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Geochemical and foraminiferal records of environmental changes during Zechstein Limestone (Lopingian) deposition in Northern Poland

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The entire Zechstein Limestone section of the Zdrada IG 8 borehole (Northern Poland) is composed of oncoid packstone that is accompanied by stromatolites in the upper part of the unit. Deposition of the Zechstein Limestone occurred in persistently subtidal environments, above the storm wave base, in mostly dysoxic conditions, and thus these conditions did not differ essentially from those characteristic for the Kupferschiefer strata. The previous supposition of vadose diagenesis is not confirmed by the isotopic study of calcite that showed its clearly marine values (average $\delta^{13}C$ and $\delta^{18}O$ values of +5.1 ±0.6‰ and –0.5 ±0.7‰, correspondingly) that are compatible with contemporaneous Lopingian deposits. The faunal restriction and the predominance of lagenids in the foraminiferal assemblage of the Zechstein Limestone indicate continual dysaerobic conditions and elevated salinity of seawater. The calculated palaeotemperature of the seawater was within the range from 23 to 33°C (or higher), and slightly (by *ca*. 1.5°C) decreased at the end of the Zechstein Limestone deposition.

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INTRODUCTION

Many ancient deep evaporite basins, with a minimum relief of 100 m (Schreiber, 1988), were density-stratified, sediment-starved and anoxic, or at best dysaerobic for long periods (Kirkland and Evans, 1981; Hite and Anders, 1991; Warren, 2006). In fact, stratification occurs in brine bodies only ten metres (or less) deep (Kendall, 2011), and thus deep bodies of brine almost always have temperature and/or salinity stratification (Kendall and Harwood, 1996). Euxinic deposits of the Kupferschiefer and co-eval carbonate facies of the shoals (e.g., Paul, 1982, 1986; Oszczepalski, 1989; Peryt, 1989) indicate the stratification of waters prior to evaporite deposition in the Zechstein basin, with euxinic conditions prevailing throughout the water column below the chemocline. Two models have been used to explain the occurrence of euxinic conditions in the Zechstein Sea: the "quasi-estuarine" model of Brongersma-Sanders (1971) proposing that it was salinity-stratified, and the model of Turner and Magaritz (1986) assuming that salinity stratification have been induced by strong freshwater inputs into the sea (see Pancost *et al*., 2002, for the discussion). The lithological succession of the Kupferschiefer, from organic-rich shale at the base, grading into a carbonate-rich shale, was interpreted as reflecting the transition, after the euxinic deposition, to normal marine conditions with elevated water salinity (Bechtel *et al*., 2002, with references therein). Although bioturbated carbonates occurring at the base of the Zechstein Limestone indicate the onset of oxygenation throughout the water column (Paul, 1986), in the basinal facies the Zechstein Limestone is a dark, laminated, marly micritic limestone with a thickness of only a few metres (Füchtbauer, 1968, 1972) that suggests that the environmental change could be minor.

Recently, a detailed study of the Kupferschiefer strata in the Zdrada IG 8 borehole (Puck Bay region, Northern Poland) was published (Pašava *et al*., 2010). The aim of this paper is to explore possibility to use foraminifers and some geochemical parameters as environmental proxies for the Zechstein Limestone with a special reference to the problem of water stratification in the deeper part of the Zechstein basin (Fig. 1); thus the coherent picture of environmental changes during deposition of basal Zechstein strata in the basinal zone of the basin can be obtained.

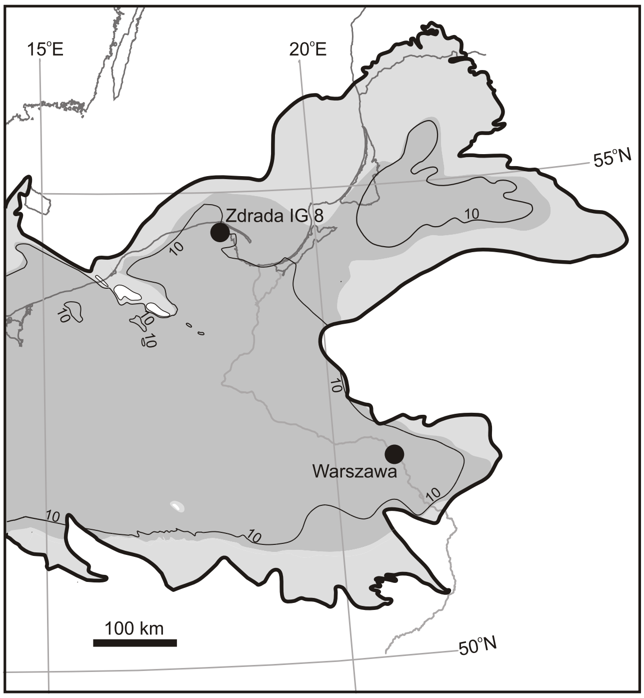

Fig. 1. The location of the Zdrada IG 8 borehole at the map showing the general palaeogeographical zones of the Zechstein Limestone

Carbonate platform (light grey) and the basin (dark grey), and the isopach 10 m in the basin zone (after Peryt *et al*., 2010)

GEOLOGICAL SETTING

The Peri-Baltic Zechstein Basin is situated in the eastern part of the vast Southern Permian Basin of Western and Central Europe (Peryt *et al*., 2010). The basal Zechstein deposits of the Puck Bay region have been first studied by Szaniawski (1966) who found oncolites and stromatolites in dolomitic limestone and dolomite composing the upper part of the Zechstein Limestone whereas limestone containing a considerable share of terrigenous material was recorded in the lower part of the unit. Subsequently, the Zechstein Limestone of the Peri-Baltic Syneclise was subject to detailed microfacies studies by Piątkowski (1980; Peryt and Piątkowski, 1976, 1977*a*, *b*). Piątkowski (1980) distinguished a lower, thicker, micritic complex and an upper, pisolitic complex, composed of stromatolitic-pisolitic beds that are usually separated by micrite and clayey micrite although in places oncoids occur in the entire pisolitic complex (Piątkowski, 1980, fig. 14). The stromatolitic-pisolitic beds intercalated by micrite and clayey micrite can be traced throughout the western part of the Peri-Baltic Gulf; towards the centre of the bay they become amalgamated and micrite disappears (Piątkowski, 1980, fig. 39). Thus, the sequence of the Zechstein Limestone is shallowing-upward, and the three cycles end with the deposition of stromatolites, followed by exposure and formation of vadose deposits (Peryt and Piątkowski, 1976, 1977*a*; Piątkowski, 1980).

The total thickness of the Zechstein Limestone and the Kupferschiefer is 10.6 m in the Zdrada IG 8 borehole (compared to 8.1–10.0 m in other boreholes located in the Zdrada Platform); roughly the same thickness occurs in other boreholes of the Puck Bay region (Peryt *et al*., 1978; *cf*. Fig. 1). The Zdrada area was located approximately 70 km from the seashore and more than 50 km from the seaward margin of the carbonate platform during Zechstein Limestone sedimentation (Peryt *et al*., 2010; Fig. 1).

MATERIAL AND METHODS

Foraminifers were studied in forty seven thin sections taken from the Zechstein Limestone (see Fig. 2 for their location). There are several classifications of Permian foraminifers including higher taxa and genera with no universally accepted interpretation (Vachard *et al*., 2010; *cf*. Nestell and Nestell, 2006). We use the system of high foraminifer taxa proposed by Mikhalevich (1998) supplemented by Pronina-Nestell and Nestell (2001).

The isotopic analyses of the calcite fraction of 20 samples were performed in the Mass Spectrometry Laboratory, Maria Curie-Skłodowska University, Lublin (Poland; analyst: Dr. T. Durakiewicz). Slabbed specimens (with other slabs used to produce standard thin sections) have been sampled selectively with a 1.5 mm diameter stainless steel drill with tungsten carbide coating used for material extraction from the surfaces of the samples. CO_2 gas was extracted from the samples by reaction of calcite with H_3PO_4 (McCrea, 1950) at 25°C in a vacuum line, following the standard. The gas was purified of H_2O on a P_2O_5 trap and collected on a cold finger. Isotopic compositions were analysed using a modified *MI1305* triple-collector mass spectrometer equipped with a gas ion source. Isobaric correction was applied. After subsequent normalization to measured certified reference materials, the isotopic composition was expressed in per mille (‰) relative to the VPDB international standard and separately to PDB. Analytical precision of both $\delta^{13}C$ and $\delta^{18}O$ in a sample was ±0.08‰. Considering the diameter of sampling (1.5 mm) and the petrographic variability shown by the studied rocks, the isotopic sampling has to be regarded as whole rock sampling. Consequently, each resulting isotopic measurement would reflect both depositional and diagenetic fluids. Some samples yielded several analyses, and thus the total number of analysed sites was 34.

Chemical analyses for base metals and trace elements were done on fourteen samples (Table 1) in accredited laboratories of the Polish Geological Institute – National Research Institute. Contents of base metals and trace elements were determined via X-ray fluorescence spectrometry (*Philips WD-XRF PW 2400*) and atomic absorption spectroscopy (AAS) methods (*Unicam Solaar 939 QZ*) and uranium by *UA-3* (Xintrec).

RESULTS

FACIES

The lowermost part of the Zechstein Limestone is composed of bedded and laminated peloid-oncoid packstone, with intercalations of oncoid packstone (Fig. 2). This packstone texture is very

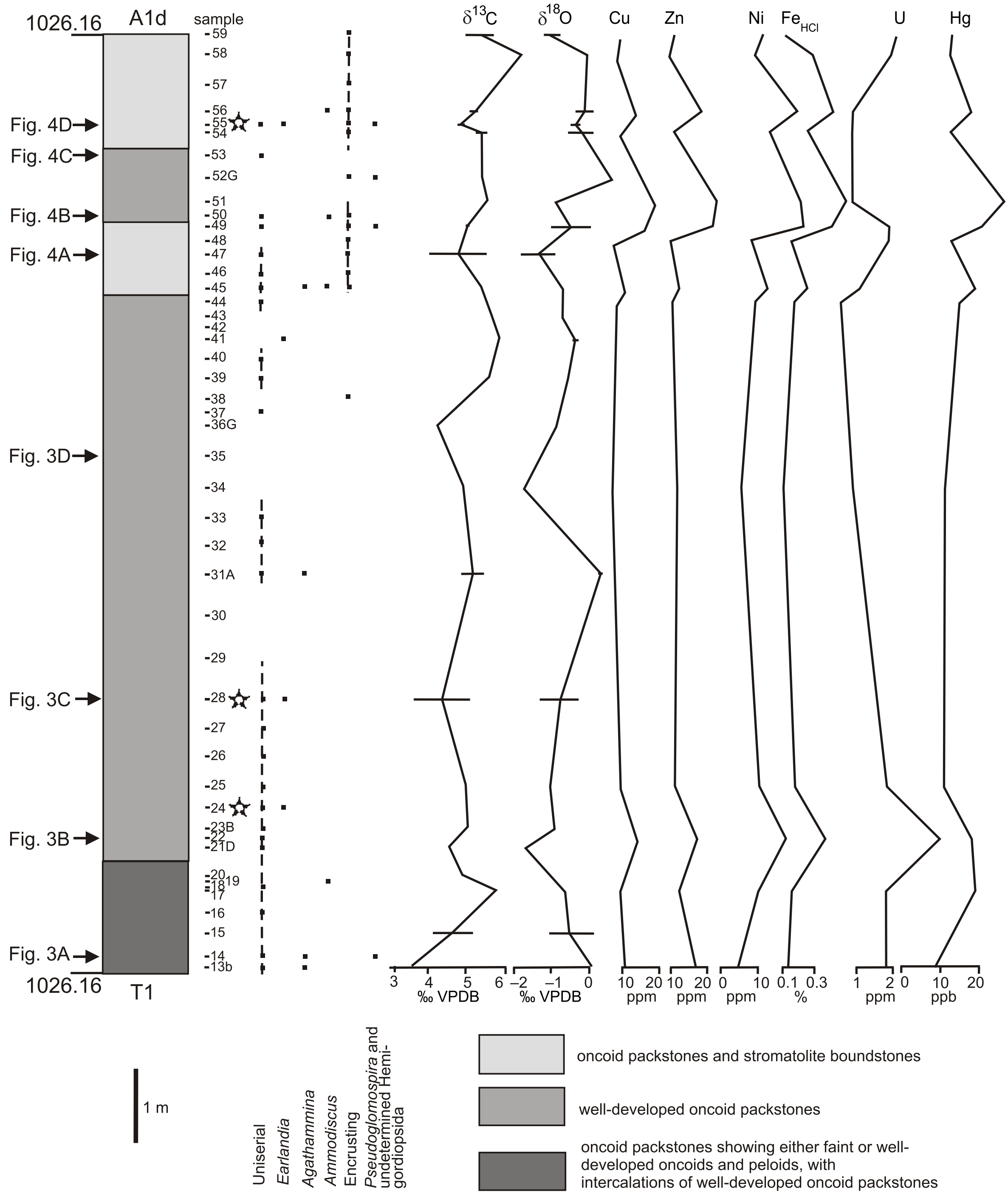

Fig. 2. The Zechstein Limestone section of the Zdrada IG 8, showing principal facies, sampling, distribution of foraminifers and the results of geochemical studies

Asterisks show the recorded (relative) frequent abundance of foraminiferal specimens; A1d – Lower Anhydrite; T1 – Kupferschiefer; the depth of the Zechstein Limestone top and base in metres

often faint (as in Fig. 3A) but there exist all possible transitions between rocks showing very faint outlines of peloids and oncoids to perfectly-developed oncoids. Most of the Zechstein Limestone section of the Zdrada IG 8 borehole is composed of oncoid packstone containing in the upper part also intercalations of stromatolites. Oncoid packstone occurring near the base of the Zechstein Limestone (Fig. 3A) and slightly higher up in the section (Fig. 3B–D) is characterized by unlaminated cortex or densely spacer micritic laminae, features typical for Phanerozoic deeper-water oncoids (Flügel, 2010). The nucleus commonly cannot be distinguished from the cortex, and oncoids show no evidence of transportation (Fig. 3C). In general, stationary growth of oncoids is usually shown by asymmetrical shapes and asymmetrical widths of laminations (Flügel, 2010). In addition, the irregular knobby surface (such as shown in Fig. 3C) indicates the absence of reworking of the oncoids (*cf.* Flügel, 2010, p. 697).

Table 1

Coefficients of metals for the Zechstein Limestone carbonate rocks of the Zdrada IG 8 borehole

Coefficient	Sample number														Kupferschiefer Pašava *et al.* (2010)
	14	18	22	25	34	44	45	48	49	51	54	56	58	59	
Ni/Co	6.0	3.7	3.6	5.5	6.0	3.3	3.3	4.5	3.3	3.1	7.0	3.5	5.0	4.0	3.55–7.29
Ni/V	0.6	0.3	0.4	0.4	0.6	1.0	0.3	0.4	0.6	0.6	0.5	0.5	0.3	0.6	0.18–0.49
V/(V + Ni)	0.6	0.8	0.7	0.7	0.6	0.5	0.8	0.7	0.6	0.6	0.7	0.7	0.8	0.6	0.67–0.84
(Cu + Mn)/Zn*	2.7	2.2	3.1	2.1	2.0	2.0	2.3	1.8	3.7	4.1	2.1	3.2	1.9	2.1	1.3–4.21

* – in the case of the Zechstein Limestone the Mn content was <0.001% and thus the coefficient that is the Cu/Zn ratio, can be up to twice as much big in a particular sample, depending on the actual Mn content

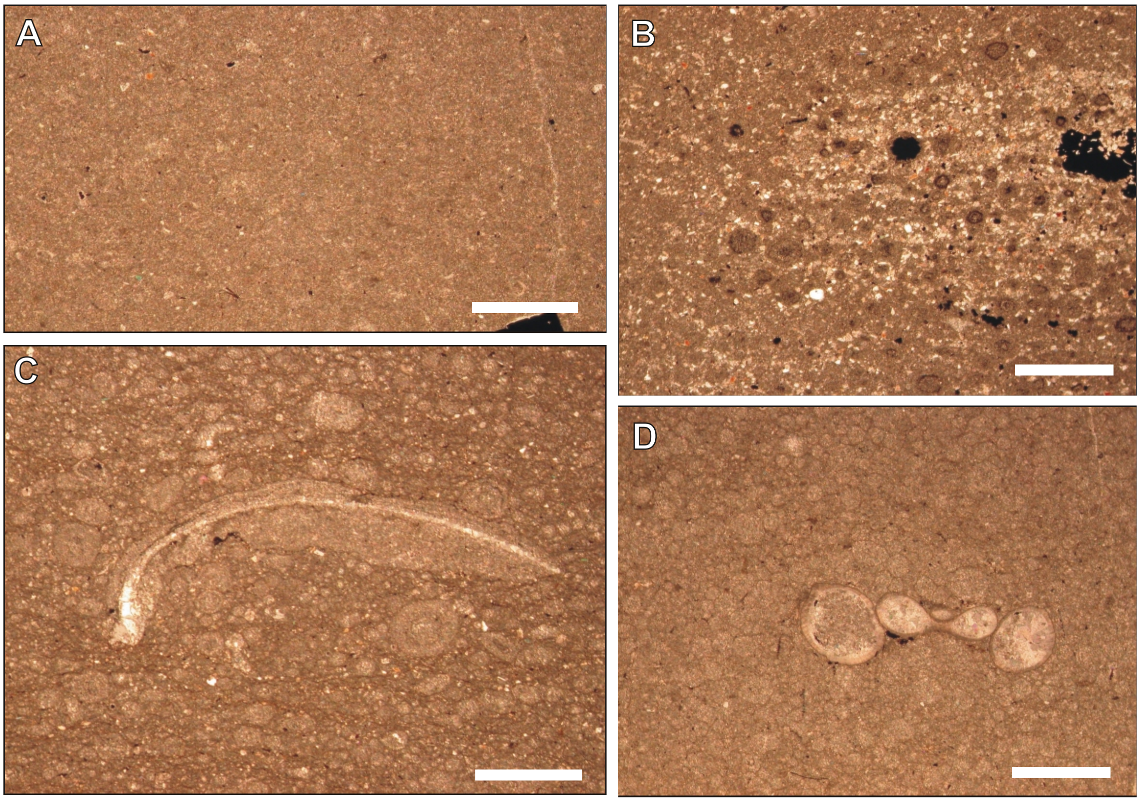

Fig. 3. Various facies of oncoid rocks of the lower part of the Zechstein Limestone of the Zdrada IG 8 borehole

A – rock showing faint outlines of peloids and oncoids (sample 14); **B** – rock showing variously developed oncoid texture – in places only outlines of those components are seen, and in other places well-developed grains occur; there are transitions between those end members (sample 22); **C** – oncoids, often showing unlaminated structure, accompanied by small microbial encrustation developed on both sides of a shell (photo centre) (sample 28); **D** – packed oncoid texture, with obliterated internal structure of most oncoids; containing a low-spired gastropod shell (sample 35); scale bar is 1 mm; the location of figured specimens is shown in Figure 2

Such oncoids were previously described as tender (Füchtbauer, 1968; Taylor and Colter, 1975; Peryt and Peryt, 1975), soft, delicate (Peryt, 1977, 1978), and oncoids of type I (Piątkowski, 1980; Becker, 2002). They were assumed to have originated in rather deeper water conditions (>30 m after Füchtbauer, 1968; 100–150 m according to Taylor and Colter, 1975; and 50–100 m after Piątkowski, 1980). Recently, Becker (2002, p. 40) concluded that the depth was within the range of several decimetres to several tens of metres. Phanerozoic marine oncoids were formed in various settings from tidally influenced marginal-marine environments to basins (Flügel, 2010, p. 132), and the Zechstein Limestone is no exception regarding such a wide range. Deeper-water oncoids are unlaminated or have densely spaced micritic laminae (Flügel, 2010).

In the upper part of the pisolitic complex, oncoids of type II occur (Fig. 4A, B; Piątkowski, 1980). The nuclei are small coated grains, intraclasts and rarely quartz grains and small bioclasts. They are accompanied by radial ooids (Fig. 4D) that are especially common in the intersticia of stromatolites (Piątkowski, 1977). The matrix is enriched in terrigenous material (mostly detrital quartz), and the oncoids are accompanied by the richest (quantitatively and qualitatively) faunal assemblage (Piątkowski, 1980). Encrustations of sessile foraminifers abound; they are especially common in the outer surfaces of

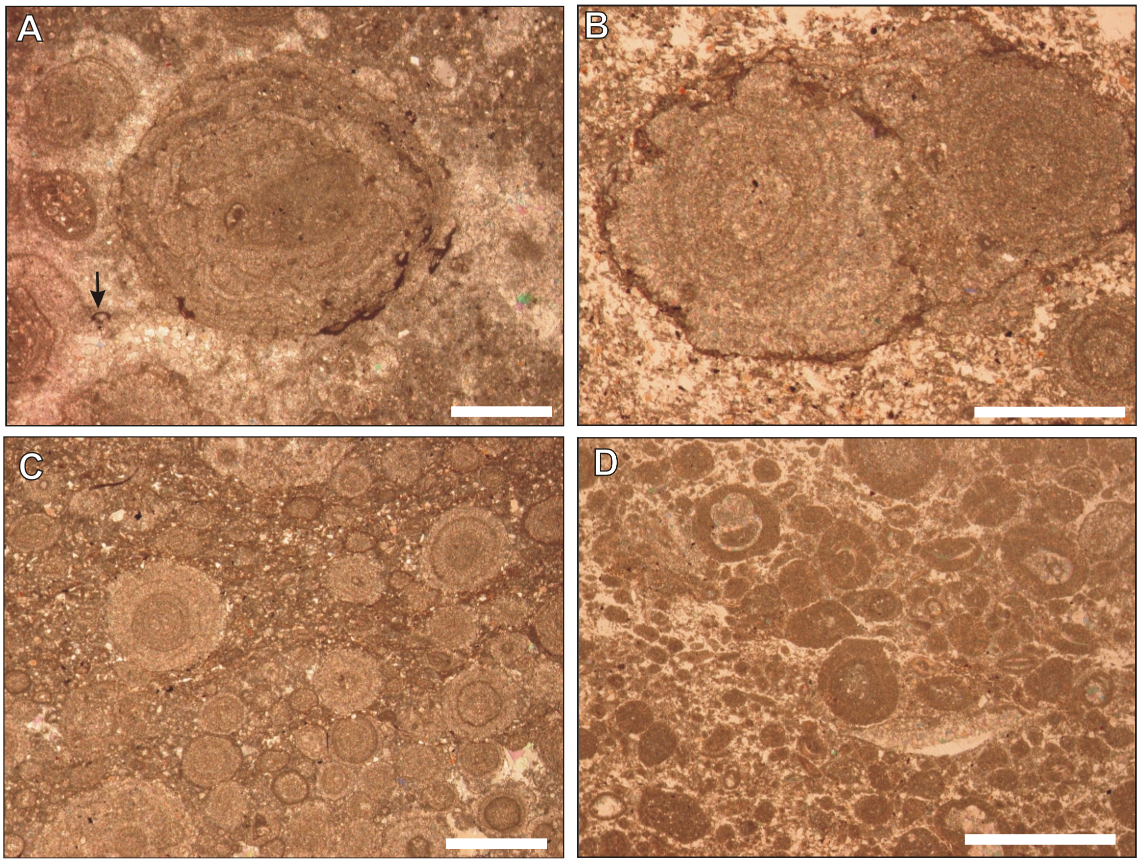

Fig. 4. Various facies of oncoid rocks of the upper part of the Zechstein Limestone of the Zdrada IG 8 borehole

A – oncoid of a complex growth history (notice encrusting foraminifers on the outer surface of the oncoid), with encrusting foraminifer growing on the supposed microbial laminae or cement crust (arrow; sample 47); **B** – co-occurring oncoid (lower right corner) and intraclast of oncoid packstone; both the intraclast and the oncoid on the left side of the intraclast show intensive corrosion and encrusting by sessile foraminifers (sample 50); **C** – oncoids showing well-developed lamination and an intraclast (close to lower left corner) of oncoid packstone (sample 53); **D** – radial ooids (some having a bioclast as a nucleus) showing an adjustment of particular grains due to pressure-solution (sample 55); scale bar is 1 mm; the location of figured specimens is shown in Figure 2

oncoids (Fig. 4A, B) which subsequently were not recolonized by algae, possibly due to the burial of oncoids by deposit. Abrasion of cyanobacterial structures (Fig. 4A, B), a concentric symmetrical growth pattern (Fig. 4B, C), and well-laminated cortices (Fig. 4A–C) indicate rolling of oncoids (Flügel, 2010). They originated within the depth range of 0 to 50 m (Piątkowski, 1980).

The types of bioclasts occurring in the Zechstein Limestone is scarce except for foraminifers and ostracods, also fragments of bivalve shells occur throughout the section, and they are accompanied by gastropods that in some samples are common. In two samples (Nos. 47A and 57) bryozoan fragments were recorded.

FORAMINIFERS

Foraminifers are rare excluding encrusting forms; in 35 standard thin sections (24 × 36 mm) 83 specimens in total were encountered, with one to eight specimens per thin section. The majority (78%) of foraminifers is uniserial forms (*Nodosaria*, *Vervilleina*, *Polarisella*, *Rectoglandulina* and *Geinitzina*); other forms (*Earlandia*, *Ammodiscus*, *Agathammina* and *Pseudoglomospira*) form only 22% of the assemblage (Fig. 5). Encrusting foraminifers were recorded in sixteen thin sections in the upper part of the pisolitic complex starting from sample 45 upward (except of samples 51, 53A and 53B where encrusting foraminifers are lacking). In addition, they occur in sample 38. Encrusting foraminifers are especially abundant in sample 54. In total, foraminifers were recorded in forty thin sections (Fig. 2). The best preserved specimens are shown in Figures 6–7.

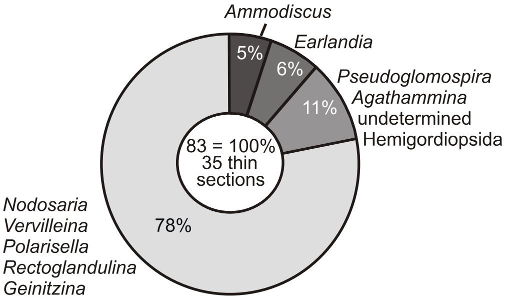

Fig. 5. Composition of foraminiferal assemblage (encrusting foraminifers excluding) in the Zechstein Limestone of the Zdrada IG 8 borehole based on thin section study

The number in the centre indicates the total number of specimens recorded

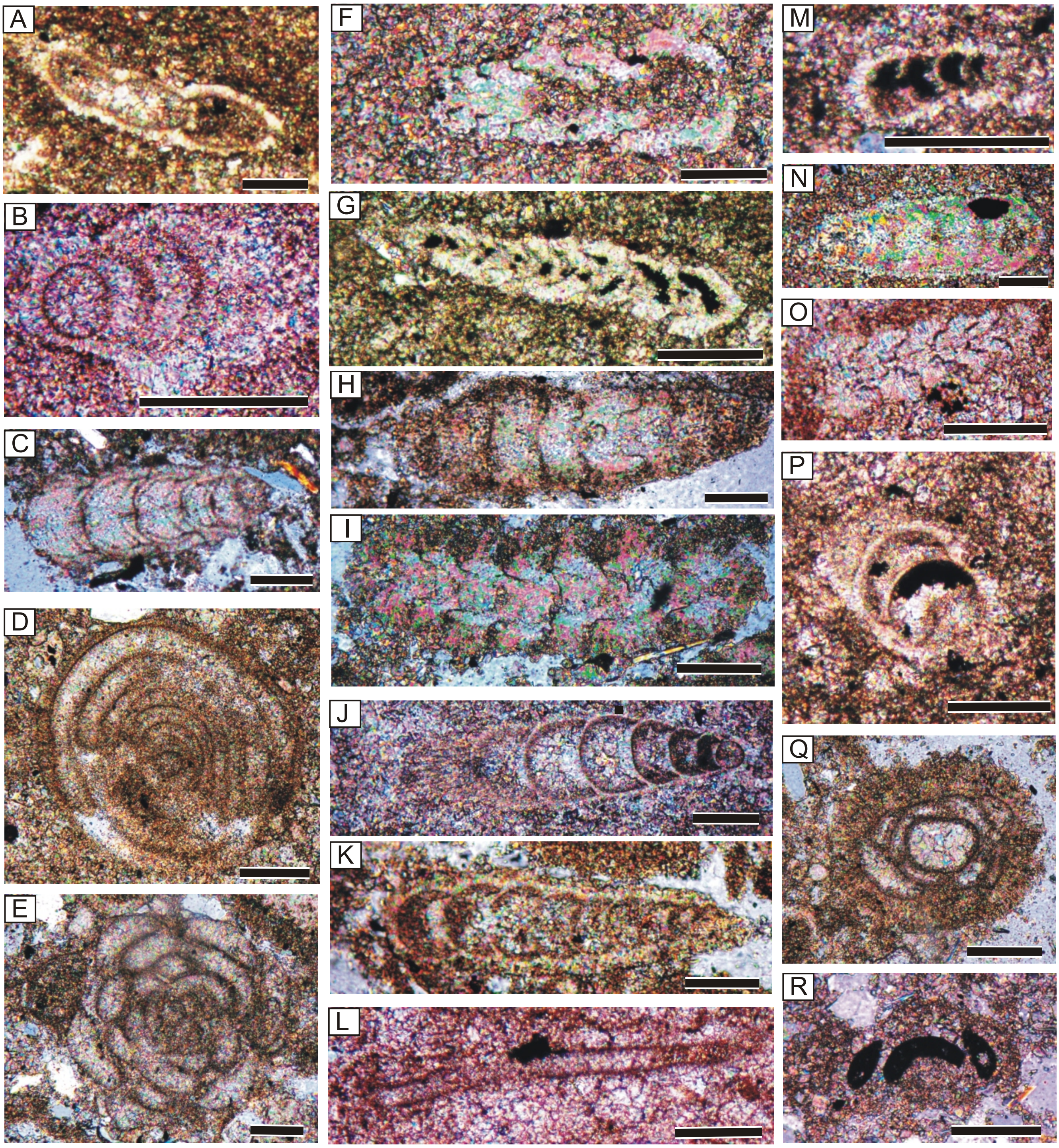

Fig. 6. Foraminifers from the Zdrada IG 8 borehole

A – *Vervilleina paalzowi* (Miklukho-Maklay), sample 28; **B, C, P** – Nodosariida indet.: B – sample 44, C – sample 50, P – sample 28; **D, R** – *Ammodiscus* sp.: D – sample 45, R – sample 50; **E, Q** – *Pseudoglomospira* sp.: E – sample 45, Q – sample 55; **F–I, O** – *Polarisella* sp.: F – sample 37, G – sample 28, H, I – sample 55, O – sample 45; **J** – *Nodosaria permiana* (Spandel), sample 47C; **K** – *Geinitzina* sp., sample 55; **L** – *Earlandia gracilis* Pantić, sample 28; **M** – *Geinitzina*? sp., sample 33; **N** – *Nodosaria* sp., sample 37; scale bar is 100 µm

Foraminifers occurring in the lower part of the Zechstein Limestone section (from its base up to sample 32) are usually dwarf forms. There are two episodes of more common appearance of foraminifers (samples 24 and 28). They are asterisked in Figure 2; in both cases, uniserial foraminifers are accompanied by *Earlandia*. Another event recorded by more common foraminifers is related to sample 55 where uniserial foraminifers are accompanied by *Earlandia, Pseudoglomospira* and undetermined Hemigordiopsida. Although the dataset is certainly too small to validate the assumption conclusively, *Agathammina* is common in the basal part of the Zechstein Limestone, and *Ammodiscus* occurs in basal and then upper parts of the

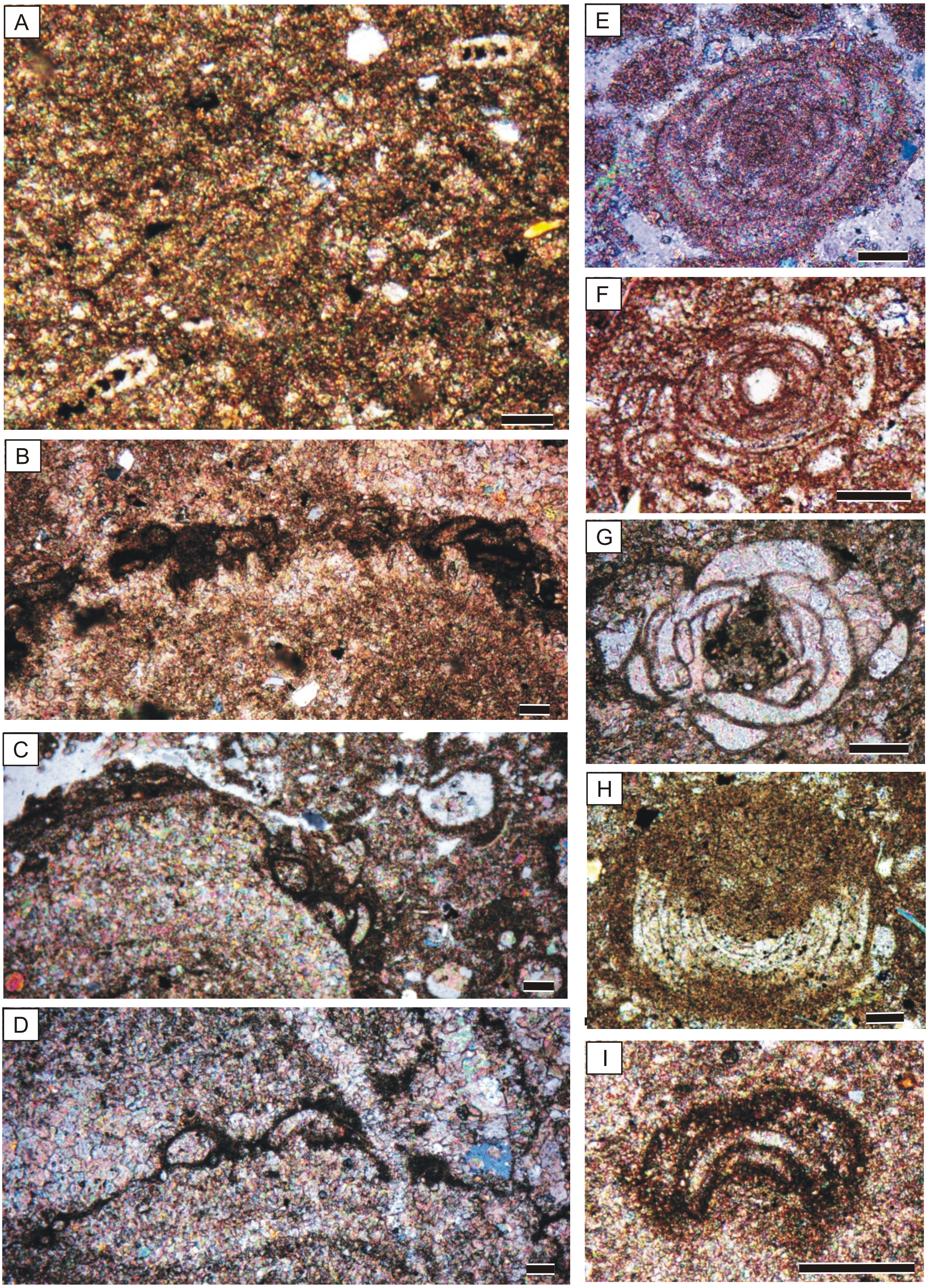

Fig. 7. Foraminifers from the Zdrada IG 8 borehole

A – *Polarisella* sp., sample 32; **B–D** – *Palaeonubecularia* sp.: B – sample 47C, C – sample 46, D – sample 54, **E–G** – Hemigordiopsida indet.: E – sample 55, F – sample 53A, G – sample 52; **H** – *Ammodiscus* sp., sample 56; **I** – ?*Ammodiscus* sp., sample 47B; scale bar is 100 µm

Zechstein Limestone. *Pseudoglomospira* and undetermined Hemigordiopsida are characteristic for the upper part of the Zechstein Limestone (Fig. 2).

GEOCHEMISTRY

The results of isotopic analyses of calcite are shown in Figure 2 and are plotted in Figure 8. The range of $\delta^{13}C$ values is from +3.6 to +6.4‰, and the average $\delta^{13}C$ value is +5.1 ±0.6‰. The $\delta^{18}O$ values show a range from –1.8 to 0.9‰, with the average of –0.5 ±0.7‰. In the section, a clearly upward increase of $\delta^{13}C$ values is noticed, from about +4.4‰ at the base of the unit to *ca*. +5.8‰ at its top (Fig. 2). The $\delta^{18}O$ values of calcite throughout the Zechstein Limestone remain quite stable (although they show a slight increase upsection, from about –0.6‰ to about –0.3‰; Fig. 2). There are several distinct deviations from those trends of $\delta^{13}C$ and $\delta^{18}O$ values (Fig. 2). Various components studied yielded similar results (Fig. 8). In particular, the fields characterizing the oncoids and the assumed vadose crusts are similar (Fig. 8); there is not much difference between the stromatolite (however, only one analysis is available) and the matrix, and between more marly limestone and pure limestone (however, each variety is characterized by only two analyses; Fig. 8).

The results of chemical analyses are shown in Figure 2. The Ni/Co, Ni/V, V/(V + Ni) and (Cu + Mo)/Zn ratios of the Zechstein Limestone rocks are shown in Table 1. These ratios are commonly regarded as indicators of an anoxic environment (e.g., Hatch and Leventhal, 1992; Jones and Manning, 1994) and Table 1 shows also the ranges of those ratios for the Kupferschiefer of the Zdrada IG 8 borehole (Pašava *et al*., 2010).

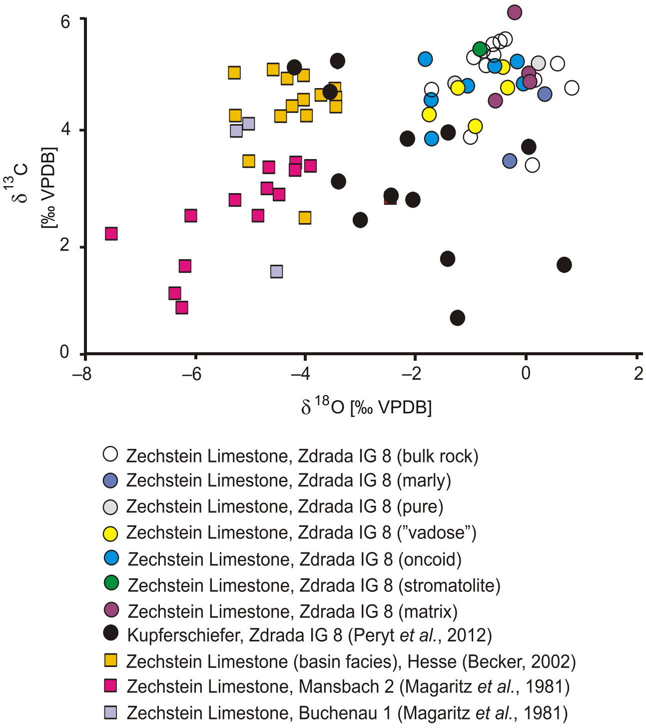

Fig. 8. Plot of $\delta^{13}C$ and $\delta^{18}O$ values of the Zechstein Limestone of the Zdrada IG 8 borehole

The bulk rocks as well as particular components of the rocks, the Kupferschiefer of the Zdrada IG 8 borehole (after Peryt *et al*., 2012) and the results of previous study of basinal facies of Zechstein Limestone in Hesse (Magaritz *et al*., 1981; Becker, 2002) are shown

INTERPRETATION AND DISCUSSION

The Zdrada IG 8 borehole shows a different development of the Zechstein Limestone compared to other sections in the Puck Bay region that consist of a thicker micritic complex in the lower and middle part and a thinner pisolitic complex in the upper part (Peryt and Piątkowski, 1977*a*, *b*; Piątkowski, 1980); the micritic complex seems to be lacking in the Zdrada IG 8 borehole. This deviation from a typical pattern could be related to the location of the borehole in a slightly deeper location than the most of other sections studied by Piątkowski (1980); during the subsequent Lower Anhydrite and Oldest Halite deposition, the borehole was located in the basinal zone (Czapowski, 1987; Peryt *et al*., 1998). However, taking into the account that there exist continual transitions between rocks with extremely vague oncoid texture and undisputed oncoid rocks, and that there occur intercalations of oncoid packstone within the micritic complex (Piątkowski, 1980), it is equally (or even more) probable that the entirely oncoidal nature of the Zdrada IG 8 section is due to a better preservation of the original fabric in that borehole, and that the occurrence of oncoids is much more common than was realized before in the Peri-Baltic area (Peryt and Piątkowski, 1976; Piątkowski, 1980).

Previously, it was assumed that during Zechstein Limestone deposition in the Puck Bay area there occurred repeatedly phases of subaerial exposure and precipitation of vadose marine products (Peryt and Piątkowski, 1976, 1977*a*; Piątkowski, 1980). Such a conclusion was based primarily on the similarity of fabrics observed in the Zechstein Limestone and in modern and fossil vadose deposits (see Piątkowski, 1980), and in particular on the occurrence of hybrid oncoids comprising parts of presumably eroded carbonate crusts (interpreted as caliche; see Peryt and Piątkowski, 1976, 1977*a*, and Piątkowski, 1980, for documentation). However, the stable isotopes do not record essential changes in water chemistry that might be expected in the isotopic composition of limestone around the boundaries of the pisolitic complex, and analyses of the bulk rocks and (rare) isotopic analyses of the assumed vadose crusts (Fig. 8) do not show any difference compared to the results characteristic for deposits regarded to be formed in a persistent subtidal environment and showing no subsequent vadose diagenesis.

The $\delta^{18}O$ values of calcite throughout the Zechstein Limestone remain quite stable (although they show a slight increase upsection, from about –0.6‰ to about –0.3‰; Fig. 2) and their range (from –1.8 to 0.9‰) is within the range previously reported from contemporaneous brachiopods (Korte *et al*., 2005, p. 346). This slight increase may reflect the decrease in temperature and/or the increase in salinity. The calculated palaeotemperatures using the equation of O'Neil *et al*. (1969), reformulated by Hays and Grossman (1991), would yield values of *ca*. 18.5°C for the base of the Zechstein Limestone, and about 17°C for its top if the $\delta^{18}O$ of water = 0‰ is assumed. Such values are clearly far below the range estimated for contemporaneous seawater and thus, to obtain temperatures similar to the Lopingian time interval (23–34°C), the assumed seawater δ^{18}O would have to be enriched in ^{18}O by about +1 to +3‰, and the ranges of temperatures would be 21.5–23°C in the first case and 31.5–33°C in the second case. Such an evaporative postulate fits well with Zechstein palaeogeography and history of deposition (Korte *et al*., 2005). If the relation observed in the modern Red Sea is applied, then the salinity in basinal Zechstein Limestone water was increased by about 1‰ (or less) compared to seawater (*cf*. Craig, 1966). In the upper part of the Zechstein Limestone of the Puck Bay area the diversity of fauna increases, and this tendency suggests that the slight increase of the δ^{18}O values of calcite upsection was due to decrease of temperature (by *ca*. 1.5°C) rather than due to the salinity increase.

The δ^{13}C values in turn show a clear increase upsection (from about +4.4‰ at the base of the unit to *ca*. +6‰ at its top; Fig. 2) that is interpreted as due to a global increase during the time span of *ca*. 1 Ma when the Zechstein Limestone was deposited.

Other geochemical parameters also show a consistency in time, especially when the coefficients are considered (Table 1) except for the iron content that is clearly higher in the upper part of the Zechstein Limestone (Fig. 2). This increased content of iron is accompanied by the increased content of quartz grains; both were related to the increased supply of terrigenous material due to fall(s) of the Zechstein Limestone sea level. As was already mentioned, the fall(s) did not result in the subaerial exposure of the Zdrada IG 8 borehole area although it does not necessarily imply that the Puck Bay region was not affected by (glaci)eustatic sea level changes recorded in the marginal parts of the Zechstein Limestone basin (see Peryt, 1986, with references therein). Piątkowski (1980) clearly indicated the correlation potential of the particular stromatolite levels throughout the western part of the Peri-Baltic Syneclise. These levels amalgamate toward the central part of the Peri-Baltic Gulf (Piątkowski, 1980). There was also observed a distinct trend of increase of the height of stromatolite columns in the basinward direction (Peryt and Piątkowski, 1977*b*) and thus, considering that even in micritic complex isolated oncoids occurring (Peryt and Piątkowski, 1976) that grew in place, those relations seem to be related rather with fluctuations of the chemocline that could not be related to sea level fluctuations.

The majority of hitherto reported isotopic results on the Zechstein Limestone come from the marginal part of the basin (e.g., Magaritz and Peryt, 1994), and in the basinal setting only the lower part of the Zechstein Limestone sections was usually studied. For example, the total thickness of studied strata (Kupferschiefer and Zechstein Limestone) in two sections (Buchenau 1 and Mansbach 2) from Central Germany was 10.7 and 13.1 m, respectively (Magaritz *et al*., 1981), but the upper part of the Zechstein Limestone in those two boreholes is lacking isotopic study. The δ^{13}C and δ^{18}O values of the Zdrada IG 8 borehole are clearly shifted towards the heavier values compared to the previously published plots from other parts of the Zechstein Limestone basin (Fig. 8). In general, the diagenesis of carbonates leads to the decrease of the both values (Hudson, 1977) and thus the most reasonable explanation is that the Zechstein Limestone deposits of the Zdrada IG 8 borehole represent the less diagenetically-affected strata compared to other cases with reported stable isotopic results.

The diversity and abundance of foraminifers is low in the Zdrada IG 8 borehole. In the lower part of the Zechstein Limestone of the Zdrada IG 8 borehole dwarf forms occur interpreted as due to either an oxygen-depleted environment (as typical calcareous benthic foraminiferal assemblages from such an environment show a predominance of small specimens – e.g., Bernhard, 1986) and/or hypersaline conditions. The predominance of lagenides throughout the Zechstein Limestone section (they form 78% of the foraminiferal assemblage; Fig. 5) suggests dysaerobic conditions (e.g., Corliss and Chen, 1988; Jorissen *et al*., 1995; Korchagin, 2011). The scarcity of foraminifers in the basinal facies of the Peri-Baltic Syneclise was already noticed by Piątkowski (1980). In contrast, rich assemblages of foraminifers occurring in the marginal facies of the Zechstein Limestone were recorded in the eastern part of the Peri-Baltic Syneclise (e.g., Suveizdis, 1975; Piątkowski, 1980; Woszczyńska, 1987; Peryt and Woszczyńska, 2001). The scarcity of foraminifers may be explained by the restrictive effect of hypersalinity in the basinal facies and its offset in the marginal zone by the influx of estuarine water. Such an interpretation was proposed by Pattison (1981) who found that the largest and most varied foraminiferal faunas extracted from the British Zechstein, including abundant *Agathammina, Ammobaculites, Ammodiscus,* and a large number of nodosariid forms came from the grey marl and argillaceous limestone of the Permian Lower Marl and Lower Magnesian Limestone in northern Nottinghamshire deposited in what were apparently comparable marginal positions in broad bights on the south side of the Zechstein Sea. Rich foraminiferal assemblages have been recorded in similar palaeogeographical position from various areas in Germany (e.g., Paalzow, 1936; Scherp, 1962; Becker, 2002) and Poland (e.g., Odrzywolska-Bieńkowa, 1961; Jurkiewicz, 1966; Alexandrowicz and Barwicz, 1972; Peryt and Peryt, 1977). In the Fore-Sudetic area Peryt and Peryt (1977) observed a distinct palaeogeographical control on the composition of foraminiferal assemblages. The assemblages from the basin centre are dominated by *Agathammina* and/or uniserial forms. Alexandrowicz and Barwicz (1970) observed that the lowermost foraminifer assemblages in the Zechstein Limestone section are dominated by *Agathammina* (only *Agathammmina pusilla*) and *Nodosaria*, and then uniserial foraminifers (mostly *Nodosaria* and *Dentalina*) prevail throughout the section.

Foraminifers are more common in the basinal sections of the Zechstein Limestone in the Fore-Sudetic area than in the Zdrada IG 8 borehole. Peryt and Peryt (1977) noticed a similar frequency of foraminifers per thin section (*ca*. 10 specimens, excluding encrusting forms) in the basin centre and in the marginal part of the basin in the Fore-Sudetic area. This difference is interpreted as due to more continued dysoxic-to-anoxic conditions and/or higher salinity of basin water in the depressions of the Peri-Baltic area that led to a dramatic decrease in both diversities and abundances of foraminiferal assemblages or even their total absence. Some studies record the permanent occurrence of benthic foraminifers throughout Oceanic Anoxic Events or short-term repopulation events (e.g., Peryt *et al*., 1994; Friedrich, 2010), and thus such events could be longer and more numerous in the Fore-Sudetic area owing to the inherited differentiated morphology and active tectonics (Kiersnowski *et al.*, 2010) that led to less stable density stratification and chemocline interface than in the Peri-Baltic area. The foraminiferal events identified in the Zdrada IG 8 borehole are related to such repopulation episodes although there is no doubt that they were more numerous considering the sampling density. These events are characterized by the increased number of foraminifers and the appearance of *Earlandia*.

The much poorer fauna combined with an extreme scarcity or lack of typically marine groups such as crinoids and corals in the central basinal part of the Peri-Baltic Syneclise was already recognized by Piekarska and Kwiatkowski (1975) who suggested abnormal conditions probably resulting from increased salinity in the Peri-Baltic Gulf separated from the open sea by shoals of the Koszalin–Chojnice Zone.

IMPLICATIONS

The occurrence of similar (or identical) facies as recorded in the pisolitic complex of the Zdrada IG 8 borehole is common for the entire Zechstein Limestone basin (Smith, 1986, p. 122 and Becker, 2002, p. 39, with references therein), although except for they occur in the Puck Bay area mostly in the topmost part (0.5–1.0 m thick) of the Zechstein Limestone (Trow Point Bed of Smith, 1986). Smith (1986) concluded that the similarities of the Trow Point Bed and the oncoidal rocks described from the southern North Sea, Northern Germany and Western and Northern Poland is such that these varied occurrences must be regarded as probable correlatives. He envisaged unusual widespread environmental conditions for the Zechstein basin at this time, and concluded that either these conditions were established in Poland earlier than elsewhere or the oncoidal rocks in England are a condensed equivalent of the much thicker sequence in Poland (Smith, 1986, p. 123). In addition, Becker (2002) recorded oncoidal rocks as forming an intercalation (0.2–1.7 m thick) in the central parts of the Hesse and Werra basins, within the upper part of the complex of homogeneous mudstone (5–8 m thick) and porous mudstone (1–3 m thick) with evaporite crystals. In Western Poland, there occur sections that are composed almost entirely of oncoid deposits (Peryt, 1978; Oszczepalski, 1980); hence it may be supposed that their actual relative scarcity is just a preservation phenomenon.

The metal ratios of the Zechstein Limestone rocks of the Zdrada IG 8 borehole (Table 1) suggest the dysoxic/anoxic environment similar to that in which the Kupferschiefer deposits originated (Pašava *et al.*, 2010), and thus in the basinal area dysoxic/anoxic conditions persisted and only in marginal areas and elevations within the basin the oxic regime could be dominant with the onset of the Zechstein Limestone sedimentation.

As was mentioned, the existing models of the Kupferschiefer deposition assume salinity stratification (Brongersma-Sanders, 1971; Turner and Magaritz, 1986). The deposition of the Zechstein Limestone in the basinal zone in Northern Poland took place under conditions of elevated salinity, as discussed above (see also Bechtel *et al.*, 2002), and it is thus reasonable to expect that the salinity stratification continued over a major time of Zechstein Limestone deposition.

CONCLUSIONS

1. The entire Zechstein Limestone section of the Zdrada IG 8 borehole is composed of oncoid packstone that are accompanied by stromatolites in the upper part of the unit. There occurs a continuous transition between the portions with well-developed oncoids to the parts where these oncoids and peloids are very vague and only their outlines can be recognized. It is possible that the deposits of the so-called micritic complex forming the lower (and middle) part of the Zechstein Limestone section in the western part of the Peri-Baltic Syneclise has been primarily an oncoid deposit.
2. Deposition of the Zechstein Limestone in the Zdrada IG 8 borehole area occurred in a persistently subtidal environment, above the storm wave base, in mostly dysoxic conditions, and thus they did not differ essentially from those characteristic of the Kupferschiefer. The previous supposition of vadose diagenesis is not confirmed by the isotopic study of calcite that showed its clearly marine values (average δ^{13}C value of +5.1 ±0.6‰ and average δ^{18}O value of –0.5 ±0.7‰) that are compatible with the contemporaneous Lopingian deposits.
3. The faunal restriction and the dwarfed forms suggest elevated salinity of seawater although geochemical data suggest that the salinity increased insignificantly (about 1‰) since the beginning of Zechstein Limestone deposition. During the deposition of the topmost part of the Zechstein Limestone section ecological conditions improved in response to the shallowing and better water circulation as can be seen in the richer faunal assemblages.
4. The calculated palaeotemperature of seawater was within the range of 23 to 33°C (or more), the higher values being more appropriate, and slightly (by *ca*. 1.5°C) decreased at the end of the Zechstein Limestone deposition.
5. Foraminiferal assemblages occurring in the Zechstein Limestone are dominated by uniserial forms that form 78% of the total assemblage (excluding encrusting foraminifers that occur in the upper part of the Zechstein Limestone), and because dysaerobic conditions are favourable for lagenides, oxygen-deprived conditions prevailed throughout the entire Zechstein Limestone deposition. Foraminifers are rare and are dwarfed forms especially in the lower part of the section,, indicating a stressed environment, probably due to dysoxic conditions. There occurred some repopulation episodes; three of them have been identified but there is no doubt that they were more common. These foraminiferal events are characterized by the increased number of foraminiferal specimens (compared to the earlier and later strata) and the appearance of *Earlandia*.

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