Geological Quarterly, 2012, **56** (4): 869–880
DOI: http://dx.doi.org/10.7306/gq.1060

Foraminifera in slump deposits of the Badenian (Middle Miocene) Green Stratified Salt in Wieliczka, Poland

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Gonera M., Bukowski K., d'Obyrn K. and Wiewiórka J. (2012) – Foraminifera in slump deposits of the Badenian (Middle Miocene) Green Stratified Salt in Wieliczka, Poland. Geol. Quart., **56** (4): 869–880, doi: 10.7306/gq.1060

Taxonomic, quantitative and isotopic study of foraminifera from mudstone and claystone xenoliths incorporated into slump facies of the Stratified Salt Member of the Wieliczka deposit shows that the majority of xenoliths represent the CPN 8 biozone (Wielician substage, Badenian, Middle Miocene). The share of the CPN 7 biozone is minor; it was recorded in two of 26 samples analysed. The source area of xenoliths was the basinal part of the Carpathian Foredeep, located far off the shoreline (shallow-water taxa are not present in the samples); it represents the upper bathyal zone, in oxygenated conditions. Inbenthic, eutrophic and opportunistic foraminifers dominate the benthic environment of the CPN 8 span of time. Increased $\delta^{18}O$ values of the *Globigerina bulloides* tests (from +1.7‰ in CPN 7 to +2.3‰ in CPN 8 sediments) was due to the change from the Middle Miocene Climate Optimum to the Middle Miocene Climate Transition at the CPN 7/CPN 8 boundary. This palaeoclimate event is the marker of the Moravian/Wielician chronostratigraphic boundary in the Central Paratethys. The Wielician shows the distinct taxonomic reduction of the Moravian planktonic foraminifera and includes the *Globigerina bulloides* Acme.

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Key words: Middle Miocene, Paratethys, salinity crisis, foraminifera, slump processes.

INTRODUCTION

Badenian evaporites are widespread in southern Poland (Fig. 1). They are mainly composed of gypsum and anhydrite with interbeds of clayey rocks and form a continuous horizon throughout most of the Carpathian Foredeep (Fig. 1B). In a narrow strip (a few kilometres wide) along the Carpathian overthrust and in the Silesia Basin area the chloride facies occurs (Wieliczka Formation – Garlicki, 1994): rock salt enriched with gypsum and anhydrite and with interbeds of claystones, siltstones and occasional sandstones. The Wieliczka Fm. varies in thickness from 30 m to over 100 m (Garlicki, 1979).

The Wieliczka deposit were formed due to folding and elevation of the salt-bearing succession. This tectonic repetition has multiplied the thickness of the salt layers. The Wieliczka deposit extends over a distance of about 10 km, and its north-south extent varies between 800 and 900 m. The salt deposit has a complex internal structure (Gaweł, 1962) and a very variable thickness (1–350 m). The greatest observed thickness is in the central part of the deposit.

Foraminifera are present in various types of detached blocks/clasts of marl and clay (xenoliths) within the salt deposits of the Wieliczka deposit and in siliciclastic rocks overlying and underlying the deposit. Studies by Reuss (1867), Małecki (1954), Łuczkowska (1967, 1978, 1985, 1995), Alexandrowicz (1975) and Łuczkowska and Rolewicz (1990) indicated that in most of the xenoliths the assemblage of the *Uvigerina costai* Zone (IIC and IID assemblages after Alexandrowicz, 1963), and less frequently the assemblage of the *Orbulina suturalis* Zone (IIA and IIB assemblages), occur (cf. Fig. 2). Rocks overlying the Wieliczka deposits contain foraminifera of the early *Velapertina indigena* Zone (IIIA assemblage; Fig. 2).

It is difficult to determine the conditions in which deposits of the Wieliczka Fm. originated based on macroscopic observation of lithology due to frequent post-sedimentary blurring of the primary structural features. In addition, the entire deposit has undergone successive phases of tectonic deformation, considerably complicating the internal structure and making it dif-

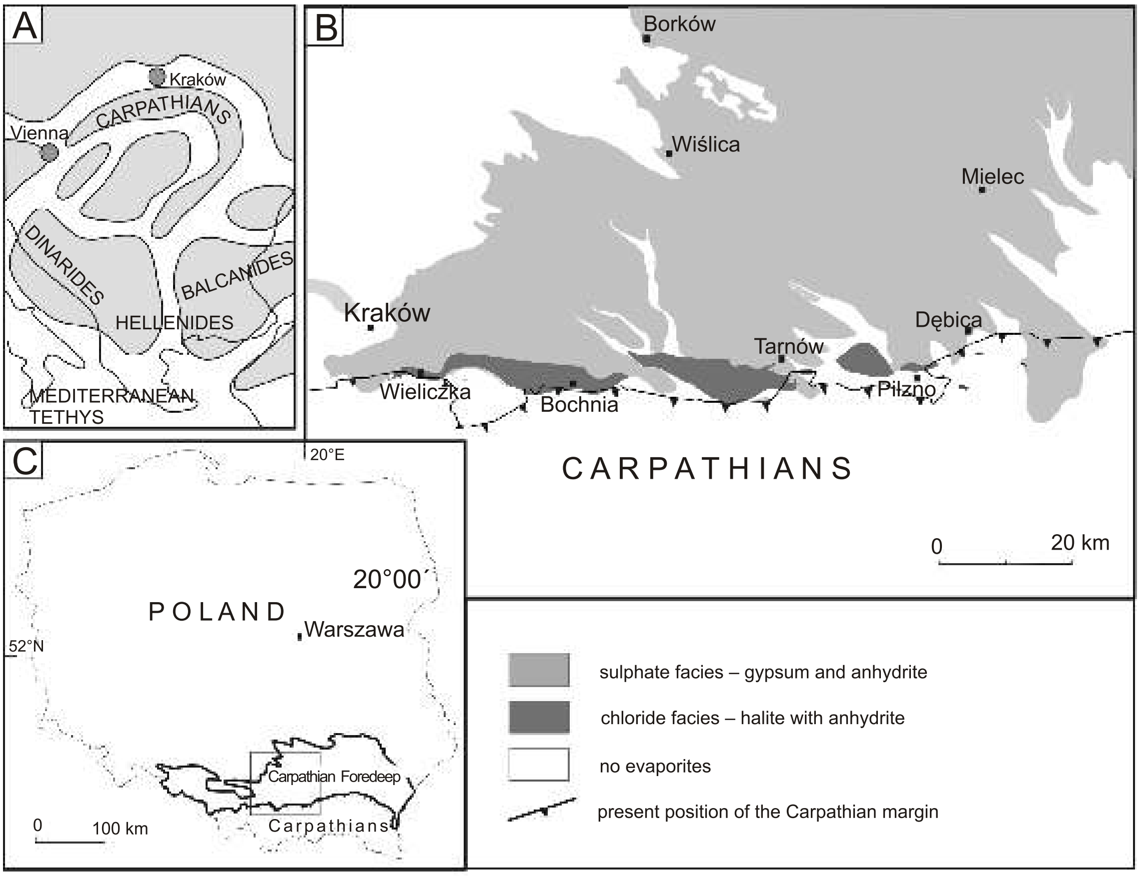

Fig. 1. Location map

A – Central Paratethys marine sedimentation (white) after Rögl and Steininiger (1984);
B, **C** – location of the Wieliczka Salt Mine (C) (after Garlicki, 1979)

Chronostratigraphy		Concept of foraminiferal stratigraphy after: 1 – Cicha et al. (1975); 2 – Papp et al. (1978); 3 – Rögl and Steininger (1984); 4 – Steininger et al. (1985); 5 – Alexandrowicz (1963, 1997); 6 – Łuczkowska (1964)				
		1–4			5	6
Badenian (Middle Miocene)	Kosovian	CPN 9	*Velapertina* Zone	*Bulimina–Bolivina* Zone	III B	*Hanzawaia crassiseptata* Zone
					III A	*Neobulimina longa* Zone
	Wielician	CPN 8	*Globigerina druryi–G. decoraperta* Zone	zone with agglutinated foraminifera	evaporite deposits	
					IID IIC	*Uvigerina costai* Zone
	Moravian	CPN 7	*Orbulina suturalis* Zone	Lagenidae Zone	IIB IIA	*Orbulina suturalis* Zone

Fig. 2. Central Paratethys stratigraphic units and location of the samples studied (dashed line)

ficult to determine primary depositional conditions. This article presents new data concerning lithologically atypical development of the Stratified Salt Member (SSM after Ślączka and Kolasa, 1997), where sedimentological observations and analysis of foraminifera shed light on these deposits.

GEOLOGICAL SETTING

The oldest rocks identified by boreholes in the direct vicinity of Wieliczka are Carboniferous and Permian siliciclastic deposits. Above these lie Jurassic limestones. At Wieliczka, these were found at depths of 300–400 m (Gaweł, 1962). They incline at a slight angle (4–18°) to the south and south-east. The Jurassic deposits are overlain by Lower Badenian marly claystones, siltstones and sandstones (Skawina Fm. after Alexandrowicz et al., 1982).

The Skawina Fm. corresponds to foraminifer assemblages IIA to IID (Fig. 2). In the top part of these deposits (Fig. 3) a 5-centimetre WT-1 tuffite layer occurs (Pawlikowski, 1975; Wiewiórka, 1979; Bukowski, 1999), the radiometric age of which has been determined at 13.81 ± 0.08 Ma (de Leeuw et al., 2010). In the upper part of the Skawina Formation, a gradual increase in the proportion of sulphates is observed; initially as gypsum cement in sandstones, followed by continuous anhydrite laminae and layers. These deposits continue uninterrupted into the Oldest Salt composed of a dozen layers of fine- and medium-grained salt with a coarse-grained salt layer appearing at the top (Wiewiórka, 1988). The level of such salts displays the greatest variation among the entire succession of the SSM and Spiza Salt deposits in the upper part of the SSM, with which it was initially identified. The thickness of the Oldest Salt is variable and ranges between 2 and 20 m.

Above the Oldest Salt, an intercalation of barren rocks composed of sandstones, siltstones and anhydrite-bearing claystones occurs. These deposits were once referred to as "Sub-salt Sandstone," as it was believed that they comprised the initial element of salt sedimentation (Gaweł, 1962). Their thickness ranges from a few to about 10 m and they occur in several beds. Within the sandstones, sedimentary structures are found: cross-bedding, ripple-marks and convolute bedding (Bukowski, 1997). Locally in the central part of the Sub-salt Sandstone, a discontinuous conglomerate bed occurs; it is about 0.5–1.0 m thick and formed of fragments of salt, anhydrite, and Carpathian flysch rocks (Charysz, 1967; Charysz and Wiewiórka, 1977). Within the Sub-salt Sandstone, two tuffite intercalations have been identified, termed WT-2 and WT-3 (Pawlikowski, 1975; Wiewiórka, 1979). The radiometric age of an analogous tuffite layer (WT-3) from the Bochnia Salt Mine has been determined at 13.6 Ma (Dudek et al., 2004; de Leeuw et al., 2010). In the upper part of the Sub-salt Sandstone, increasingly numerous layers of anhydrite appear and the contribution of sandstones clearly diminishes. This represents a gradual transition to the sedimentation of the Green Stratified Salt.

The Green Stratified Salt consists of 4–5 layers of rock salt separated by claystone beds with anhydrite. The Green Stratified Salt is found in the form of coarse grains and in some parts, crystals with sizes up to 10 cm in diameter. The grains are turbid in appearance because of the presence of clayey suspension and nodular anhydrite concentrations. Due to the presence of clays, the halite crystals take on a slightly greenish hue from which the name of the entire succession is derived. Some halite crystals have a zonal (chevron) structure caused by linearly positioned fluid inclusions. In the upper parts of the salt beds clear deformation has been observed, which are interpreted as erosional surfaces generated by flowing water (Pawlikowski, 1975). In the oldest Green Stratified Salt layer (GSS IV), slump deposits have been observed (Fig. 4).

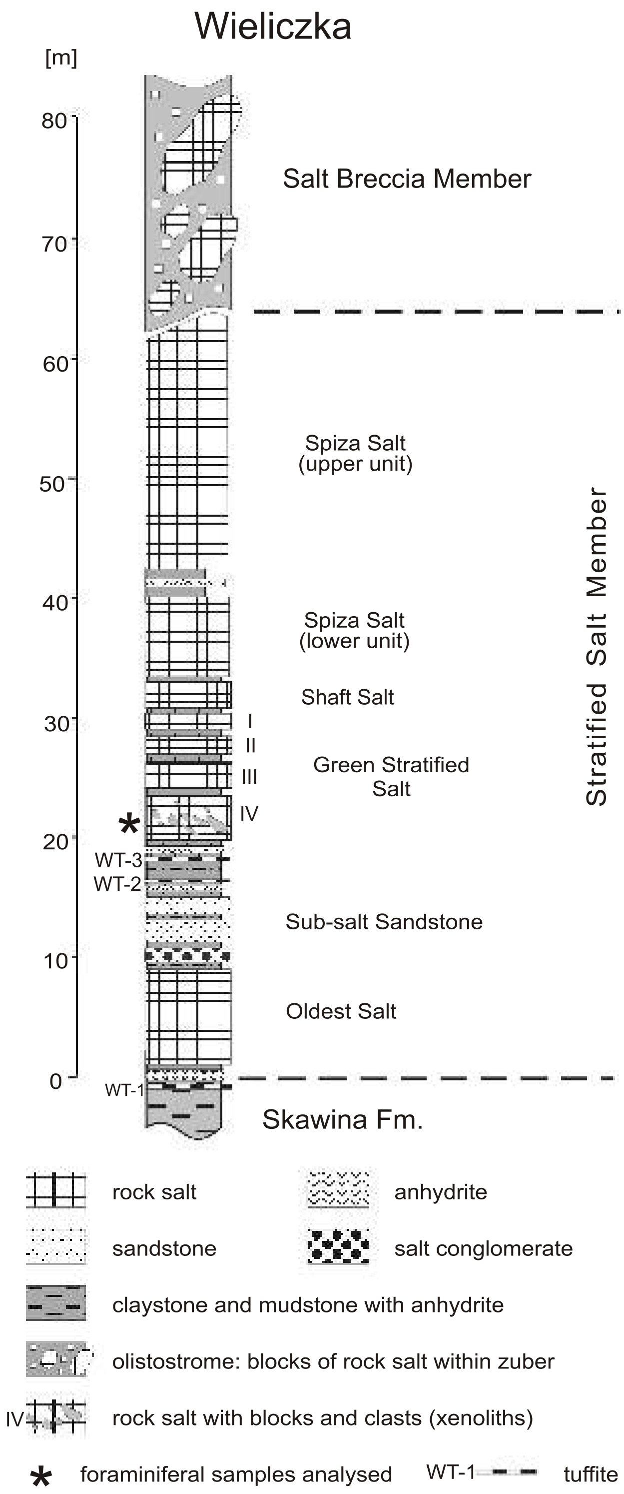

Fig. 3. Wieliczka lithostratigraphic profile (after Wiewiórka, 1988)

MATERIAL AND METHODS

The lithology of the Green Stratified Salt was analysed throughout the entire area of its occurrence at the Wieliczka Salt Mine (Bukowski, 1992). Overall, a total of approximately

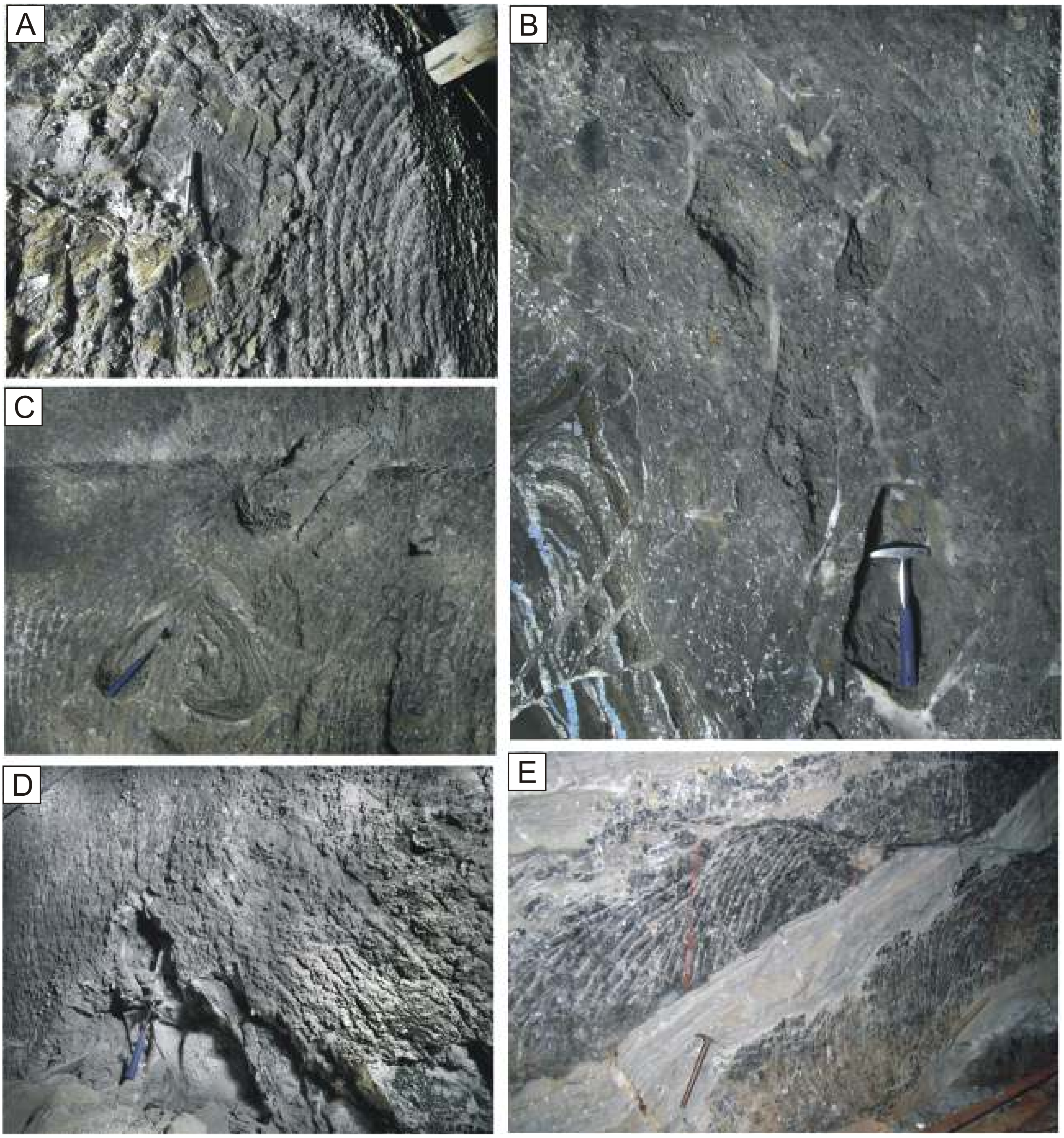

Fig. 4. Photographs of different types of xenoliths occurring in the Green Stratified Salts in Wieliczka Salt Mine

A – clast of claystone (August Gallery, Mine level III); **B** – blocks of claystones scattered within GSS IV (dip heading between Mine level III and IV); **C** – synsedimentary deformation in slump sheet (Karol Marek Gallery, Mine level III); **D** – redeposited block of mudstone (Schwind Gallery, Mine level II lower); **E** – first and second beds of Green Stratified Salt (Karol Marek Gallery, Mine level III). Photos by J. Przybyło (A–D) and K. Bukowski (E)

500 metres of sections located mainly at exploitation Level III of the mine, was studied. The documenting work was aimed at selecting those exposures which allow tracing the lithology of the lower part of the Stratified Salt Member (Fig. 5).

Samples for foraminiferal study were taken from eight sites, where atypical formation of the GSS IV was observed (Appendix 1 – supplementary file*). Six of these sites are located at Level III of the mine, one is located at Level IV (Maylath Gallery) and one sample at Level II n (Schwind Gallery); in an E–W direction the distance between sampled sites is just over 1 km. A total of 26 rock samples were collected from the clayey-marly xenoliths occurring in the GSS IV. Samples were subject to standard maceration procedure and then washed on a 0.1 mm sieve and the resulting residue (fraction

* Supplementary files are available on website: www.gq.pgi.gov.pl

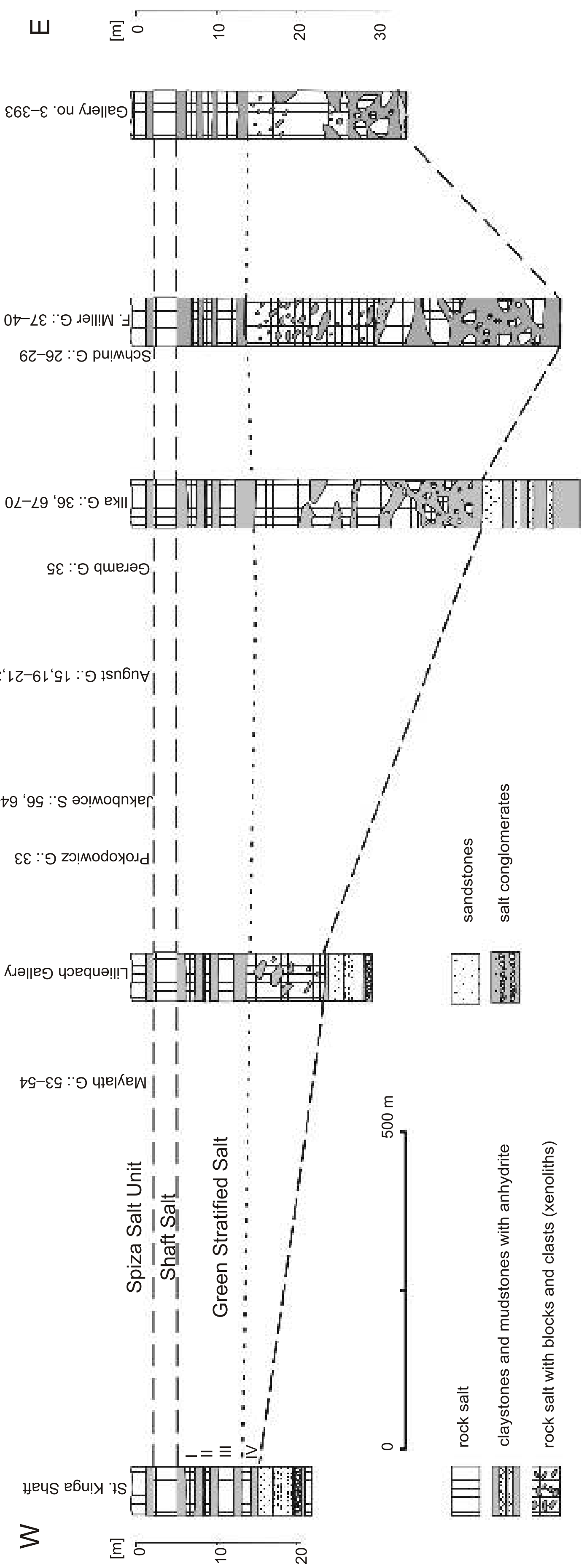

Fig. 5. Lithostratigraphic correlation of the Green Stratified Salts in the central and eastern parts of the Wieliczka Salt Mine

above 0.1 mm) was analysed stereomicroscopically. Foraminifera were determined taxonomically, and their number in the same volume (ca. 1 cm^3 of residue) was calculated.

Actualistic principles have been applied to palaeoenvironmental evaluation of the foraminifera regarding bathymetry (e.g., Murray, 1973, 1991; Gibson, 1989). The oxygen-nutrient conditions in these habitats have been estimated based on the foraminifer ecogroup proportion (Gonera, 2001 and Baldi, 2006, with references therein). For the assessment, the following were adopted as epibenthic taxa: Miliolina, *Lenticulina*, *Eponides*, *Cibicides*, *Heterolepa* and *Hansenisca.* The following taxa were adopted as inbenthic foraminifera: Nodosariidae, *Lagena*, *Glandulina*, *Bolivina*, *Cassidulina*, *Globocassidulina*, *Bulimina*, *Uvigerina*, *Valvulineria*, *Sphaeroidina*, *Nonion*, *Melonis*, and *Pullenia*. Certain characteristic taxa are proxies of trophic conditions (van der Zwaan, 1985; Jorrisen et al., 1992). The following are connected with organic-rich (eutrophic) niches: *Bolivina*, *Bulimina*, *Uvigerina*, *Globocassidulina laevigata* and *Valvulineria*. *Valvulineria* and *Cibicides* are also treated as opportunistic taxa, having an ecological preference for extremely unstable trophic conditions (Gonera, 2001; with references therein).

Globigerina bulloides, *Uvigerina* spp. and *Bulimina* spp. were selected for isotopic analyses. Well-preserved tests of benthic (*Uvigerina*, *Bulimina*) and planktonic (*Globigerina bulloides*) foraminifera have been analysed as regards oxygen and carbon stable isotopes. The specimens filled by pyrite/evaporites were avoided during the picking. Therefore it is assumed that the effect of infilling by these minerals on the stable isotope composition was negligible. This method was applied in the analysis of 22 rocky samples (xenoliths) with the use of 43 weighed foraminiferal-test samples, which yielded the following pairs of data: $\delta^{18}O$ and $\delta^{13}C$ for each weighed sample. The determination of $\delta^{18}O$ and $\delta^{13}C$ was carried out in the GeoZentrum Nordbayern Laboratory of the Friedrich-Alexander-Universität in Erlangen-Nürnberg, Germany. All values are reported in permil relative to V-PDB by assigning a $\delta^{13}C$ value of +1.95‰ and a $\delta^{18}O$ value of –2.20‰ to NBS19. Reproducibility was checked by replicate analyses of laboratory standards and is better than ±0.01–0.03‰.

RESULTS

SEDIMENTOLOGICAL OBSERVATIONS

Intercalations of siliciclastic material separating the particular beds of Green Stratified Salt are clastic-evaporite deposits 0.5 to 1.0 m thick. These are mudstones and claystones with anhydrite layers, consisting mainly of clay minerals, quartz, gypsum, anhydrite and halite. These are clearly laminated rocks of a light to dark gray colour. The laminae are 0.1 mm to several millimetres thick. The deposits are separated by layers of anhydrite several centimetres thick, and a characteristic tendency of decreasing sulphate toward the top of the GSS is observed. Anhydrites are hard, compact, and are white in colour with a slightly bluish tinge. These also occur in the form of parallel layers, often with an enterolithic structure and in opposing intersecting veins. Anhydrite also occurs in the form of isolated nodules of a size between several millimetres and several centimetres.

In the western and central parts of the Wieliczka deposit (the area between Barycz and Saint Kinga Shaft), the thickness of the GSS is about 12 m, with an average thickness of salt layers ranging between 0.5 and 3 m. In many galleries in the eastern part of the mine, a constant pattern is observed: the top three salt layers (I–III) are formed in a similar manner, while the lowest one (IV in Fig. 3) is characterized by a very clear increase in thickness: in the western part of the bed, it has a constant thickness of approximately 0.5 m, and to the east, the thickness increases to reach its maximum value of approximately 30 m in the vicinity of the Wilson Shaft (near the Gallery no. 3–393 in Fig. 5).

In GSS IV, not only the thickness, but also the lithology departs considerably from those of the typical GSS bed (i.e. GSS I–III). From the top to the bottom of GSS IV, the following lithologically distinct parts are clearly distinguished:

– A (about 20–50 cm thick): a large quantity of clay material, which creates a kind of a matrix in which single, usually rounded, crystals of transparent halite and anhydrite nodules occur; clay content is ca. 60%;
– B (several meters thick): stained-glass structure salt is present, long axes of claystone and siltstone xenoliths (10–20 cm in diameter) are orientated parallel to the top/base of the layer;
– C (a few meters thick): with an increasing proportion of nodular anhydrite (locally up to several tens of percent), also with a significant increase in the size of scattered claystones and siltstones xenoliths (blocks and clasts), reaching a size between several tens of centimetres and several meters across;
– D (up to several meters thick): there is a clear predominance of the clayey fraction in which fragments of sulphates and halite are set; macroscopically, the deposit resembles marly claystone with halite crystals.

Fragments of salt and anhydrite present in the silty-clayey sediment are scattered and distributed chaotically. There is no sign of the currents activity, graded bedding or lamination. The layer is bordered by sandstones of the Sub-salt Sandstone (at the bottom), and by siltstones and claystones forming the terrigenous intercalation between GSS III and GSS IV (at the top). Further east, the GSS IV layer gradually thins until it completely disappears in the Sułków area where the presence of anhydrite with claystone was discovered at this lithostratigraphic position (Bukowski, 1992). The total extent of this unusually formed GSS IV level in an E–W direction is about 3 km.

FORAMINIFERA

Residua of the micropalaeontological samples (mudstone and claystone xenolith blocks and clasts) of the B and C parts of GSS IV consists of microfossils and mineral particles. The mineral grains in all the samples are similar, comprising pyrite and evaporite minerals (anhydrite and gypsum of secondary origin). In some samples, small amounts of pyroclastic quartz are present. Pyrite is found in a number of forms; sticks of most likely organic origin are common (Bathysiphonidae or coprolite pseudomorphs).

Foraminifera are abundant in twenty four of the samples, while in two samples only scarce specimens are present (Appendix 1). Besides foraminifera, in some samples small amounts of carbonised plants, and single bolboforms, ostracods, chitin fragments of larger organisms, sea urchins, and sponge spicules were also found.

Planktonic foraminifera of samples 56 and 37 are typical of IIB assemblage CPN 7 (*Orbulina suturalis* Zone; Fig. 2). In the remaining twenty two samples, the taxonomic set of foraminifera is typical of the *Uvigerina costai* Zone (IIC, IID assemblages). samples 64 and 28 are barren of foraminifera; they may belong to the *Uvigerina costai* Zone due to the scarcity or absence of foraminifera in some deposits of IIC zone (Alexandrowicz, 1963, with references therein).

The samples placed in the CPN 7 *Orbulina suturalis* Zone (samples 37 and 56) are characterized by taxonomically varied plankton (Appendix 1), which represents 71.4% (sample 37) and 70.1% (sample 56) of the foraminifera assemblage. *Globigerinoides quadrilobatus* dominates in the plankton (78 and 60% respectively) and *Globigerina bulloides* is the second most frequent taxon (11.4 and 28.4% respectively). Among the benthic foraminifera, *Bulimina* spp. dominate in sample 37 (42%) while in sample 56, Nodosariidae and *Sphaeroidina bulloides* are dominant (19% and 10% respectively), and quite common are: *Bulimina* (7.8%), *Valvulineria complanata* (6.7%) and *Melonis pampilioides* (7.0%).

In the samples of CPN 8 (*Uvigerina costai* Zone) the fauna of pelagic foraminifera is monotypic. Only *Globigerina bulloides* is present, with its percentage varying considerably (Fig. 6). Among benthic foraminifera, three taxa are clearly dominant: *Bulimina* spp., *Uvigerina* spp. and *Valvulineria complanata*. Overall, these amount to between 41% (sample 33) and 100% (sample 15) of the benthic foraminifera, accounting on average for 75% of their composition (Fig. 7). In some samples, *Pseudotriplasia minuta*, the index taxon of the IID assemblage, is present. In some samples of this zone,

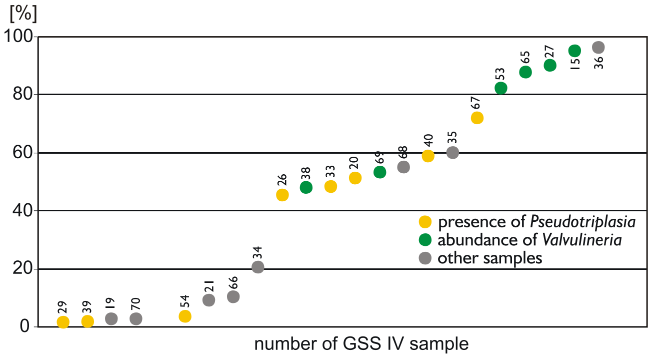

Fig. 6. Percentage of *Globigerina bulloides*, presence of *Pseudotriplasia* and abundance of *Valvulineria* in the *Uvigerina costai* Zone samples of GSS IV

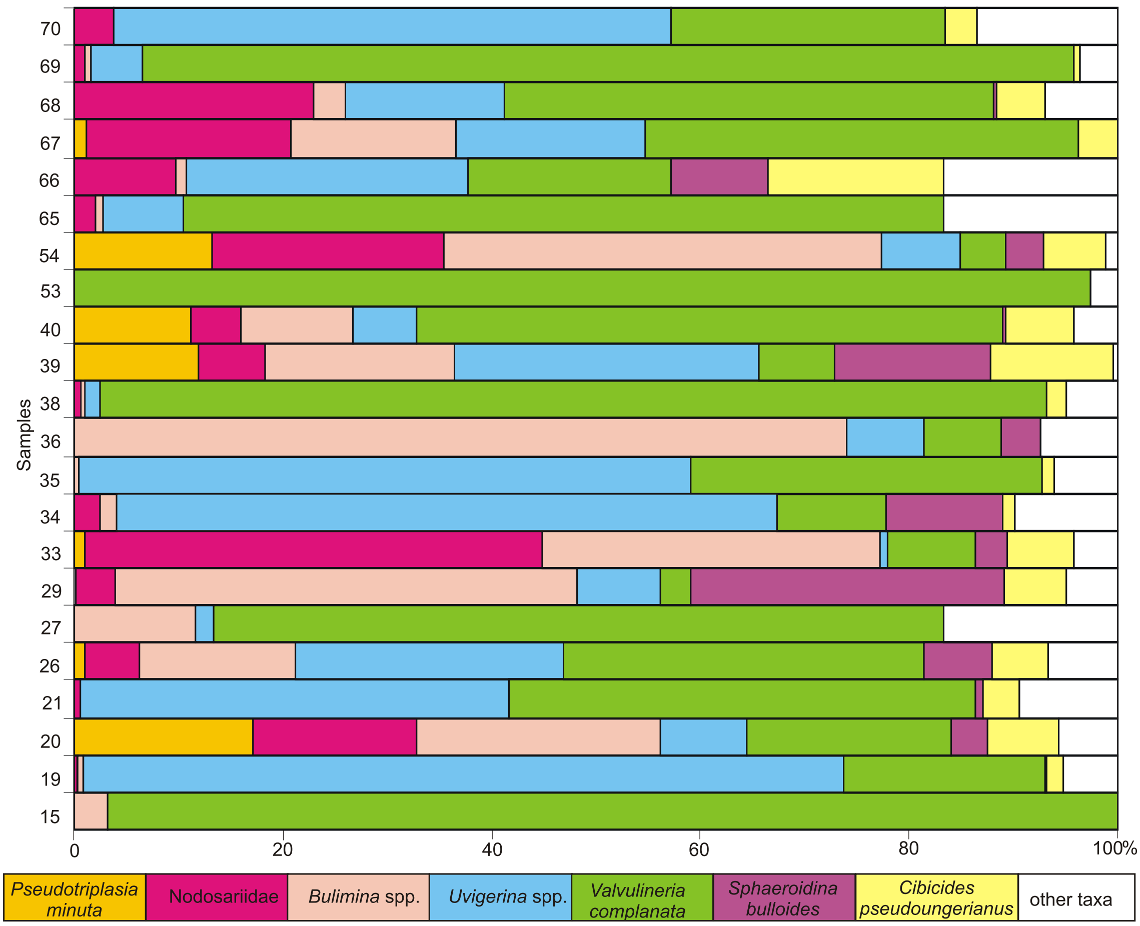

Fig. 7. The relative frequencies (percentages) of the most common benthic taxa in the *Uvigerina costai* Zone samples of GSS IV

Nodosariidae, *Sphaeroidina bulloides* and *Cibicides pseudoungerianus* amount for a significant percentage.

The $\delta^{18}O$ value of *Globigerina bulloides* tests (planktonic foraminifera) in the *Orbulina suturalis* Zone reaches +1.7‰ and is lower than in younger samples (Appendix 2). The *Globigerina bulloides* tests in the *Uvigerina costai* Zone reach an average $\delta^{18}O$ value of +2.3 ± 0.2‰ (after eliminating the border values in sample 53). The average value of $\delta^{18}O$ of *Uvigerina* spp. and *Bulimina* spp. (benthic foraminifera) in CPN 7 (*Orbulina suturalis* Zone) samples are: +2.2‰ (*Uvigerina*) and +2.0‰ (*Bulimina*). In CPN 8 (*Uvigerina costai* Zone) these values are higher: +3.0 ± 0.2‰) and +2.9 ± 0.2‰) respectively.

The isotopic signature of the two benthic taxa analysed (*Uvigerina* spp. and *Bulimina* spp.) is similar in the case of $\delta^{18}O$ (Appendix 2). The resemblance between the two in the $\delta^{13}C$ record is less clear; while it is similar in some samples and in the others it differs.

The record of $\delta^{13}C$ in CPN 8 *Globigerina bulloides* is highly variable (we have only one signature from CPN 7). The value varies between –0.3‰ and +2.0‰, with a mean value of +0.7 ± 0.6‰. The variability is equally high for $\delta^{13}C$ in *Uvigerina* spp. (mean value of –0.2 ± 0.4‰) and *Bulimina* spp. (mean value of –0.1 ± 0.4‰).

INTERPRETATION

SEDIMENTOLOGY

The presence of submarine mass movements in the Wieliczka deposit has already been described by Kolasa and Ślączka (1985a, b) and Ślączka and Kolasa (1997). According to these authors, cohesive flow deposits and olistostromes occur in the upper parts of the Stratified Salt Member (Fig. 3) and Salt Breccia Member. Small-scale deformation caused by mass movements is also observed in siliciclastic intercalations. One of these is in GSS IV (Fig. 4D) and represents a shift which probably arose due to small gravitational flows of unlithified deposits.

The unusual development of the deposits described in GSS IV indicates that these were created as a result of cohesive flow during sedimentation. Such a hypothesis is corroborated by the following:

- bed thickness is several times greater than usual;
- both the formations lying above and below the base level of salt are aligned and show no internal disturbance;
- in GSS IV, blocks and clasts of the Skawina Fm., the Oldest Salt and the Sub-salt Sandstone are found;
- scattered blocks (xenoliths) are observed to be aligned (long axes parallel flow);

- typical deformation patches are observed (fragments of beds, one of whose edges is bent upwards (Fig. 4D);
- in the middle part of the level, the largest blocks of siliciclastic rocks are found;
- at the base, no larger fragments are found, but the proportion of particulate clayey material, formed by crushing during the slippage, increases;
- below the base, there are no silty-clay intercalations which are usually found beneath the salt bed; most likely flow occurred immediately on top of this layer, which led to it being mixed with salt.

PALAEOENVIRONMENT OF THE XENOLITH SAMPLES

Despite much knowledge of the influence of bathymetry and temperature on the distribution of foraminifera, numerous other factors play a role, and the environmental conditions determining the distributions of foraminifera are still being investigated (Murray, 2001). However, some taxa are used as indices and proxies for certain habitats that facilitate palaeoenvironmental reconstruction.

Appendix 3 shows the proportion of ecological indicators (foraminifera ecogroups) in the samples analysed. In the material analysed, *Valvulineria*, as foraminifera of organic-rich (eutrophic) conditions, is "capable" of generating the largest numbers (Fig. 7).

The taxa indicate a normal marine environment (Murray, 1991; Bé, 1977). In the samples studied, there is no admixture of shallow-water taxa. The low proportion of *Bolivina* (Appendix 1), a taxon which is well-adapted to oxygen-deficienct conditions (Perez-Cruz and Machain-Castillo, 1990), may indicate that the benthic environment of the foraminifera analysed was sufficiently oxygenated; nonetheless taxa typical of organic-rich conditions are common in many samples (Appendix 3). The data concerning the proportion of indicator ecogroups in the xenoliths (Appendix 3) provide information on oxygen and nutrient conditions of their habitats, and hence of the palaeoenvironment of the parent rock.

In the CPN 7 deposits (samples 37 and 56), the proportion of planktonic foraminifera exceeds 70%, and their taxonomic composition is diverse and is typical of warm seas (Appendix 1; Bé, 1977). Numerous *Globigerinoides* indicate that the shallow pelagic zone was richer in food than the deeper parts (the other planktonic taxa are not numerous). As can be inferred from ecological data (e.g., Murray, 1991 with references therein) the benthic foraminifera of these samples are characteristic of the outer shelf/upper bathyal zone. It was a warm-water, normal marine environment of depth exceeding 200 m.

The planktonic foraminifera assemblage in the deposits assigned to CPN 8 is radically different (Appendix 3). Only *Globigerina bulloides* is present and its quantity is extremely variable (mean value 45.5%, σ = 33.7). In the benthic foraminifera assemblage the proportion of taxa typical of organic-rich conditions varies significantly (from 1.8 to 81.5%). In the CPN 8 group of samples, opportunistic foraminifera constantly account for a significant proportion of the sample (mean value 44.9%, σ = 30.4), exceeding 92% of its composition in some samples.

The results of the stable isotope analyses provide additional information on the environmental features of the xenoliths. *Globigerina bulloides*, *Uvigerina* spp. and *Bulimina* spp. are commonly analysed taxa in isotopic studies of recent and fossil foraminifera (Kováčová and Hudáčková, 2009). Available isotopic data on the CPN 8 time span (Appendix 2; Fig. 8), allows us to present statistically generalized conclusions.

The state of water column stratification for the samples assigned to the CPN 8 Zone is calculated by Δ δ^{18}O between *G. bulloides* (pelagic) and benthic taxa. The difference is 0.7‰. As the foraminifera taxa of the biozone indicate normal salinity of seawater, temperature is clearly responsible for this difference. The temperature differed by approximately 4°C between the deeper pelagic zone and the bottom of the basin. On the other hand, the bottom temperature can be estimated at approximately 5–7°C (which follows from the thermocline conditions at a depth exceeding 200 m). These estimates indicate that the average temperature of the pelagic water amounted to approximately 9–11°C.

The carbon isotope record measured in the planktonic foraminifera indicates highly diverse surface water productivity conditions when their test formed. High productivity at the surface provided organic matter (and food) to the benthic community. However, this supply was highly variable (large fluctuations of δ^{13}C values in Fig. 8A), and the primary production at

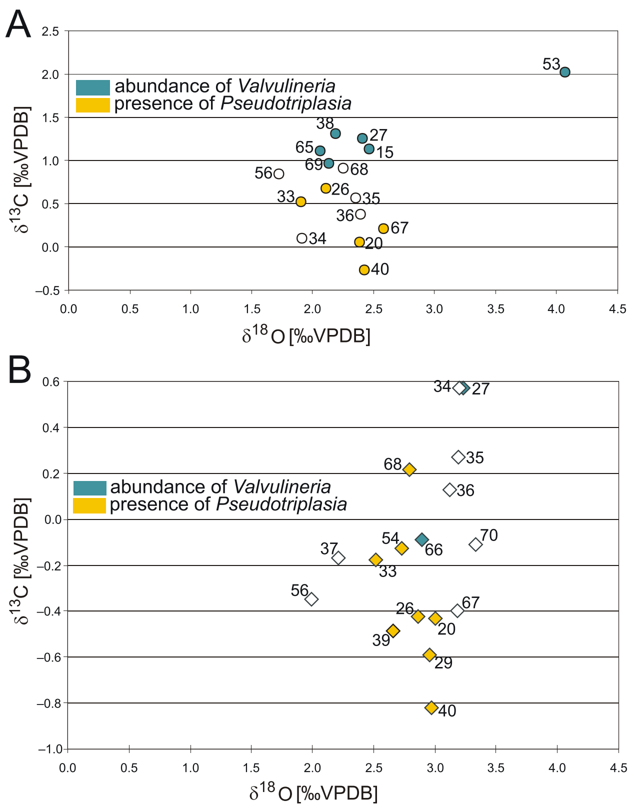

Fig. 8. Plot of foraminiferal oxygen and carbon isotope values of samples from GSS IV

A – *Globigerina bulloides*; **B** – *Bulimina* spp. and *Uvigerina* spp. mean values; in addition, colours characterise the samples in terms of the occurrence of *Pseudotriplasia* and *Valvulineria*: white symbols indicate the samples lacking *Pseudotriplasia* and with small numbers of *Valvulineria* (data on sample 65 are not included in B) the surface would have to be equally unstable. This would be determined by an unstable nutrient inflow to the photic layer of the sea. As the samples analysed are xenoliths, it has to be concluded that either the strength of these processes (nutrient supply and primary production development) was subject to strong fluctuations (from explosion to disappearance), or we are dealing with some kind of temporal succession (as we observe detached, redeposited blocks). If this is the latter case, the only one of the directions, towards either explosion or disappearance, has occurred.

To resolve this question the following taxa can be used as indices of stratigraphic sequence: *Pseudotriplasia* as typical of IID and samples containing almost exclusively *Valvulineria* (acme interval of this taxon) as typical of IIC (Alexandrowicz, 1963). Xenolith samples in GSS IV analysed according to these stratigraphic keys display characteristic isotope values (Fig. 8). Both in the planktonic (Fig. 8A) and in the benthic foraminifers (Fig. 8B), samples containing abundant *Valvulineria* (samples: 65, 69, 68, 38, 27 and 15) provide a record of a lower temperature (more positive δ^{18}O values) than that observed in IIB (sample 56) and a deficiency of food supply (highly positive δ^{13}C in Fig. 8). Samples containing *Pseudotriplasia* (samples: 20, 40, 67, 33, 26, 54, 39 and 29) display temperature similar to those recorded by samples with *Valvulineria*, while the content of δ^{13}C in those is much lower (more negative δ^{13}C values in Fig. 8) which indicates an large input of organic matter from primary production during sedimentation of this younger biostratigraphic unit.

DISCUSSION

The basic problem for researchers analysing the Wieliczka deposit encounter is the origin of its internal structure. Gaweł (1962), and then Poborski and Skoczylas-Ciszewska (1963), assumed that the tectonic transformation of the southernmost part of deposit (now the Salt Breccia Member) occurred as a result of overthrusting of the rock mass from the Carpathian orogen from the south to the north, and then superimposing this on the northernmost part of the deposit (now Stratified Salt Member). This hypothesis constitutes the so-called tectonic model of deposit formation. Połtowicz (1977) presented a similar concept, with the difference that he suggested the salt deposit to be formed not as a result of the advancing Carpathian orogen, but via gravitational slides caused by the disturbance of the balance between the Carpathian Foredeep and the Carpathians. The northward shift of the basin bottom subsidence zone with the Carpathian Basin to the north with simultaneous elevation of the Carpathian Mountains led to the creation of detachment zones within the rock mass, and then their flowing in the direction of the depression being created.

A different hypothesis was presented by Kolasa and Ślączka (1985a, b). Based on the many documented redeposited sediments (olistostromes) occurring both in the Salt Breccia Member and in the Stratified Salt Member (Ślączka and Kolasa, 1997), they concluded that the determining factor in the formation of the salt succession was submarine mass movements. In their model, boulder deposits are thought to have flowed from the south to the top of the stratiform deposit in the form of a massive underwater landslide, creating a system of olistostromes. In both the tectonic models (Gaweł, 1962; Poborski and Skoczylas-Ciszewska, 1963; Połtowicz, 1977) and the sedimentary model (Kolasa and Ślączka, 1985a, b), salts have been formed as a result of the evaporation of seawater.

Facies differentiation in the salt-bearing deposits indicates changing depth and sedimentation rate during the deposition of the salt succession along with clastic deposits. Variation in grain composition and the presence of different types of sedimentary structures are observed depending on the distance from the basin margins, the depth and bottom morphology. The increased salinity of the seawater is also reflected in the formation of the deposits. Thus the appearance of the rock salt succession is preceded by a decrease in the size of detrital grains, the occurrence of horizontal lamination, an increased content of sulphates, and generally a decrease in the rate of clastic sedimentation. During sedimentation on an inclined slope, cohesive flows were generated, which flowed down carrying silty-salt deposits. These flows were deposited in local depressions in the form of salt claystone micrite (marly claystone with halite crystals) and clayey salt zuber that were saturated with sulphates to varying degrees.

The taxonomic composition of planktonic foraminifera (Globigerinina) in the xenoliths (redeposited clasts and blocks) is the same as in the other parts of the Carpathian Foredeep Basin in the *Orbulina suturalis* Zone (IIB assemblage of CPN 7), and *Uvigerina costai* Zone (IIC, D assemblages of CPN 8). On the other hand, the benthic foraminifera in the xenoliths can be assigned to a particular part of the Skawina Beds sedimentation. The xenolith assemblages differ from those of the Upper Silesia region by a negligible proportion of “Lanzendorf fauna” (Alexandrowicz, 1963; Gonera, 1997) and, by an absence of coastal, shallow-water foraminifera the xenoliths differ from the Skawina Beds known from the vicinity of Kraków (Alexandrowicz, 1964) and parautochthonous Badenian sediments of the Carpathians (Gonera, 1994). The taxonomic composition of foraminifera in xenoliths resembles that of the Skawina beds described by Kirchner (1956) from the basinal part of the Carpathian Foredeep sea (Bochnia–Mielec–Pilzno in Fig. 1). This similarity is clearly due to the same palaeoenvironmental conditions of the Carpathian Foredeep Basin and the source area of the xenoliths.

At present, the closest locations with similar foraminiferal fauna are those located in the vicinity of Skawina (Alexandrowicz, 1973), Wrząsowice (Gonera et al., 1990) and Konary (Łuczkowska, 1955). All of these are situated SW of the Wieliczka Salt Mine, in the autochthonous Badenian deposits of the Carpathian Foredeep. However, the Skawina Beds at Konary contain a considerable admixture of coastal, shallow-water foraminifera, which are not present in GSS IV xenoliths. In turn, the Skawina Beds around Skawina (their stratotype location) contain a significant proportion of “Lanzendorf fauna” (cf. Grill, 1941), which is only subordinate in GSS IV xenoliths. The Wrząsowice site has an identical taxonomic composition as in the xenoliths, but the Wrząsowice profile has conglomerate intercalations within the *Uvigerina costai* Zone, and such pebbles are not present in the xenoliths of GSS IV. This would indicate that the GSS IV sedimentary basin was sourced by Skawina Beds of "purely" deep-water facies, which was part of the Bochnia–Mielec–Pilzno facies described above.

Xenoliths analysed in stratigraphic order have characteristic isotope values (Fig. 8). Both plankton and benthos of the CPN 7 samples (IIB assemblage) have higher palaeotemperature records (as indicated by $\delta^{18}O$ values) than those of corresponding isotopes in samples with *Valvulineria* (Appendix 2; Fig. 8). Samples with *Pseudotriplasia* have temperatures similar to those of *Valvulineria* samples, while the $\delta^{13}C$ content in those is much lower, which indicates a higher input of organic matter (primary production increase). Similar characteristics of oxygen and carbon stable isotopes occur in the Moravian and Wielician deposits of the Skawina Formation in the Upper Silesia Basin (Durakiewicz et al., 1997; Gonera et al., 2000, 2003; Gonera and Bukowski, 2012). The difference is in the $\delta^{13}C$ contents in IIB: in the Upper Silesia Basin $\delta^{13}C$ are more positive (probably due to weaker primary production).

Foraminiferal oxygen and carbon stable isotopes have been measured at Borków (Fig. 1) below evaporite deposits (Peryt and Gedl, 2010). *Bulimina elongata* and *Globigerina bulloides* $\delta^{18}O$ records for this site are: +1.7‰, +2.6‰ and –1.5‰, +1.2‰, respectively. These values locate the samples near the CPN 7/8 boundary, even if no foraminifer index taxa are found in these deposits. At the site, $\delta^{13}C$ values are almost the same for benthic and planktonic foraminifera (–0.7 to +0.1‰ in *Bulimina elongata* and –0.7 to 0.0‰ in *Globigerina bulloides*), which is observed neither in the Upper Silesia Basin nor in the GSS IV Skawina Beds xenoliths.

In the Devinska Nová Ves Badenian faciostratotype section (eastern part of the Vienna Basin) the foraminifers of the CPN 8 have been analysed by Kováčová and Hudáčková (2009). *Globigerina bulloides* and *Uvigerina semiornata* in these deposits have $\delta^{18}O$ values of +0.2 (SD 0.6) and +1.9 (SD 0.2) respectively.

Planktonic foraminifera (*Globigerinoides trilobus*) of the Badenian stratotype section in Baden-Sooss (western part of the Vienna Basin) display $\delta^{18}O$ oscillation near –1.6‰ (Báldi and Hohenegger, 2008) and their $\delta^{13}C$ oscillates around +2.6‰. Benthic foraminifera of this section (*Hoeglundina elegans*) have $\delta^{18}O$ values +1.8‰ in the lower part and +2.0‰ in the upper part (Báldi and Hohenegger, 2008), while its $\delta^{13}C$ is at the level of +2.0‰ in the lower part, increasing to +2.8‰ in the upper part of the section. These data indicate that the Baden-Sooss stratotype section contains deposits corresponding to assemblages IIA–IIB of the Upper Silesia Basin. The younger units, below the Badenian evaporite (IIC–IID assemblages), developed in both the Upper Silesia Basin (Bicchi et al., 2003) and the currently analysed sources area of the GSS IV clasts, are not present in the Baden-Sooss deposits.

The CPN 8 deposits in the three areas mentioned – Devinska Nová Ves, Upper Silesia and GSS IV xenoliths – can be palaeogeographically arranged with regard to foraminiferal $\delta^{18}O$ values. *Uvigerina* and *Globigerina bulloides* data, as palaeotemperature indices of the basin bottom and pelagic waters, indicate shallower and warmer waters in the area of Devinska Nová Ves, whereas Silesia Basin had deeper and cooler pelagic waters. In turn, the deepest and most cool pelagic waters were in the part of the Carpathian Foredeep where the parent strata of the xenoliths described from Wieliczka GSS IV originated.

CONCLUSIONS

1. Our studies support the model of submarine redeposition of salt deposits in Wieliczka described by Kolasa and Ślączka (1985a, b) and Ślączka and Kolasa (1997).

2. During the Green Stratified Salt (GSS) IV sedimentation on an inclined slope, submarine mass movements (landslides, submarine flows) were generated. Salts flowing into the deeper parts of the basin were mixed with earlier formations: the Skawina Beds, the Oldest Salt and Sub-salt Sandstone, debris from which have been preserved in GSS IV.

3. The majority of GSS IV marls and clays xenoliths belong to the IIC–IID assemblages (*Uvigerina costai* Zone of the Badenian). The IIB assemblage (*Orbulina suturalis* Zone) has only been found in two samples (out of 26 analysed).

4. Foraminifera in the xenoliths represent the upper bathyal biofacies of the Skawina Fm., taxonomically analogous to that described by Kirchner (1956) from the basinal part of the Badenian marine basin in Poland (Bochnia–Mielec–Pilzno area).

5. The foraminifer assemblage of the *Uvigerina costai* Zone in the samples studied is typical of the below-evaporatic Wielician elsewhere in the Carpathian Foredeep Basin (Alexandrowicz, 1963). This is consistent with the biostratigraphic importance of *Valvulineria* and *Pseudotriplasia* as index taxa for the below-evaporite Wielician in the basin part of the Carpathian Foredeep.

6. The *Globigerina bulloides* Acme and unstable trophic conditions in the pelagic realm of CPN 8 are indicators of the Middle Miocene Climate Transition in the Carpathian Foredeep area. The mean $\delta^{18}O$ value for *Globigerina bulloides* recorded in GSS IV at this time is 2.3‰ (with σ 0.2).

7. *Bulimina* and *Uvigerina* incorporate in their shells similar amounts of $\delta^{18}O$. Therefore, comparative analyses are possible for isotopic studies performed on only one of these taxa, either *Uvigerina* or *Bulimina*, in different locations.

Acknowledgements. The authors would like to thank the reviewers N. Hudáčková and A. Garlicki for comments that helped improve the manuscript. The isotopic analyses have been financed by the research Project AGH No. 11.11.140.562., funded by the Polish Ministry of Sciences and Higher Education, to K. Bukowski.

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