# Non-marine evaporites in the Lower Miocene of Upper Silesia (Carpathian Foreland Basin, Poland)

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**Abstract:** A continual record of Eggenburgian to Late Badenian deposition, mostly in non-marine environments during the Early Miocene and in marine settings during the Middle Miocene time periods, was studied in the Woszczyce IG1 borehole (Zawada Basin, the Upper Silesia segment of the Carpathian Foreland Basin). In addition to the earlier-described Early Miocene foraminiferal assemblages, a Late Ottnangian pollen assemblage, which can be correlated with the MF4 Zone from Slovakia was found. Anhydrite-bearing deposits occur some 25 m below the Lower Badenian Skawina Formation. The foraminifers found immediately above the anhydrite-bearing complex and the redeposited foraminifers recorded in the lowermost part of the complex indicate its Karpatian age. The anhydrite is replacing gypsum, which originally formed displacive lenticular crystals within claystones and siltstones. The $\delta^{34}S$ values of anhydrite (+2.17 ‰ to +9.2 ‰, average +4.4 ‰) are considerably lower and the $\delta^{18}O$ values (+18.0 ‰ to +22.0 ‰, average +20.1 ‰) are considerably higher than the values characteristic for Miocene marine sulphates. On the other hand, the range of $\delta^{34}S$ values found in the anhydrites of the Woszczyce IG1 borehole is similar to the range recorded in the sulphur from Carboniferous coals. The sulphate was recycled and evaporite deposits in the Woszczyce IG1 borehole, and thus in the entire Zawada Basin, formed from recycled solutes. Thus, the anhydrite-bearing sequence originated in a non-marine environment, in which periodically saline conditions prevailed.

**Key words:** Karpatian, lacustrine environment, Ottnangian palynomorphs, oxygen isotopes, sulphur isotopes, anhydrite.

## Introduction

The Carpathian Foredeep Basin is a typical peripheral foredeep basin filled with synorogenic flysch and molasse sediments, mainly deltaic and turbiditic siliciclastic deposits of Miocene age. Evaporites of Early and Middle Miocene age also occur in it (e.g. Garlicki 1979; Stoica & Gherasie 1981; Kovalevich & Petrichenko 1997; Fig. 1). In the Polish part of the Foredeep, evaporites are Badenian in age; the nannoplankton study of sections in Upper Silesia showed that the Badenian gypsum corresponds to the lower part of the NN6 Zone (Peryt 1997). In the Ukrainian part of the Carpathian Foredeep the number of evaporite formations and their stratigraphical position are still under discussion although it seems that in addition to the Badenian, the most important phases of evaporite deposition are related to the Karpatian and Eggenburgian (Wójtowicz et al. 2003).

The evaporites of the Carpathian Foredeep Basin formed at the transition between marine and continental sedimentation as a consequence of restriction to the open sea caused by tectonics during the Alpine orogenesis and/or sea-level changes. Traditionally it was thought that these evaporites are marine in origin. However, geochemical modelling of the Badenian evaporites (Cendón et al. 2004) showed that the general hydrological evolution of the basin is explained as a restricted basin with an important continental input and ongoing recycling process.

In the Upper Silesia segment of the Carpathian Foreland Basin, in the W–E elongated Zawada Basin located between Rybnik and Oświęcim (Fig. 2), anhydrite-bearing deposits were recorded approximately 250 m below the Badenian evaporites and some 25 m below the Lower Badenian Skawina Formation (Jura 2001). The aim of this paper is to present recent results of stratigraphic and geochemical studies on the anhydrite-bearing sequence whose origin has remained enigmatic so far.

## Geological setting

The Paleogene time period was traditionally regarded as a period of intensive inversion and erosion in the western part of the Carpathian foreland area, with local accumulations of continental deposits (Picha 1979, 1996; Moryc 1985), until discovery of marine autochthonous deposits at the base of the Lower Miocene molasses (Oszczypko & Oszczypko-Clowes 2003, with references therein). These findings show that there existed a broad Eggenburgian foreland basin in the Northern

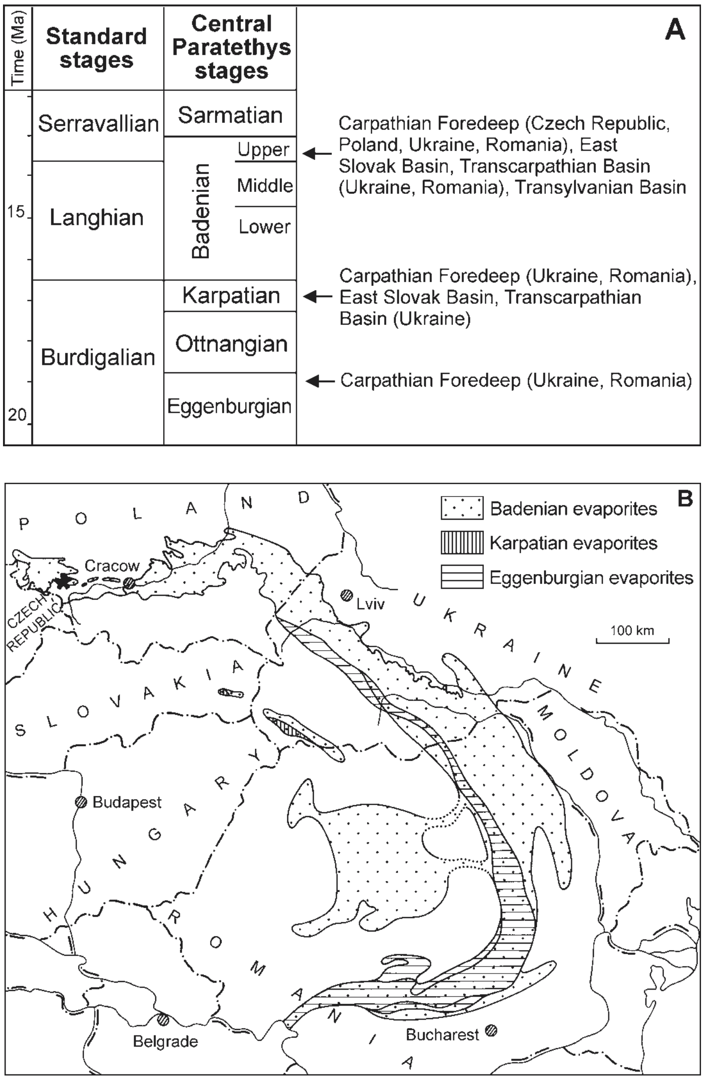


**Fig. 1.** Occurrence of Miocene evaporites in the Carpathian region in time (A) and space (B); asterisked (in B) is the location of the Zawada Basin.

Outer Carpathians and the adjacent part of the European Platform, followed by Late Ottnangian folding and the uplift and overthrust of the Outer Carpathians onto the foreland platform (Oszczypko 1998; Kováč et al. 1998; Oszczypko & Oszczypko-Clowes 2003). During the Karpatian, intensive subsidence and deposition in the inner foredeep took place, and during the Late Karpatian–Early Badenian, a relatively deep sea flooded both the foreland plate and the Carpathians (e.g. Adámek et al. 2003), leading to deposition of the marly mudstones of the Skawina Formation.

In Upper Silesia the Eggenburgian transgression event onto the southern edge of the European Platform was probably recorded in the Woszczyce IG1 borehole (Oszczypko & Oszczypko-Clowes 2003), located in the Zawada Basin (Figs. 2, 3). The Zawada Basin occurs south of the Bełk–Oświęcim regional fault, which plays an important role in the structure of the Carboniferous deposits of the Upper Silesia Coal Basin. This fault originated (or was reactivated) due to Alpine tectonic movements (Kotas 1985; Jureczka & Kotas 1995). The central, deepest part of the Zawada Basin is related to that portion of the Bełk-Oświęcim fault where the greatest downthrows of Carboniferous deposits are recorded, about 500–600 m compared to 100–200 m east and west of that structure (Fig. 3).

In the entire area of the Upper Silesia Coal Basin, at the top of the coal-bearing Carboniferous deposits occur weathered and/or thermally-modified deposits (termed "red beds"), which originated due to oxidation or spontaneous heating of coal (Lipiarski 2001) at the temperature range between several hundred and >1000 ºC (Kralik 1984).

The Carboniferous deposits are overlain by the Röt deposits; they were recorded in the depth interval 706.8–719 m in the Woszczyce IG1 borehole (Senkowiczowa 1991; Fig. 3). The Röt deposits contain Lower Miocene foraminiferal fauna (Odrzywolska-Bieńkowa 1986); single specimens of *Globorotalia peripheroronda* Blow et Banner, *Globoquadrina langhiana* Cita et Gelati and *Globigerinoides trilobus* (Reuss) have been recognized. This indicates the reworking of the Röt deposits during transgression which led to their mixing with Lower Miocene (Ottnangian) microfauna.

The Röt deposits are overlain by marls and red claystones 203.9 m thick (Fig. 4). Jura (1986) distinguished the following lithological complexes within this interval:

— 550.4–576.0 m: claystones and marly claystones with fish fragments;

— 576.0–627.5 m: anhydritic claystones with claystone and rare mudstone and tuffite intercalations (locally dolomitic or bituminous), mostly massive;

— 627.5–675.9 m: mudstones locally dolomitic with claystone intercalations and fish fragments;

— 675.9–683.8 m: intercalated beds of dolomite and claystone;

— 683.8–686.8 m: marls and limestones/dolomites;

— 686.8–705.2 m: brownish (in places green) medium- and fine-grained sandstone with a sandy claystone intercalation (at the depth of 700.5–701.0 m), in places abundant pyrite, locally horizontal lamination, more rarely flaser and small-scale cross-stratification; the contact with the underlying breccia sharp, possibly erosive;

— 705.2–706.8 m: breccia composed of clasts (1–5 cm across) of nodular limestone, marly limestone, claystone and rare quartz grains.

Below the depth of 668.5 m rare specimens of ostracod *Cytherissa* sp. (occurring from Paleogene to date in deeper parts of fresh-water lakes or in shallow lakes and brackish water) and oogonia of *Chara tenuitecta levis* Straub. (known from the Aquitanian-Burdigalian border in southern Germany) were found (Odrzywolska-Bieńkowa 1986). An abundant assemblage of mostly benthic foraminifers occurs at the depth of 573.5 and 574 m. It was regarded by Odrzywolska-Bieńkowa (1986) as similar to the Karpatian assemblages of the Czech Republic, although the presence of planktonic species *Praeorbulina glomerosa* Blow in the assemblages advocates rather an early Badenian age (Cicha et al. 1998, 2003).

The above-characterized interval is covered by the Lower Badenian Skawina Formation (346.5–550.4 m) overlain by

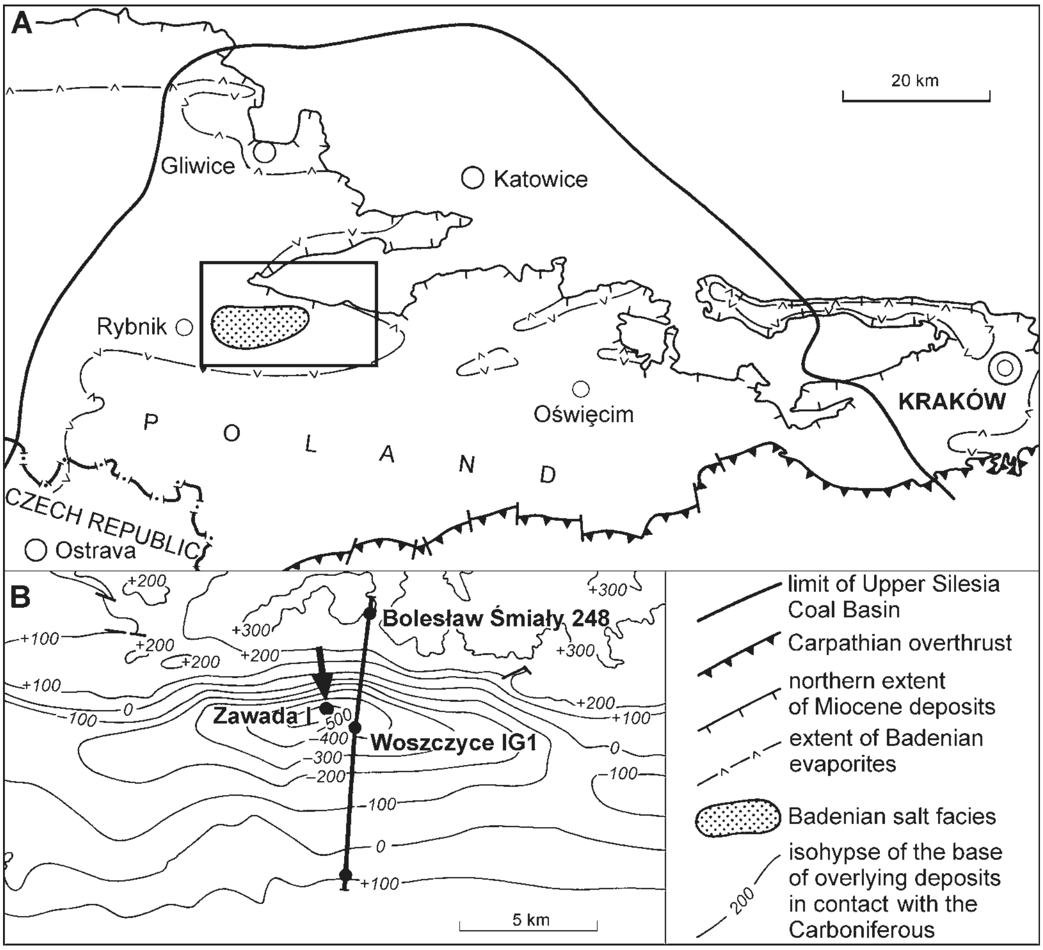


**Fig. 2. A** — Occurrence of Miocene deposits in Upper Silesia (after Kubica 1998). **B** — Map of the top of the Carboniferous deposits (after Buła & Kotas 1994) showing the location of the Zawada I and Woszczyce IG1 boreholes.

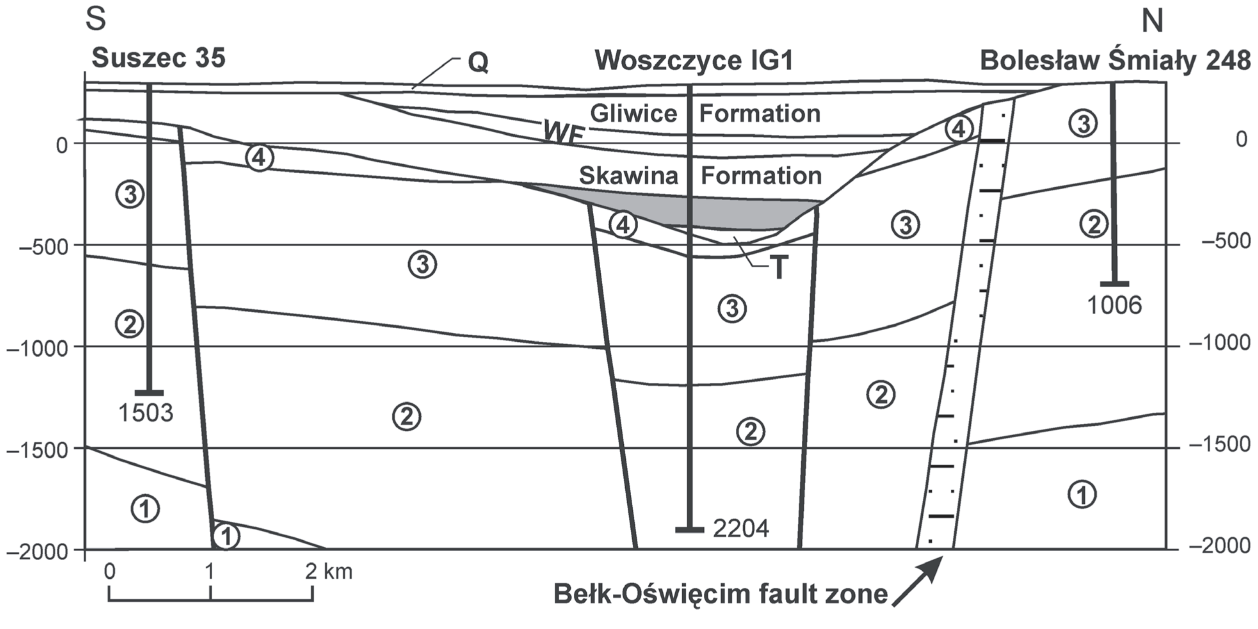


**Fig. 3.** Geological cross-section through the Zawada Basin showing the distribution of Lower Miocene deposits (in grey). **Q** — Quaternary, **T** — Röt, **WF** — Wieliczka Formation. **1–4** — Carboniferous (1: Namurian B–C — Upper Silesian Sandstone Series, 2: Westphalian B — Siltstone Series — Załęże Beds, 3: Westphalian B — Siltstone Series — Orzesze Beds, 4: Westphalian B–D — Cracow Sandstone Series).

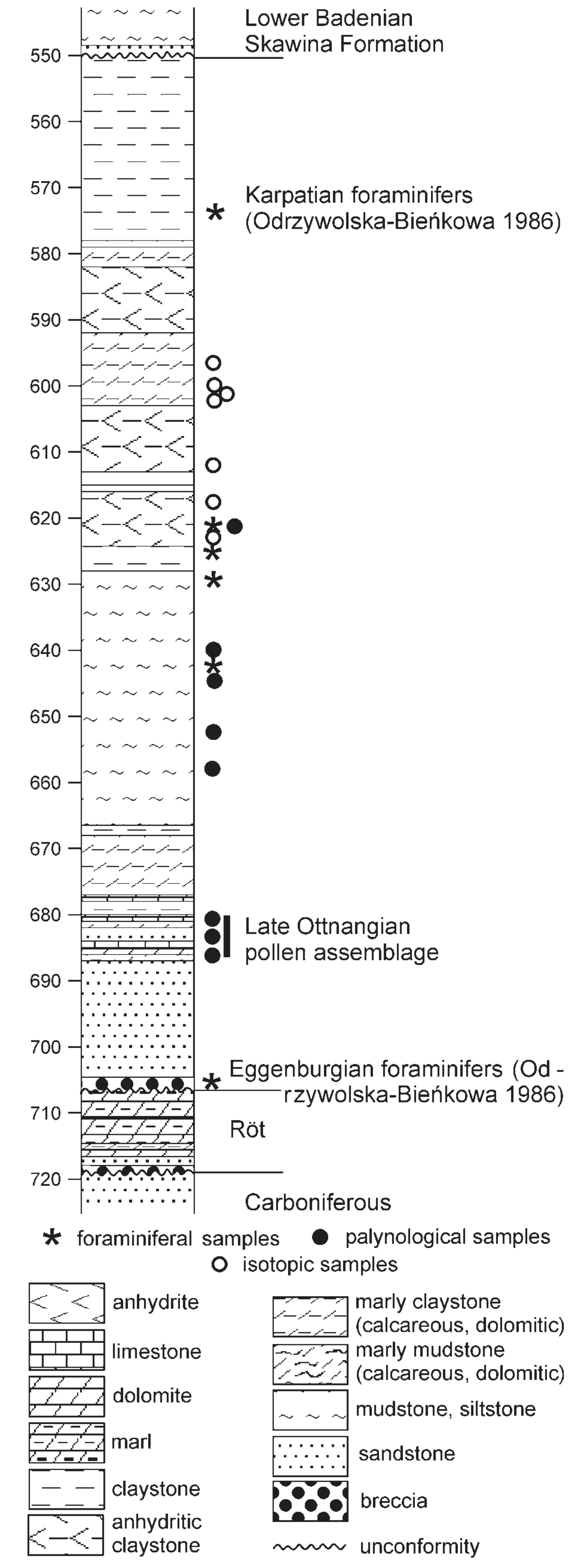


**Fig. 4.** Sedimentary log of the interval contained between the Lower Badenian Skawina Formation and the Carboniferous in the Woszczyce IG1 borehole.

the Wieliczka Formation (245.0–346.5 m) (Garlicki 1994; Alexandrowicz 1997). The top 58.0 m of the Woszczyce IG1 borehole section are Quaternary deposits.

## Methods

For the purpose of this study fifty-four samples for micropaleontological study were collected by Z. Buła from the interval of 584.0–699.0 m. Foraminiferal investigations (done by B. Olszewska) applied to whole the interval studied while studies of calcareous nannoplankton (by M. Garecka) and palynological studies (by B. Słodkowska) were carried out only on selected samples (twenty and eight samples, respectively). Preparation of samples for foraminiferal investigations included washing and drying disintegrated samples, picking up microfossils and designating their nature, quantity and age. Samples for study of calcareous nannoplankton were prepared according to standard techniques. Samples chosen for palynological studies were macerated, and the treatment involved crumbling of rocks and collecting ca. 5 g of sediment from inside each sample. Carbonates were removed using 10% HCl. The material was subsequently boiled in 7% KOH in order to eliminate humic compounds. The mineral fraction was isolated from organic matter by means of dense-media separation and with a use of cadmium iodide and potassium iodide of density 2.21 g/cm$^3$. Organic matter was macerated using the acetolysis method. 20×20 mm glycerine preparations for microscopic studies were made out of the obtained macerate. The preparations were analysed using the "Leica" ARISTOPLAN biological microscope at magnification of 400× and 1000×.

The strontium content of nine core samples (collected by T.M. Peryt) was measured using an XRF spectrometer (Philips PW 2400). 6 g of sample and 1.5 g of wax were pressed into a powder pellet (40 mm in diameter). Total uncertainty of analysis is about 5 %.

Seven samples of sulphate rocks were selected by I. Pluta and T.M. Peryt for sulphur and oxygen stable isotope analysis at the Mass Spectrometry Laboratory, Maria Curie-Sklodowska University, Lublin; the analyses were done by S. Hałas. The isotopic compositions, $\delta^{34}S$ and $\delta^{18}O$, were analysed by a dual inlet and triple collector mass spectrometer on $SO_2$ and $CO_2$ gases, respectively. The $SO_2$ was extracted by the method developed in the Lublin laboratory (Halas & Szaran 2001), whereas $CO_2$ was prepared by the method described by Mizutani (1971). Typically 8 to 12 mg of $BaSO_4$ was used in each preparation. The reproducibility of the two delta analyses (2 standard deviations) was about 0.16 ‰.

## Results and interpretation

The anhydrite is the commonest sulphate mineral occurring as an admixture in dolomitic claystones and siltstones. The commonest clay minerals are illite and illite/smectite. The content of clay minerals in the anhydrite-bearing rocks ranges from 10 % to 60 %, and the dolomite content is 3–27 %. The anhydrite content is 20–55 %. Only rarely does the anhydrite content exceed 50 % of rock volume and the most common mode of occurrence of the anhydrite is millimetric (rarely up to 4 cm) crystals arranged parallel to the bedding (Fig. 5). The anhydrite is replacing gypsum, which formed displacive lenticular crystals within the claystones (Fig. 5). Thus the gypsum grew below the groundwater table, mostly within clayey deposits, as is common in recent sabkhas of Abu Dhabi (e.g. Shearman 1963) and in many recent and ancient continental basins (e.g. Truc 1979; Handford 1982; Türkmen & Özkul 1999). In some cases the anhydrite replacements of displacive lenticular gypsum crystals form almost continuous laminae resembling the pavement of post-sedimentary gypsum described from a recent paralic salt basin of Tunisia (Perthuisot 1975). The gypsum was replaced by the anhydrite during burial and secondary gypsum occurs locally.

The most frequent fossils are fragments of fish and sponge spicules. Carbonized remnants of land (?) plants are also frequent. Occasionally, in variable quantities, pseudomorphs of echinoderm spines were recorded. Foraminifera were observed sporadically (Fig. 4). The richest assemblage was found at the depth of 620.9 m in beige mudstones. The recognized species: *Textularia gramen* d'Orbigny, *Textulariella* sp., *Siphonaperta* sp., *Ammonia beccarii* (Linne) had tests covered with fine sand particles suggesting redeposition. The lack of diagnostic species precluded a precise age designation, however the occurrence of the assemblage occurring between the distinct early Early Miocene and Badenian faunas may imply its late Early Miocene age. The mode of preservation of encountered specimens suggests their redeposition. In the sample from the depth of 624.7 m few, poorly preserved specimens of large *Ammonia beccarii* (Linne) have been found. In other cases (depth 628.0 and 642.3 isolated specimens of *Rhabdammina* cf. *exilis* Mjatliuk have been found, accompanied by few diatom frustules. Sponge spicules, fish remnants and carbonized plant fragments were more abundant in the studied material suggesting rather shallow sedimentary settings and possibly high river run-off. No calcareous nannoplankton was found.

After using standard laboratory preparation methods, the palynological matter with numerous palynomorphs (sporomorphs) and palynoclasts (phytoclasts) has been isolated. Their frequency was diverse: in some samples it was low and in others it was satisfactory. The state of preservation of the sporomorphs was poor. The surface of the specimens was often effaced, worn out with the traces of inconvenient external factors. The determination of the sporomorphs was based on

**Fig. 5.** Anhydrite replacing displacive lenticular crystals of gypsum within claystone (coin diameter is 15 mm).

the morphological system; using the natural systematic of plants as far as it was possible. Among the phytoclasts, black and brown wood debris are very common. The occurrence of the sporomorphs (68 taxa and 3 taxonomically undefined categories) is shown in Table 1.

Two pollen assemblages were distinguished: the lower one at the depth of 681.2–687.2 m and the upper one at the depth of 620.9–658.2 m; the sample from the depth of 658.2 m is transitional between the two assemblages (Table 2).

The lower assemblage contains rich and very well preserved sporomorphs. An important role in this assemblage is played by gymnosperm pollen with dominant *Pinuspollenites* and *Sciadopityspollenites, Inaperturopollenites hiatus, Sequoiapollenites*. A significant share consists of very poorly preserved pollen from the Pinaceae family, making unreasonable more precise taxonomical identification. The angiosperm pollen assemblage contains many species and has quantification differential in the domination of individual taxa. In the lower part of this interval a significant role is played by *Caryapollenites, Pterocaryapollenites, Intratriporopollenites instructus, Ericipites ericius*, while in its upper part *Intratriporopollenites instructus, Castaneoideaepollis pusillus, C. oviformis, Tricolporopollenites pseudocingulum, Quercoidites, Engelhardtioipollenites punctatus, Ericipites ericius, E. callidus, Caryapollenites, Pterocaryapollenites, Liquidambarpollenites* and others form a greater share. No marine phytoplankton or other palynological indicators of marine facies were recorded. The differences in the pollen spectra composition are connected with the variability of the plant communities: the middle part of the interval records a domination of the riparian forest community and the lower and upper parts correspond to mixed forest communities. The phytogenic material was accumulated in freshwater and low hydrodynamic conditions as indicated by a considerable quantity of phytoclasts. The plant vegetation adjacent to the sedimentary basin indicates a warm and humid climate.

A different pollen assemblage at the depth of 620.9–658.2 m is characterized by a poor state of preservation of sporomorphs, with the effaced pollen grain surface due to unfavourable physical and chemical conditions during the deposition and diagenesis. Spores with many pre-Paleogene species are frequent elements of the assemblage. Only pre-Paleogene species and worn-out grains of the Pinaceae family occur among gymnosperm pollen grains. Another evidence of redeposition is the presence of the Upper Cretaceous–Lower Paleogene Normapolles pollen grains — the extinct group of angiosperm plants. The typical Paleogene and Neogene angiosperm taxa include *Ericipites ericius, Quercoidites, Ulmipollenites, Betulaepollenites, Myricipites microcoryphaeus, Quercoidites microhenrici, Q. henrici, Platycaryapollenites, Tetracolporopollenites, Engelhardtioipollenites punctataus, Tricolporopollenites pseudocingulum, Castaneoideaepollis pusillus* and *C. oviformis*. There is no record of marine influence within this palynomorph assemblage. Abundant phytoclasts in the form of black, non-transparent, wood debris indicate periodical emergence and oxidation of palynological matter. Plants growing around the basin shores represented mixed mesophilous forest. Slight quantitative differences in the share of individual taxa suggest the temperature oscillation and the

**Table 1:** Sporomorphs in the Woszczyce IG1 borehole.

| Taxon | 620.9 | 641.4 | 647.7 | 652.5 | 658.2 | 681.2 | 682.1 | 687.2 |
|---|---|---|---|---|---|---|---|---|
| **Spores** | | | | | | | | |
| *Cicatricosisporites paradorogensis* | | | + | | | | | |
| *Cingulatisporis* | | + | + | + | + | | | |
| *Gleicheniidites* | + | | + | + | | | | |
| *Laevigatosporites haardti* | | | + | | | | | |
| *Lycopodiaceaesporis* | + | | | | | | | |
| *Neogenisporis* | | | | | | | + | |
| *Osmundacidites primarius* | | | | | | + | | |
| *Retitriletes* | | | + | | | | | |
| *Rugulatisporis quintus* | + | | | | | | | |
| *Todisporis* | + | | | | | | | |
| *Toroispotis* | | | + | | | | | |
| *Trilobosporites* | + | | | | | | | |
| Pre-Paleogene | + | + | + | + | | | | |
| indeterminate | | | + | | + | + | + | |
| **Gymnosperms** | | | | | | | | |
| *Araucariapollenites* | + | | | | | | | |
| *Ephedripites* | | | | | | | | + |
| *Inaperturopollenites dubius* | | | | | | | + | |
| *Inaperturopollenites hiatus* | | | | | + | | + | |
| Pinaceae (pre-Paleogene) | + | + | | | | | | |
| Pinaceae (indeterminate) | | + | + | + | + | + | + | |
| *Pinuspollenites* | | | | | | + | + | + |
| *Sciadopityspollenites* | | | | | | + | + | |
| *Sequoiapollenites* | | | | | | + | | + |
| *Tsugaepollenites* | | | | | + | | | |
| Pre-Cretaceous | + | | | | | | | |
| **Angiosperms** | | | | | | | | |
| *Alnipollenites* | | | + | | + | | | |
| *Aralaiaceoipollenites edmundii* | | | + | | | + | | |
| *Betulaepollenites* | + | + | + | + | | | | |
| *Betulaepollenites betuloides* | | + | | | + | | + | |
| *Caprifoliipites* | | | | | | | + | |
| *Carpinipites* | | + | | | | | + | |
| *Caryapollenites* | | + | + | + | + | + | + | + |
| *Castaneoideaepollis oviformis* | | + | + | | + | | + | |
| *Castaneoideaepollis pusillus* | + | + | + | | + | + | + | + |
| *Celtipollenites* | + | | | | | | | |
| *Cercidiphyllidites* | | | | | | | + | |
| *Chenopodipollis* | | | | | | + | | |
| *Cornaceoipollenites satzveyensis* | | | | | | + | | |
| *Engelhaedtiopollenites punctatus* | | + | + | + | + | + | + | + |
| *Ericipites callidus* | | | | | | | + | |
| *Ericipites ericius* | + | + | | | + | + | + | |
| *Ilexpollenites margaritatus* | | | | | | + | | |
| *Ilexpollenites propinquus* | | + | + | | + | + | + | |
| *Intratriporopollenites insculptus* | | | | | + | | | |
| *Intratriporopollenites instructus* | + | | | | + | + | + | + |
| *Liquidambarpollenites* | + | | + | + | | + | + | |
| *Liriodendroipollis* | | | | | + | | | |
| *Myricipites* | | | + | + | + | + | | |
| *Myricipites microcoryphaeus* | | + | | | + | | | |
| *Nyssapollenites* | | | | | + | + | + | |
| *Platanipollis ipelensis* | | | | | | | + | |
| *Platycaryapollenites* | + | + | + | | + | + | | + |
| *Platycaryapollenites miocaenicus* | | | | | + | | | |
| *Pterocaryapollenites* | | + | | | | + | + | + |
| *Quercoidites* | + | + | + | | + | | + | |
| *Quercoidites henrici* | + | + | + | | | | | |
| *Quercoidites microhenrici* | | + | | | + | | | |
| *Sapotaceoipollenites oblongus* | | | | | | + | | |
| *Sparganiaceaepollenites* | | | | | | | | + |
| *Symplocoipollenites latiporis* | | | | | + | | | |
| *Tetracolporopollenites* | | | + | + | + | | | |
| *Tricolporopollenites bruhlensis* | | | | | + | | | |
| *Tricolporopollenites exactus* | | | | | | | + | |
| *Tricolporopollenites fallax* | | | | | + | | | |
| *Tricolporopollenites megaexactus* | | | | | + | + | | |
| *Tricolporopollenites porasper* | | + | + | | | | | |
| *Tricolporopollenites pseudocingulum* | + | + | + | | + | + | + | + |
| *Tricolporopollenites wackersdorfensis* | | | | | | + | + | |
| *Ulmipollenites undulosus* | | | + | + | + | + | + | + |
| **Normapolles** | | | | | | | | |
| *Nudopollis* | + | | | | | | | |
| *Oculopollis* | | + | | | | | | |

domination of less or more thermophilous plant vegetation. The stratigraphic position of this interval based on the palynological study is enigmatic.

The strontium content in the bulk rock samples is 0.04–0.47 % (Table 3). Although it is within the range characteristic for ancient anhydrites (Dean 1978), quite substantial differences between the particular samples are probably related to a varied degree of supersaturation of the interstitial brines (see Rosell et al. 1998 for discussion).

The $\delta^{34}S$ values of the studied samples are +2.17 ‰ to +9.2 ‰ (average +4.4 ‰) and the $\delta^{18}O$ values are from +18.0 ‰ to +22.0 ‰ (average +20.1 ‰) (Table 3). The $\delta^{34}S$ values are considerably lower and the $\delta^{18}O$ values are considerably higher compared to the values characteristic for the Miocene marine sulphates (Fig. 6). The $\delta^{34}S$ values are also considerably lower than those displayed by the Röt sulphates (27.1 ‰–32.0 ‰; Kovalevych et al. 2002) and therefore the studied anhydrites cannot be interpreted as the result of the recycling of the Röt sulphates in non-marine settings. On the other hand, the range of $\delta^{34}S$ values found in the anhydrites of Woszczyce IG1 borehole is within the range recorded in the Carboniferous coals occurring in the mines of the southern part of the Upper Silesia Coal Basin (from +3.5 ‰ to +9.1 ‰ — Pluta 2002). Accordingly, it is interpreted that sulphate ions originated in a near-surface zone due to the oxidation of sulphides occurring in the Carboniferous coals and then were transported by meteoric water to the basin centre (Pluta & Halas 2005) where the sulphate-bearing deposits accumulated in non-marine settings. It should be noted that the $\delta^{34}S$ values show a clear upward-decrease trend (with one exception); the reason may be the reservoir effect.

Low $\delta^{34}S$ values of anhydrites are accompanied by high $\delta^{18}O$ values. In the non-marine gypsum of the Tertiary Ebro Basin, a similar differentiation was attributed by Utrilla et al. (1992) to bacterial sulphate reduction in the sedimentary environment. However, in order to explain such unusual ranges of the $\delta^{34}S$ and $\delta^{18}O$ values recorded in Ebro Basin, these authors invoke somewhat specific conditions (the dual layer system), because normally during the sulphate reduction the remaining solution is enriched both in $^{34}S$ and $^{18}O$ (Mizutani & Rafter 1973). On the other hand the high $\delta^{18}O$ and low $\delta^{34}S$ values recorded in the Zawada Basin anhydrite are consistent with those observed in sulphate ions of recent summer rains in Poland (Trembaczowski & Halas 1991) and in the sulphates extracted from dry ashes collected from industrial sites (Pluta 2000). The atmospheric and dry-ash sulphate ions have the same origin: they are formed from $SO_2$ being a by-product of fuel burning, and the main reason for the high $\delta^{18}O$ values is high temperature burning of the pyrite-bearing coals. During that process the oxygen isotope were exchanged between the water and $SO_2$ in a hot cloud. In anhydrites of the Zawada Basin, the original ranges of isotope ratios are likely to have been somewhat altered by other geochemical processes such as the redox reactions.

The dry-ash sulphate originated due to the industrial coal burning has, however, somewhat higher $\delta^{18}O$ (from +22.8 ‰

**Table 2:** Characteristics of palynological spectra.

| Lithology | Depth [m] | Significant components of palynological matter | Plant community/ climate | Age |
|---|---|---|---|---|
| anhydritic claystone | 620.9 | frequency low, two types of sporomorphs preservation, spores pre-Paleogene, gymnosperms: Pinaceae pre-Paleogene, angiosperms: Normapolles, *Ericipites ericius, Quercoidites, Ulmipollenites*, phytoclasts: mass black wood debris | mesophilous forest/temperate | **Paleogene and Neogene undivided with redeposited older elements (Triassic, Jurassic and Cretaceous)** |
| siltstone, grey-green | 641.4 | frequency satisfactory, poor preservation of sporomorphs, spores pre-Paleogene, gymnosperms: Pinaceae pre-Paleogene, *Araucariapollenites*, angiosperms common: Normapolles, *Myricipites microcoryphaeus, Quercoidites microhenrici, Q. henrici, Tricolporopollenites pseudocingulum*, phytoclasts: common black wood debris | mesophilous forest/temperate | |
| siltstone, grey-green | 647.7 | frequency satisfactory, poor preservation of sporomorphs, spores pre-Paleogene and old Paleogene, gymnosperms: Pinaceae worn-out, angiosperms: *Engelhardtioipollenites punctatus, Tetracolporopollenites, Tricolporopollenites pseudocingulum, Platycaryapollenites, Quercoidites*, phytoclasts: common black wood debris | mesophilous forest/warm temperate | |
| siltstone, grey-green | 652.5 | frequency very low, poor preservation of sporomorphs, spores pre-Paleogene and old Paleogene, gymnosperms: Pinaceae worn-out, angiosperms: *Engelhardtioipollenites punctatus, Tetracolporopollenites, Ulmipollenites, Betulaepollenites*, phytoclasts: common black wood debris | mesophilous forest/warm temperate | |
| siltstone, grey-green | 658.2 | frequency high, poor preservation of sporomorphs, spores indeterminate, gymnosperms: Pinaceae worn-out, angiosperms abundant: *Castaneoideaepollis pusillus, C. oviformis, Engelhardtioipollenites punctatus, Quercoidites microhenrici, Tricolporopollenites pseudocingulum, Tetracolporopollenites*, phytoclasts: abundant black wood debris | mesophilous forest/temperate | |
| claystone, sandstone, limestone, marl | 681.2 | frequency and state of preservation sporomorphs satisfactory, spores indeterminate, gymnosperms: *Pinuspollenites,* Pinaceae worn-out, angiosperms: *Ericipites ericius, Pterocaryapollenites, Caryapollenites*, phytoclasts: abundant black and brown wood debris | riparian forest/temperate | **Early Miocene (Late Ottnangian, MF4)** |
| claystone, sandstone, limestone, marl | 682.1 | frequency and state of preservation sporomorphs satisfactory, spores indeterminate, gymnosperms: *Pinuspollenites,* Pinaceae worn-out, angiosperms abundant: *Intratriporopollenites instructus, Castaneoideaepollis pusillus, C. oviformis, Engelhardtioipollenites punctatus, Quercoidites, Tricolporopollenites pseudocingulum*, phytoclasts: abundant black wood debris | mesophilous forest/warm temperate | |
| sandstone with humus | 687.2 | frequency very low, poor preservation of sporomorphs, gymnosperms: *Pinuspollenites*, angiosperms rare: *Castaneoideaepollis pusillus, Engelhardtioipollenites punctatus, Pterocaryapollenites*, rare phytoclasts | mesophilous forest/warm temperate | |

**Table 3:** Strontium content and isotopic composition of sulphates from the Woszczyce IG1 borehole.

| Depth (m) | Sr content (ppm) | $\delta^{34}$SCDT (‰) | $\delta^{18}$OSMOW (‰) |
|---|---|---|---|
| 584.6 | 436 | | |
| 596.8 | | +2.44 | +18.96 |
| 600.0 | 1737 | | |
| 600.2 | 1716 | +3.37 | +20.85 |
| 600.8 | 4692 | +2.07 | +20.69 |
| 602.1 | 2296 | +3.15 | +20.70 |
| 611.6 | 2582 | | |
| 612.2 | 1232 | | |
| 612.9 | | +4.99 | +19.34 |
| 613.1 | 470 | | |
| 613.3 | 813 | | |
| 618.0 | | +5.09 | +18.04 |
| 623.0 | | +9.23 | +22.0 |

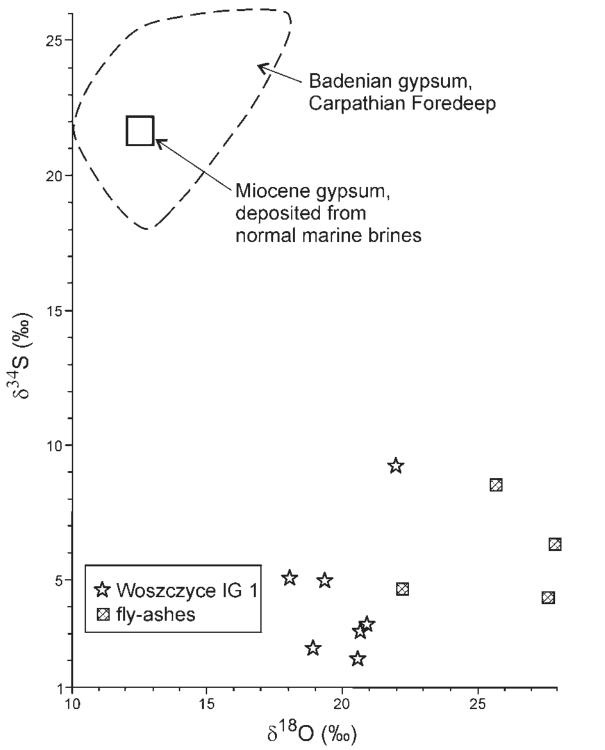


**Fig. 6.** Isotopic plot (box showing the range of values for Miocene gypsum deposited from normal marine brines after Paytan et al. 1998; Badenian sulphate data after Peryt et al. 2002; fly-ashes of Carboniferous coal burning after Pluta & Hałas 2005).

to +27.9 ‰ — Pluta 2000) than the summer rainwater sulphate and the anhydrites of the Zawada Basin, because the sulphates formed in high chimneys underwent more favourable conditions for their enrichment in $^{18}$O due to the oxygen isotope exchange with water vapour.

Altogether the results indicate that the anhydrite-bearing sequence originated in a non-marine environment.

## Discussion and conclusions

In the Zawada Basin, the Röt deposits are overlain by marls and red claystones. In the Zawada I borehole; in the upper part of this complex, 31 m below its top, one specimen of mollusc (*Pecten* n. sp. cf. *P. semicingulatus*) was found and the Oligocene age of the complex was accepted on this basis (Michael 1913). However, our data contradict such an assumption. The Zawada Basin represents a continual record of Eggenburgian to Late Badenian deposition, mostly in non-marine environments during the Early Miocene and in marine settings during the Middle Miocene time period. The marine influence is recorded due to the presence of marine foraminiferal assemblages at the base of the Miocene sequence in the Woszczyce IG1 borehole (i.e. near the Egerian/Eggenburgian boundary — cf. Oszczypko & Oszczypko-Clowes 2003), below, within and above the anhydrite-bearing deposits (which probably represent the Karpatian) and in the Badenian formations (Odrzywolska-Bieńkowa 1986). The timing of those marine inflows fits the general evolution of the Carpathian Foreland Basin (Kováč et al. 2003; Oszczypko & Oszczypko-Clowes 2003).

Palynological study showed that the lower part of the interval contained between the Lower Badenian and Eggenburgian deposits contains the pollen assemblage, which can be correlated with the Late Ottnangian MF4 Zone from Slovakia (Planderová 1990) where a significant participation of the Arctotertiary element was noticed, especially in the riparian forest community (Doláková & Slamková 2003). In the same interval Odrzywolska-Bieńkowa (1986) found oogonia of *Chara tenuitecta levis* Straub. They are known from the Aquitanian-Burdigalian border in southern Germany and thus either the oogonia are reworked or they appeared in the Woszczyce IG1 borehole later than in southern Germany.

Most of the pre-Badenian deposits in the Zawada Basin originated in periodically emerged non-marine settings. This refers to the anhydrite-bearing sequence. Evaporites need a climate aridization to be formed, and the occurrence of Karpatian evaporites in the Ukrainian part (Korenevskiy et al. 1977) and the Romanian part (Stoica & Gherasie 1981) of the Carpathian Foredeep Basin as well as in the East Slovak Basin (Kováč et al. 1994) indicates a regional climate aridization during the Karpatian time period.

The anhydrite-bearing deposits in the Woszczyce IG1 borehole are related to lacustrine deposits, in which periodical saline conditions prevailed. The resulting brines were rich in sulphate ions formed, as indicated by the sulphate isotopic composition ($\delta^{34}$S, $\delta^{18}$O) of anhydrite, in near-surface conditions during oxidation of sulphides or spontaneous heating of coal-bearing deposits and then the sulphate recycling from the more peripheral parts of the Zawada Basin (cf. Fig. 3). Accordingly, evaporite deposits in the Woszczyce IG1 borehole, and thus in the entire Zawada Basin, formed from recycled solutes. Taberner et al. (2000) concluded that evaporite units could be entirely formed from solutes recycled from previous units. The case of Karpatian evaporites in the Woszczyce IG1 borehole fits this general conclusion although the provenance of sulphate ions is more complex than a simple dissolution of previous evaporites.

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