from the bottom sediment. The red colour is expressed by a large proportion of infraunal forms indicating better, deeper redox boundary layer, and mesotrophic to even oligotrophic conditions.

CONCLUSION

(1) Following the standard foraminiferal zonation scheme of Geroch & Nowak (1984), the studied variegated shales can be correlated with the *Uvigerinammina jankoi* Zone. The Godula beds can be correlated to the *Caudammina gigantea* Zone.

(2) The age of the variegated shales is Lower Turonian–Lower Santonian, and the Godula beds are Upper Santonian–Campanian.

(3) The foraminifera from the variegated shales are dominated by infraunal, semi-infraunal forms. This suggests aerobic bottom water conditions associated with low organic matter availability. Such conditions are related to slow sedimentation in low energy, well-oxygenated and oligotrophic environment.

(4) The foraminiferal assemblages from the Godula beds are composed of predominantly epifaunal forms, which collected food from the bottom sediment. It may suggest that sedimentation took place under high energy conditions, where food was supplied by bottom currents, with a relatively higher flux of organic matter.

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