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Sedimentology and geochemistry of the Middle Miocene (Badenian) salt-bearing succession from East Slovakian Basin (Zbudza Formation)

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Abstract: The Middle Miocene (Badenian) evaporites have formed within more or less restricted basins, occupying the Carpathian Foredeep and inner depressions in the East Slovakian Basin of the Carpathians. Their deposition coincided with the increased tectonic activity in the Carpathians, evidenced by volcanic eruptions (widespread volcaniclastics) and frequent earthquakes. These phenomena apparently initiated landslides, submarine slumps and turbidity currents which formed deposits characterized by rapid facies changes and relatively limited lateral continuity. The clastic–evaporitic deposition in the Zbudza area (East Slovakian Basin) was controlled by frequent tectonic and seismic phenomena and high continental clastic supply that produced repeated slump sediments with dominant proximal mass flows and distal flows and diverse salt types (salt/clay rhythmites, finer halite–arenites, coarse halite–rudites). These zones are separated by primary salt units (halite) precipitated *in situ* from bottom brines during calm periods. The observed cyclicity (I–V cycles) reflects varied tectonic activity of the basin margins, that mechanically remobilized the sediments from marginal salt pans, flats and adjacent uplifts, and could be correlable with cycles in the Wieliczka Formation from Carpathian Foredeep.

Middle Miocene (Badenian) evaporites have formed within more or less restricted basins, occupying the Carpathian Foredeep (Wieliczka Formation in Poland and Tirass Suite in Ukraine) and in the inner depressions of the Carpathians (e.g. East Slovakian Basin; Zbudza Formation). The deposition coincided with the increased tectonic activity of the Carpathian area, evidenced by volcanic eruptions (widespread volcanoclastics) and common earthquakes (Peryt & Kasprzyk 1992). These phenomena initiated landslides, submarine slumps and turbidity currents, which formed deposits characterized by rapid facies changes and relatively limited areal extent (e.g. Bukowski 1997; Ślączka & Kolasa 1997).

The Badenian evaporitic succession within the East Slovakian Basin (Inner Carpathians, in the area between Košice and Michalovce), known as the Zbudza Formation (>150 m thick, with halite beds up to 75 m thick intercalated with siliciclastics and anhydrite) were studied in detail, enabling a reconstruction of their depositional mechanisms and environment. They are commonly the equivalent of the evaporites of the Carpathian Foredeep.

Geological setting

The studied salt-bearing succession was deposited in the Paratethys seaway. The Paratethys was an enclosed sea that existed from Oligocene to Middle Miocene times and consisted of an interrelated chain of basins of diverse tectonic origin. These basins were covered most of the time by the same water mass, which shared a common aquatic biota, and was a link between the Mediterranean and the Indo-Pacific areas (Bàldi *et al.* 2002).

Both the Carpathian Foredeep and adjacent marginal basins located in the Inner Carpathians belong to the Central Paratethys (the area from Bavaria to the Eastern Carpathians). It was developed between the Carpathian orogene to the south and the Palaeozoic Platform of Eastern Europe to the north and the Precambrian East-European Platform to the southeast (Fig. 1). Evaporites of the Middle-Upper Badenian age (the period equivalent to the Upper Langhian-Lower Serravallian (Fig. 2) have accumulated in the foredeep area stretching from Upper Silesia in Poland (Garlicki 1979, 1994*a*, *b*) and on into the Doftana Valley in

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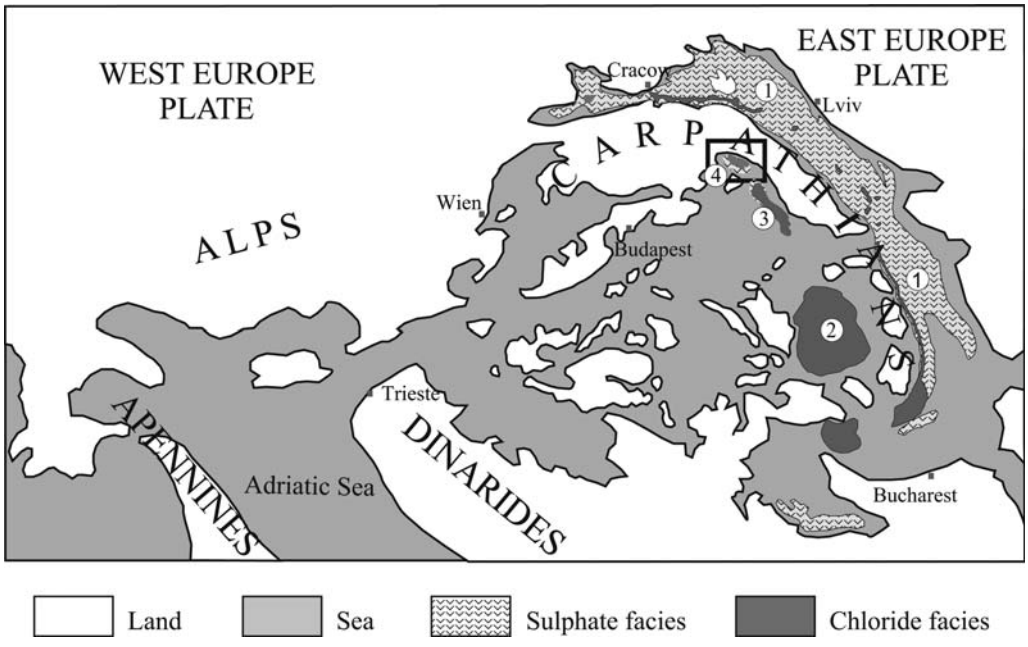


Fig. 1. Distribution of evaporites (chloride and sulphate facies) in the Central Paratethys (after Bąbel 2004 and references therein) during the 'Badenian salinity crisis' projected onto the palaeogeography of Middle to Late Badenian Carpatho-Pannonian Basin. The paleogeographic map was simplified and compiled after Rögl (1998*a*, *b*), Studencka *et al.* (1998) and Popov *et al.* (2004). 1, Carpathian Foredeep; 2, Transylvanian Basin; 3, Transcarpathian Basin; 4, East Slovakian Basin (study area).

Romania (Crihan 1999; Mărunţeanu 1999). Contemporaneous evaporites also were deposited in the Transylvanian Basin in Romania (Balintoni & Petrescu 2002), the Trans-Carpathian Basin of the Ukraine (Kityk *et al.* 1983) and the East Slovakian Basin (Karoli *et al.* 1997).

The East Slovakian Basin was the most northern part of the extensive Pannonian Basin and it formed in an intermountain depression having a generally 'horst-and-graben style' of morphology (Vass *et al.* 2000) that resulted in mainly syndepositional fault activity (Figs 1 & 3). It was created in the Lower Miocene (Eggenburgian stage) along the internal side of the Klippen Belt as a narrow NW–SE oriented depression and that persisted until the Pliocene. The depression infill is mainly marine but toward the top of the section the deposits are replaced by the deltaic and lacustrine deposits of the Sarmatian–Pannonian age (Paratethys equivalent stages to the Serravallian and Tortonian). Their total thickness in the depression centre reaches 8–9 km (Vass *et al.* 2000). Two evaporite horizons, dominated by chlorides (rock salt with siliciclastic and anhydrite interbeds), occur within the marine succession. The lower horizon of the early Miocene (the Lower Karpatian stage) age is distinguished as the Solna Bania Formation and developed locally in the western part of East Slovakian Basin (Karoli *et al.* 1997). The upper horizon of the middle Miocene (the Badenian stage) is defined as the Zbudza Formation covering most of the basin area (Vass & Čverčko 1985).

The evaporite series of the Middle Miocene (Badenian) age, known from the Carpathian region and based on the most recent stratigraphic data, were formed at the boundary of nannoplankton zones NN5/NN6 and/or to the lower part of NN6 zone (e.g. Peryt 1997; Chira & Draghici 2002). According to some authors this episode lasted up to the boundary of NN6/NN7 zone (Andreyeva-Grigorovich *et al.* 2003).

The Zbudza Formation, recognized by Vas & Čverčko (1985), is traditionally included as the upper part of Middle Badenian (Vass *et al.* 2000) or to the lower part of the Upper Badenian (Gasparikova 1963; Zlinska 2004). Its position in the stratigraphic succession (Fig. 2) corresponds with the uppermost stratigraphic divisions within the Central Paratethys. This relationship is supported by a single radiometric dating from tuffite intercalations found within the salt-bearing series from Bochnia (13.6 $\pm$ 0.2 Ma; Dudek *et al.* 2004).

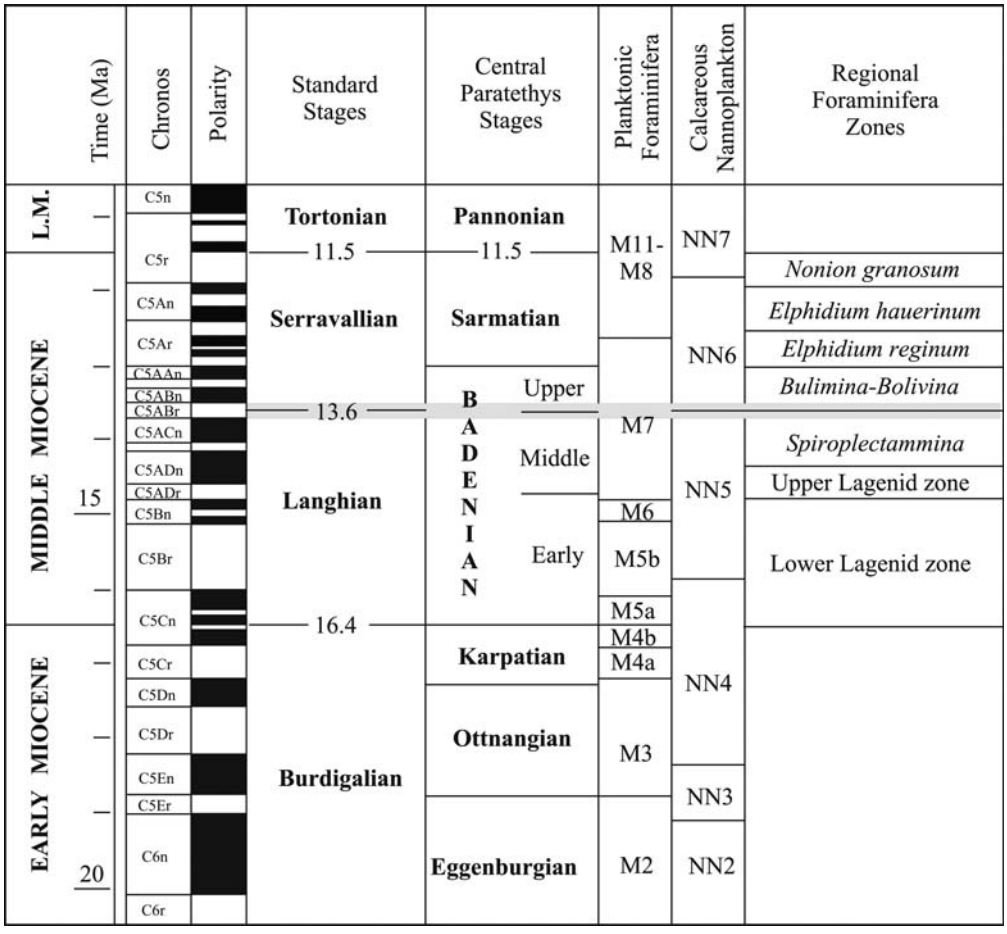


Fig. 2. The modified Miocene geochronology and biostratigraphy (after Harzhauser *et al.* 2003). Note re-calibrated position of the Langhian/Serravallian boundary now located at 13.59 Ma (Foresi *et al.* 2002) based on the LAD of *Sphenolithus heteromorphus*. This event is marked by the NN5/NN6 boundary and corresponds to the Badenian salinity crisis (Peryt 1997; Chira & Draghici 2002; Andreyeva-Grigorovich *et al.* 2003; Krézsek & Filipescu 2005), the age of which was defined by K-A dating of tuffite from Wieliczka Fm (*c.* 13.6 $\pm$ 0.2 Ma, after Dudek *et al.* 2004). The shaded area indicates the stratigraphic position of the Zbudza and Wieliczka formations.

Lithology and facies of the clastic-evaporitic deposition in the Zbudza area

Deposits of Zbudza Formation accumulated in local depressions of the eastern part of East Slovakian Basin and they cover an area of *c.* 350 km^2 (Fig. 3). This evaporite horizon was first noted in several places during the gas-oil exploration in the 1950s, but it proved economically viable only in the Michalovce region (Janáček 1958, 1959, 1960; Slávik 1967*a*). In the 1990s six new wells were drilled (from P-2 to P-8, Fig. 3) and this salt-bearing series (100–140 m thick) was detected at depths ranging from 440 to 530 m.

Salt-bearing deposits in all studied profiles (Fig. 4) contain pure or clayey halites interbedded with siliciclastics (laminated siltstones and claystones, sandstones and conglomerates) and nodular anhydrites. The chlorides range in appearance from chaotic to stratified (laminated, graded and cross-bedded) and are subdivided into four distinct macroscopic facies:

(A) coarse halite–rudite to halite breccia (Fig. 5a & b);
(B) fine halite–arenites (Fig. 5a);
(C) fine crystalline halites with clay laminae (Fig. 5c);
(D) chevron halite layers (Fig. 5d).

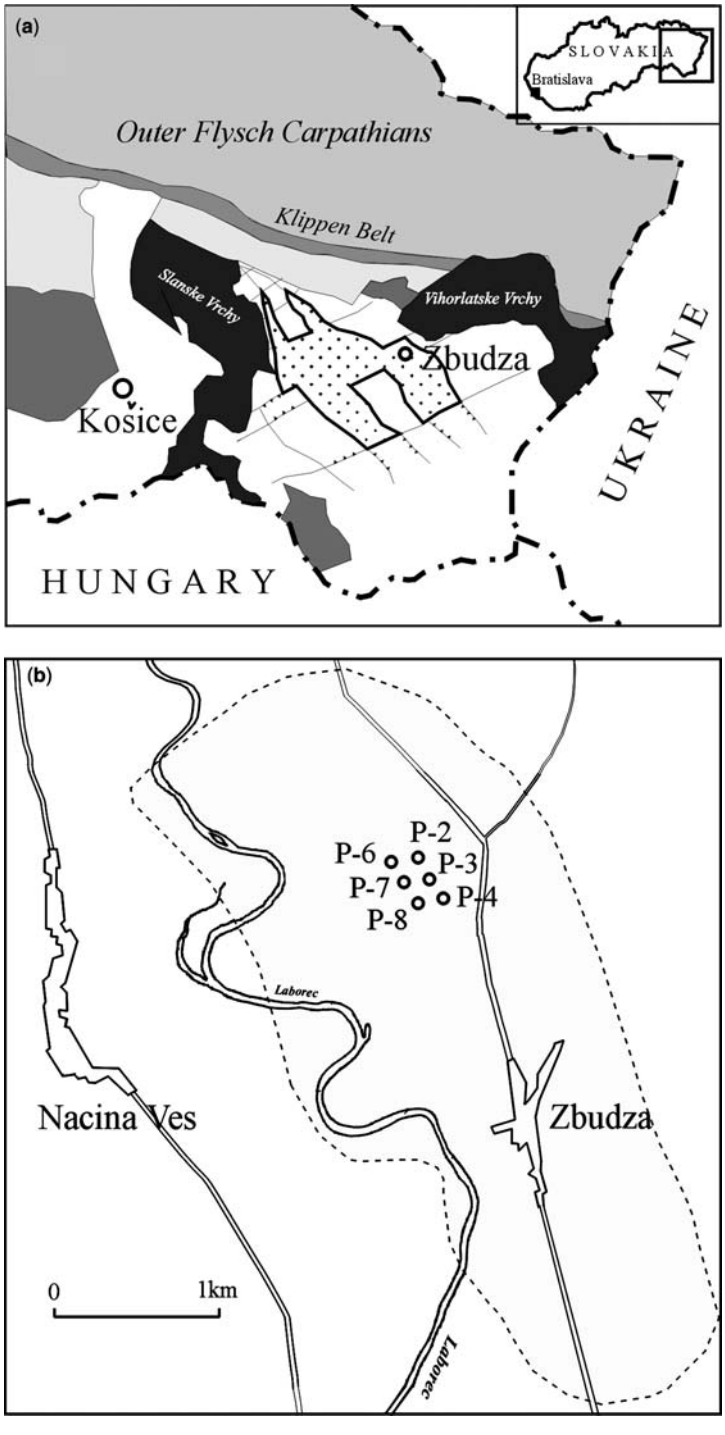


Fig. 3. Location of the study area in this paper. (**a**) Schematic map of East Slovakian Basin with the location of Zbudza Formation (dotted area) (after Karoli *et al.* 1997; Vass *et al.* 2000). (**b**) The Zbudza salt deposit area (shaded and outlined with a dashed line) together with locations of studied boreholes.

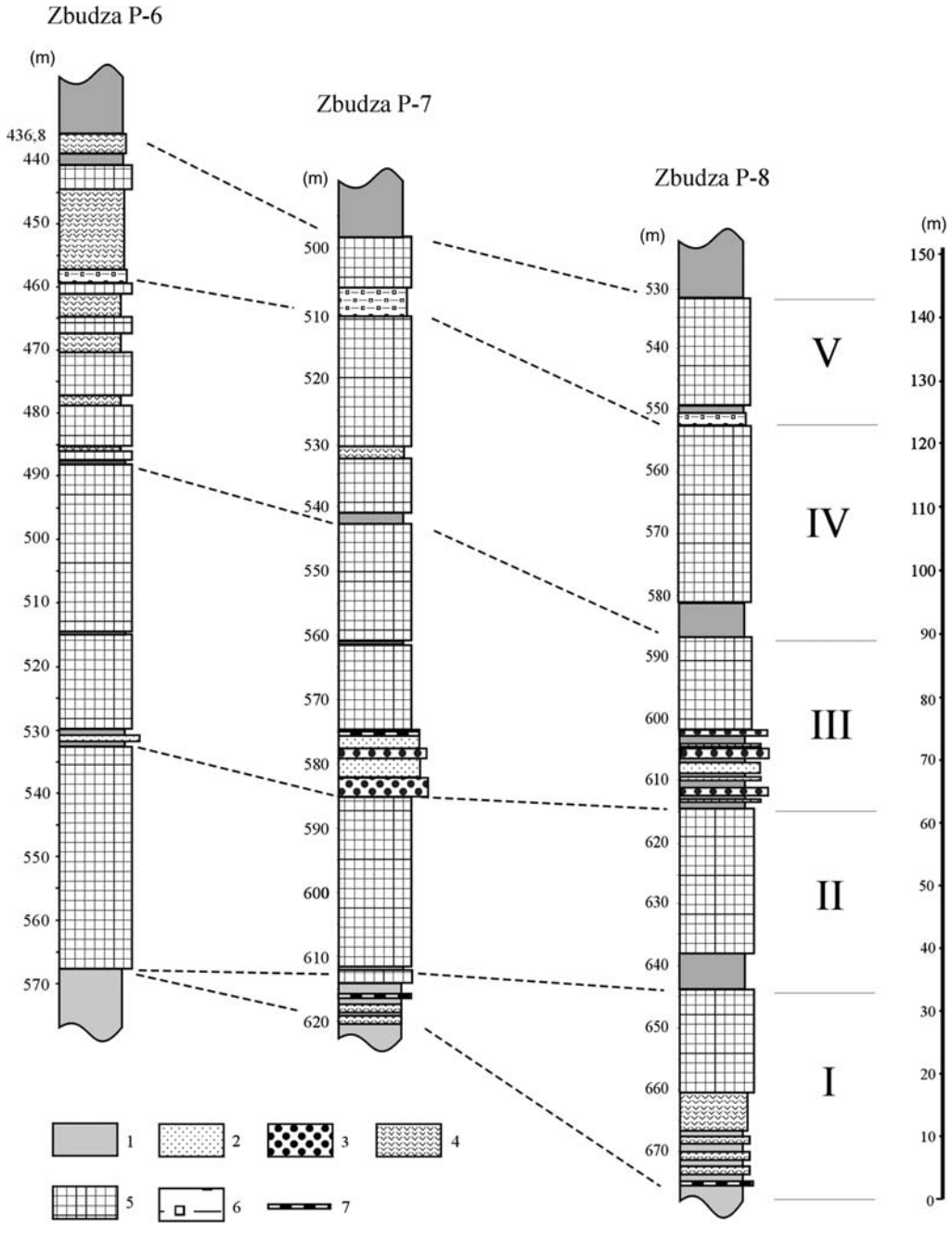


Fig. 4. Schematic lithological profiles of three studied boreholes with correlation of five observed sedimentary cycles (I–V). Legend: 1, claystone and mudstone; 2, sandstone; 3, conglomerate; 4, anhydrite; 5, salt; 6, mixed clay-salt rock (zuber); 7, tuffite.

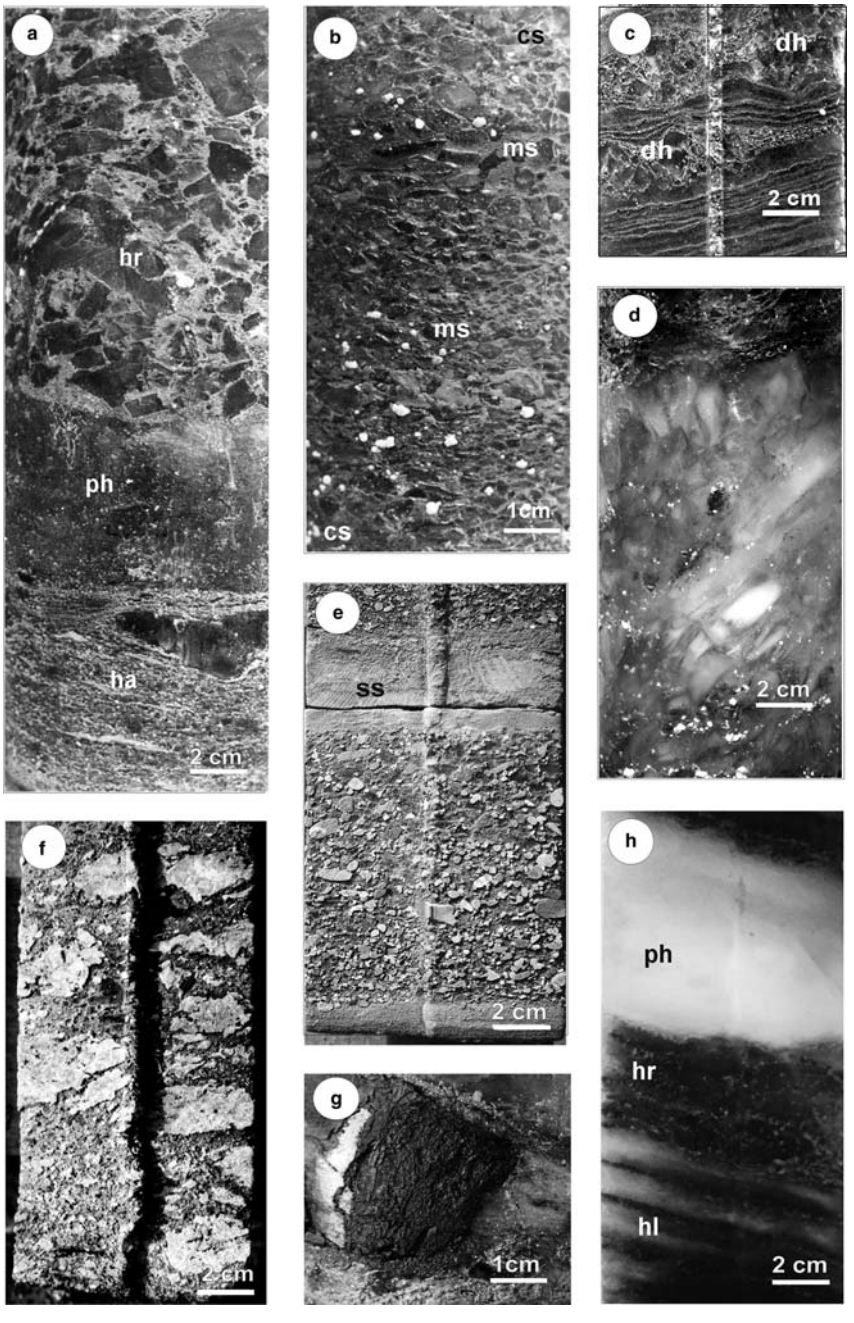


Fig. 5. Photographs of different types of sedimentary structures occurring in the salt-bearing succession. (**a**) Primary halite (ph) layer separating halite–arenite (ha, facies B) and halite–rudite (hr, facies A). Zbudza Fm P-7 well, depth 567 m. (**b**) Clast-supported (cs) and matrix-supported (ms) halite–rudite (facies A). Zbudza Fm, P-7 well, depth 537 m. (**c**) Displacive halite crystals (dh) between clay-rich parallel and wavy laminae (light) within fine halite. Salt–clay rhythmites (facies C), Zbudza Fm, P-6 well, depth 532 m. (**d**) 'Cloudy' elongate halite crystals (fluid-rich) after chevron halite. Zbudza Fm P-6 well, depth 460 m. (**e**) Conglomerate and fine, halite-cemented sandstone (ss) interbeds from the Zbudza Fm, P-8 well, depth 613 m. (**f**) Nodular anhydrite clasts within a halite-clay matrix. Zbudza Fm, P-8 well, depth 603 m. (**g**) Lignite clast within a halite–rudite. Zbudza Fm, P-2 well, depth 538 m. (**h**) Tectonically deformed salt – pure recrystallized halite (ph), halite–rudite (hr) and laminated halite (hl). Zbudza Fm, P-8 well depth 647 m.

Facies A: halite–rudites

Description These rocks are composed of salt debris and crystals, mixed with anhydrite nodules and sporadically contain clasts of other rocks, e.g. shales, limestones or sandstones, distributed/located within the fine to pelitic matrix (Fig. 5a & b). Also present are a range of structureless halite–rudites, devoid of clast selection and preferred orientation, as well as varieties having both normal and reversed grading.

Halite particles vary from 0.5 to 5 cm in diameter, but the larger ones (up to several centimetres) are commonly slightly rounded but the finer ones are commonly angular. Grains and clasts bearing relic chevron and hopper structures and of diagenetic cloudy halite are dominant. Very large clasts of transparent halite are most common in rocks with a higher clay content and some have regularly developed corners (primary euhedral halite crystals) evidencing their generation as intrasediment displacive halite. These rocks also contain up to several percent of anhydrite nodules. Terrigenous material (clay matter, quartz grains) content is up about 12% and is concentrated at grains boundaries, producing a stained-glass structure, or in flames with rare subtle lamination.

Locally in the top of the Zbudza Formation profile (Fig. 4) the mixed clay–salt deposits become increasingly common, with a clay matrix of up to 50%, called by miners 'zubers' (such rocks have a halite content from 15 to 85%; Poborski 1959). Zubers contain clasts of halite and nodular anhydrite 4–8 cm in diameter (Fig. 5f) and blocks of halite–rudites and of very large transparent halite, all dispersed within the clay matrix. The high volume, size and shape of these clasts permit these rocks to be classified as a salt breccia.

Common clasts of other sedimentary rocks noticed in halite–rudites include rounded fragments of claystones, marls and sandstones (Fig. 5e). Also present are dispersed and carbonized plant remains, especially abundant in the lower part of Zbudza Formation (Fig. 5g).

Interpretation These halite–rudites were interpreted as proximal mass flow deposits, accumulated in the most proximal part of a subaqueous slump fan from density currents highly overloaded with both pelitic and coarse clastic material (Fig. 10-1).

Facies B: halite–arenites

Description This facies includes fine-grained halite rocks, more homogenous than the halite–rudites and frequently laminated with clay matter. They commonly coexist with the halite–rudites forming rhythmic couplets (cycles) (Fig. 5a), with thickness of each halite-arenite unit up to 10 cm.

Interpretation Halite–arenites represent:

- distal mass flow deposits, formed in the seaward part of subaqueous slump fans from density currents, dominantly transporting fine clastics (Fig. 10-1),
- resedimented deposits produced by any traction currents (wave and gravity), replacing bottom clastic material.

Fine clay laminae occurred within this facies resulting from a suspension drop of pelitic material during the fair-weather periods separating the dynamic current and wave events. Commonly observed coexisting arenite and rudite layers resulted from redeposition by currents (both density and wave) of primary halite crystals and sediment fragments coming both from emerged and eroded coastal salt pans and from local bottom sediments. In some layers, the halite–arenite bed with such a depositional rhythm is overlain by a thin halite layer with *in situ* chevron crystals, indicating the calm period of intensive halite bottom growth.

Facies C: fine crystalline halites with clay laminae

Description This rock variety is characterized by regular rhythms of fine halite interlaminated with clayey matter. Halite layers (up to 10 cm thick), composed of primary precipitated finely crystalline, monomorphic halite, are separated by clay laminae (up to 1 cm), producing a parallel and/or wavy rock lamination. Also frequent interbeds of primary chevron halite are observed in this variety as well as having displacive halite crystals within clay laminae (Fig. 5c).

Interpretation This facies was interpreted as a primary salt deposit, precipitated relatively slowly on a basin bottom (Fig. 10-1) from halite-concentrated bottom brines during calm periods. Interbedded clay laminae represent a pelitic fallout from more diluted top brines.

Facies D: layers with chevron halite crystals

Description These layers are commonly observed as the interbeds within the laminated salts but also sometimes they accompany halite–rudite and halite–arenite cycles. The thickness of homogenous units with chevron halite in the Zbudza Formation profiles reached a thickness of 40 cm and they were topped with a clay lamina (Fig. 5d).

Interpretation This rock variety represents a primary salt deposit, precipitated quickly from highly concentrated brines that probably correspond to a distinct drop of water level (Fig. 10-2). Top clay lamina, covering the chevrons, could reflect: (a) an ensuing water level rise with input of fresh waters and subsequent accumulation of additional pelites (b) an event of density currents, transporting continental material seaward.

Horizontal beds of the varied salt varieties, described above, occur in most of the studied profiles or they are slightly inclined but locally some fairly thick deformed intervals were observed (several metres thick) particularly in the upper part of the Zbudza Formation, evidenced by a higher bed inclination (30–70°) and oblique veins of secondary fibrous salt and gypsum. Salt in these zones became highly recrystallized and both laminated halites and halite–arenites were transformed to a striped variety of salt (a foliation effect) and later to the transparent giant halite (Fig. 5h). This process has apparently developed due to a displacement of the mineral component, e.g. clay matter between the points of higher and lower pressure. Probably in a halite–rudite variety, when subjected to an intensive stress, the clay matrix behaved as a lubricant, transferring the deformation without destroying the primary rock structure.

Cyclicity of the Zbudza Formation

The salt-bearing series of the Zbudza Formation examined in this study may be subdivided into five chloride-bearing sedimentary cycles, separated by beds of siliciclastics and sulphates. The onset of each cycle coincides with a distinct increase in the content of terrigenous siliciclastics (Figs 4 & 6). Cycles were identified and correlated, based on the results of sedimentological and geochemical profiling supplemented with well-log data, which is exactly matched by gamma and neutron–gamma curves of the variable content of clay (a main component of the water-insoluble residues; Fig. 6).

The lowest cycle (cycle I) begins with claystones having nodular clayey anhydrite intercalations, indicating onset of the first stages of evaporite formation. Within these intercalations carbonized floral remains are common (Fig. 5g). Above this facies the laminated halite–arenites and halite–rudites occur. Such a complete succession of the first cycle, up to 30 m thick, is observed only in the P-8 well but in other bore-holes it is reduced in thickness and is represented only by a single bed of halite–rudites, up several metres thick (wells P-2 and P-7), anhydrite (in the P-3 well) or is entirely absent/possibly eroded, e.g. the P-6 well (Fig. 4).

The second overlying cycle (cycle II) begins with a claystone layer with carbonized flora and sandy flame structures (Figs 4 & 6), overlain by a series of halite–arenites and halite–rudites locally replaced by rhythmites containing primary chevron halite crystals. These chlorides are almost pure halite with a very low content of clayey matter and anhydrite (up to several percent). This cycle is about 30 m thick.

The third cycle (cycle III) begins with a series of conglomerates and fine sandstones, 8–12 m thick (Figs 4 & 6), that are commonly crossbedded, forming several sandy and gravelly subcycles (Fig. 5e). Clasts are weakly sorted, composed of sandstones, shales and carbonates as well as common halite and anhydrite clasts. The overlying *c.* 30 m thick series of halite–rudites and halite–arenites there are mechanically redeposited sediments, interbedded with the primary halite precipitates. Subangular halite clasts predominate, together with oval ones are and their size varies from 0.2 to 5 cm. Clast-supported halite–rudite beds accompanied by rhythmites with fine precipitated halite (cumulates) and *in situ* chevron halite layers compose numerous subcycles with a component thickness less than 50 cm.

The fourth cycle (cycle IV) begins with a *c.* 2 m thick claystone bed (Figs 4 & 6) with displacive halite crystals, corresponding to an event of maximum brine refreshment/solution and accumulation of delivered suspended pelitic material. Overlying this basal clay is an 8.5–12.5 m thick series of matrix-supported halite–rudites with decimetre-thick marly intercalations containing sporadic plant remains. This halite–rudite probably represents the product of slide/slump deposits developed along a basin slope (for analogues see Roveri *et al.* 2003). Clay content in this cycle is significantly higher, up to about 20–30% (Fig. 6). Upward the rudites are overlain by a nodular anhydrite bed 2.5 m thick, produced by the next basin brine refreshment. The upper part of the fourth cycle is built of subcycles consisting of rhythmites and halite–rudites but it has been significantly deformed (beds are inclined at an angle of *c.* 40°) and the primary salt structure was apparently destroyed due to later recrystallization (Fig. 5h).

The uppermost fifth cycle (cycle V) begins with several metres thick bed of clayey anhydrite (Fig. 6), suggesting a new brine refreshment. The sulphates are overlain by 3 m thick layer of mixed salt–clay rock (called 'zuber') with chaotically dispersed halite and nodular anhydrite clasts 4–8 cm in diameter (Fig. 5f) and blocks of halite–rudite and secondary, displacive, very large halite crystals within a clay matrix. Salt deposits are present above the zuber series (halite–rudites and rhythmites) and they apparently represent altered slope

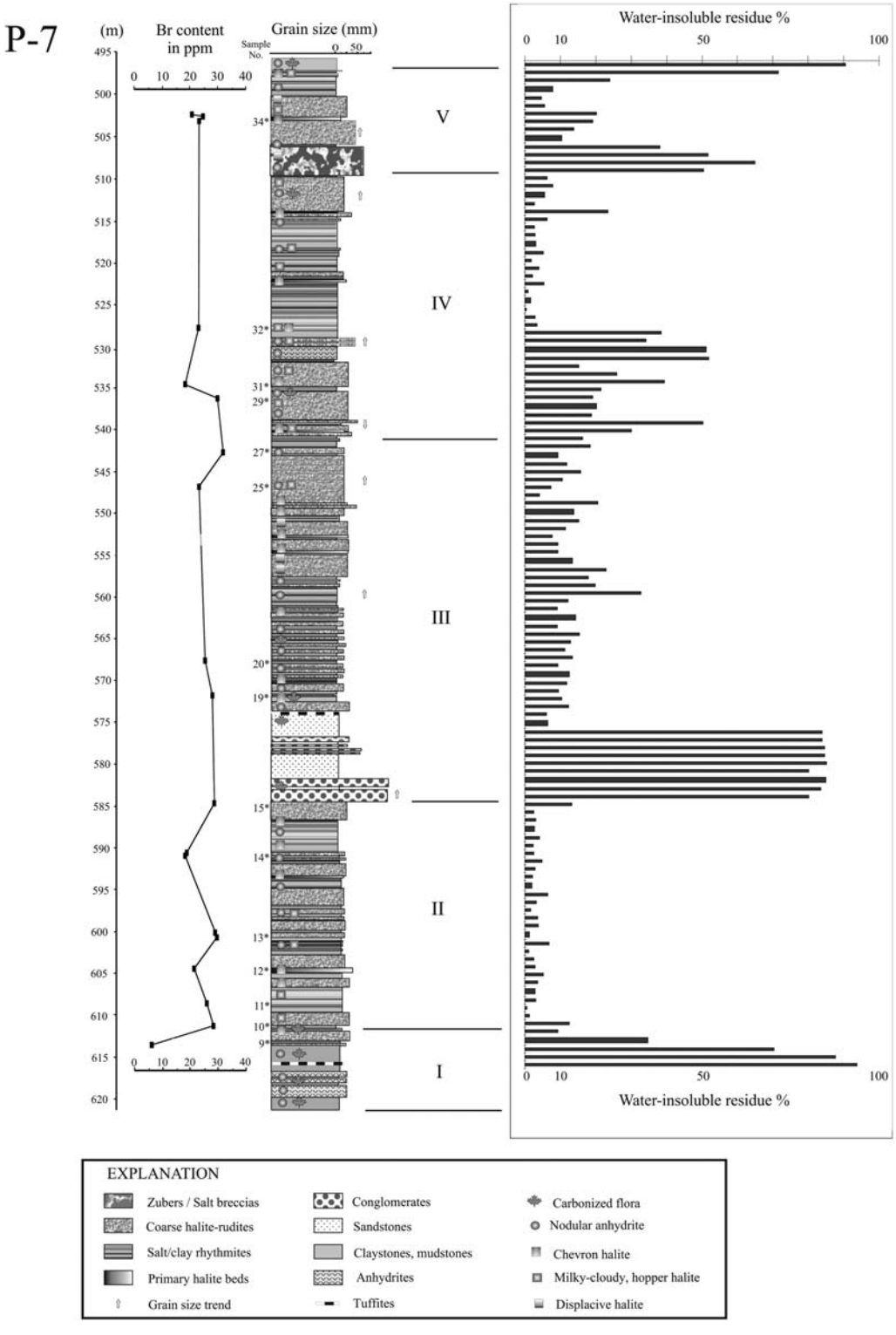


Fig. 6. Distribution of bromine and water-insoluble residue and lithological succession of deposits of the Zbudza Formation in P-7 profile. The lowest part of each cycle (I–V) is marked by a distinct increase in terrigenous material.

slide sediments and are the products of calm chemical precipitation (sections P-3, P-7 and P-8 – Figs 4 & 6) or (see P-6 section in Fig. 4) they are mainly sulphates that resulted from brine refreshment.

The Zbudza Formation, in the studied sections, is overlain by open marine siltstones, called the Lastomir Formation that apparently marks the late Badenian ingression of open marine water into the East Slovakian Basin (Vass *et al.* 2000).

Geochemistry

Methodology

Geochemical analyses were carried out on 289 samples taken from wells P-6 and P-7. Applying 'classical' methods (e.g. argentometric analysis of chlorine concentration) the content of such main components as NaCl, Ca, Mg, K, SO_4, HCO_3 water-insoluble residue (e.g. in the P-7 section, Fig. 6) were determined in 255 samples but the content of these main components and trace elements were defined in 34 point samples using ICP and INNA methods (Baedecker 1987).

Bromine content was analysed (INNA method) in 34 point samples of pure halite (without the insolubles) taken from wells P-6 and P-7 (Table 1). Oxygen and sulphur isotope content of the anhydrite was determined in 10 point samples taken from wells P-6 and P-7 (Table 2, Fig. 7). Both $\delta^{34}S$ and $\delta^{18}O$ were analysed by a dual inlet and triple collector mass spectrometer analysing SO_2 and CO_2 gases, respectively. SO_2 was extracted by the method developed in the Lublin laboratory (Hałas & Szaran 1999), whereas CO_2 was prepared by the method described by Mizutani (1971). The reproducibility of both the delta analyses was about 0.16‰ (Table 2).

The chemical composition of solutions from individual inclusions has been determined by ultramicrochemical (or glass capillary) analyses described by Petrichenko (1973), which makes it possible to analyse a solution volume in the range 0.001–0.0001 μm^3 and extract the solution from inclusions of 40–50 μm across and greater. The solution from individual inclusions was extracted by special conical capillary with interior diameter of 3–5 μm at the tip of the cone. Each element was determined directly in the capillary by standard chemical analysis. This method could define the content of ions K^+, Mg^{2+}, Ca^{2+} and SO_4^{2-} in inclusion brines so several tens of such determinations were carried out for the primary inclusions and a dozen or so on the secondary ones. Samples for such studies were prepared from chevron halite crystals taken from wells P-2, P-3, P-6, P-7 and P-8 (Galamay *et al.* 2004) and results were compared with earlier published data (Galamay & Karoli 1997; Kovalevich & Petrichenko 1997).

Results

Determination of the content of the main components in channel samples taken from each meter of core demonstrated that salts of greatest purity are located in the lower part of Zbudza Formation (in the first cycle). They are composed of nearly pure rock salt (NaCl more than 95%) with a low content of insolubles (clay matter and sulphates). The content of terrigenous material increases upward the Zbudza Formation, resulting in the occurrence of more and more clayey salts.

The studied rock salts of Zbudza Formation are characterized by a variable content of three main components: NaCl, $CaSO_4$ and water-insoluble residues (Fig. 6). Relations of these components remain similar throughout the formation, *c.* 77% NaCl, 20–22% water-insoluble residue and 1–3% $CaSO_4$. The ranges of potassium and magnesium contents are very similar in salts from both analysed cores and are relatively low. Concentrations of potassium and magnesium in salts from the Zbudza Formation apparently are related to the admixture of terrigenous material, i.e. clay content in the analysed salts. Potassium content varies from 0.01 to 0.49%, and the Mg content is between 0.01 and 0.77% (Table 1).

Concentrations of these elements as well as aluminium (0.01–1.53%) and iron (0.01–0.61%)

Table 1. *NaCl, Br, K, Mg content in rock salt rocks of the Zbudza Formation*

Element	Well	Number of samples	Range	Mean
NaCl (%)	P-6	127	8.19–98.19	77.13
	P-7	121	14.44–98.54	78.31
Br (ppm)	P-6	15	16–36	26.9
	P-7	19	6–35	23.9
K (%)	P-6	15	0.01–0.49	0.08
	P-7	19	0.01–0.49	0.12
Mg (%)	P-6	15	0.01–0.63	0.15
	P-7	19	0.01–0.77	0.20

are slightly higher in samples taken from the P-7 borehole; however the difference resulted from a greater admixture of terrigenous material in the studied well. Strontium content varied from 5 to 5338 ppm, and is closely related to the amount of dispersed anhydrite (the average Sr content is higher in P-6 core material, 680 ppm in comparison to 498 ppm for samples from P-7 well).

The content of other minor and trace elements in the studied deposits are commonly low and undifferentiated. Several trace elements are connected with non-chloride minerals occurred in the salts, for example, sulphates, carbonates and clay minerals.

Bromine content in Zbudza Formation salts varies between 5.8 and 36 ppm. Similarly low values of bromine concentrations were established earlier in this area from halite sampled in borehole Ep-2 (Galamay & Karoli 1997) although through the whole interval the bromine content was somewhat variable: 13–89 ppm. The average bromine concentration in core material from P-6 and P-7 boreholes (24 and 27 ppm) is close to the average content of this element in zuber rocks from both the Wieliczka and Bochnia salt mines. Such low bromine concentrations in the salts indicate that bromine content in their parent brines was not characteristic for brines of purely marine origin. The bromine distribution in salt profile P-7 is illustrated in Figure 6.

The narrow range of the bromine content is reasonable evidence of small variety of parent brines concentrations during salt sedimentation period. It is very likely that the salts in this study were precipitated from secondary brines that formed due to dissolution of earlier salts deposited in other places. Marine waters with an influx of meteoritic waters probably were the main cause of dissolution, though a particularly low bromine content (5.8 ppm), determined in the sample taken from the bottom of salt profile, indicates that at the onset of salt sedimentation waters of non-marine origin also contained dissolved earlier primary salts.

The oxygen and sulphur isotope compositions of analysed anhydrite samples show a wide scatter of values from 11.16 to 13.15‰ SMOW for oxygen and from 18.28 to 24.45‰ CDT for sulphur (Table 2; Fig. 7). Average values are respectively 12.34 ± 0.47 and 22.22 ± 0.87‰. Overall, these results correspond well to the isotopic composition of Badenian anhydrites in the Carpathian Foredeep and associated halite in Wieliczka and Bochnia salt deposits (Claypool *et al.* 1980; Parafiniuk & Hałas 1997; Bukowski & Szaran 1997; Peryt *et al.* 1998, 2002; Kasprzyk 2003). Similar $\delta^{18}O$ and $\delta^{34}S$ were also documented for the Badenian primary gypsum deposits in the Carpathian Foredeep in Poland, Czech Republic and Ukraine (e.g. Parafiniuk *et al.* 1994; Hałas *et al.* 1996; Kasprzyk 1997; Peryt *et al.* 1997; 2002; Peryt 2001).

Data on the chemical composition of the brines in primary inclusions in the chevron halite crystals from the Zbudza Formation indicate that the brines of this basin were of the Na–K–Mg–SO_4 type (Galamy *et al.* 2004). The ratios of the K^+, Mg^{2+} and SO_4^{2-} ions were almost analogous to the ratios in the Badenian seawater, which differed from the contemporaneous seawater (McCaffrey *et al.* 1987) in terms of the reduced content of Mg^{2+} ions by approximately 20% and SO_4^{2-} ions by approximately 40% (Kovalevich *et al.* 1998; Zimmermann 2000; Poberezhskyy & Kovalevich 2001). Such lower sulphate values, typical for other Miocene basins of the Carpathian area (Fig. 8) as well, might be due to the chemical evolution of the Phanerozoic ocean (Kovalevich *et al.* 1998; Horita *et al.* 2002) or may be due to inflow of considerable amounts of continental fresh waters and terrigenous materials into the basin (Galamay *et al.* 1997; Cendón *et al.* 2004).

Table 2. *Isotopic composition of anhydrite in the Zbudza Formation*

Sample	Depth (m)	Anhydrite type	$\delta^{18}O‰_{SMOW}$	$\delta^{34}S‰_{CDT}$
P-6/27a	469.9	Nodular anhydrite with halite pore fill (50%)	12.40	22.10
P-6/27b	469.9	and halite clasts	12.34	22.21
P-6/28	461.1	Massive nodular anhydrite	13.15	22.92
P-6/30	457.0	Porous nodular anhydrite	12.34	22.08
P-6/31	437.0	Anhydritic conglomerate with clay matrix	12.44	22.92
P-6/35	436.7	Anhydritic conglomerate with clay matrix	12.94	24.45
P-7/31	533.5	Halite-rudite with a matrix of nodular anhydrite	12.58	22.95
P-7/8a	612.6	Nodular anhydrite with clay laminae/flame structures and fine clasts of halite and sedimentary rocks	12.47	22.08
P-7/8b	612.6	Br content in halite: very low probable recycling?	11.16	22.19
P-7/2	619.5	Finely laminated anhydrite	11.17	18.28

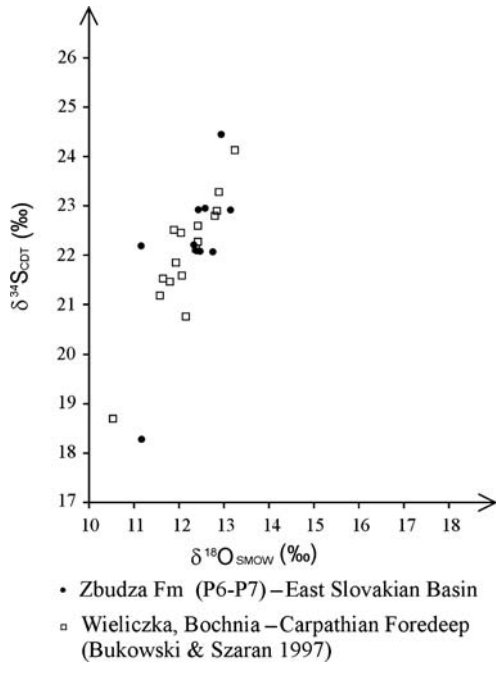


Fig. 7. Plot of ^{34}S and ^{18}O values measured from the anhydrite in the Zbudza salt deposit. Isotopic compositions for Badenian anhydrite from Wieliczka and Bochnia salt mines in the Carpathian Foredeep, Poland, are also shown (data from Bukowski & Szaran 1997).

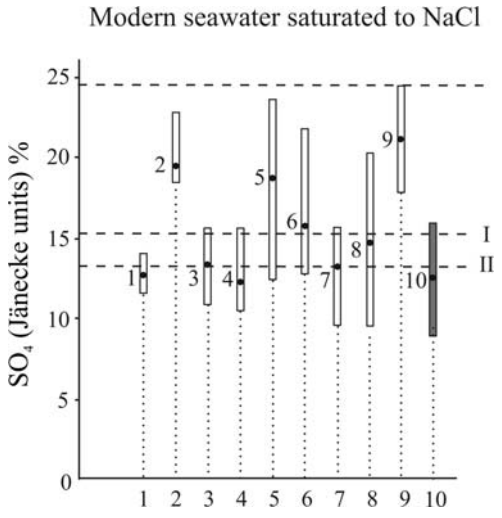


Fig. 8. Content of the SO_4 ion in primary fluid inclusions of sedimentary halite (given in Jänecke units) as measured from different boreholes, mines and localities in the Badenian evaporites of the Carpathian region (after Galamay *et al.* 2004). I, Badenian seawater (Galamay *et al.* 2004); II, Badenian seawater (Zimmermann 2000). Dots indicate locations: 1, Bochnia mine, Carpathian Foredeep, Poland (Kovalevich & Petrichenko 1997; $n = 2$ samples); 2, Łeżkowice Z-1 and Woszczyce IG-1 boreholes, Carpathian Foredeep, Poland (Garcia-Veigas *et al.* 1997; $n = 6$ samples); 3, Wieliczka mine, Carpathian Foredeep, Poland (Kovalevich & Petrichenko 1997; $n = 5$ samples); 4, Wieliczka mine, Carpathian Foredeep, Poland (Galamay *et al.* 1997; $n = 20$ samples); 5, Selets-Stupnitsy and Zabolotiv localities, Carpathian Foredeep, Ukraine (Kovalevich & Petrichenko 1997; $n = 20$ samples); 6, Slanic-Prahova mine, Carpathian Foredeep, Romania (Kovalevich & Petrichenko 1997; $n = 5$ samples); 7, Ep-2 and Zb-1 boreholes, East Slovakian Basin (Kovalevich & Petrichenko 1997; $n = 4$ samples); 8, Transylvanian Basin, Romania ($n = 4$ samples); 9, Solotvyne mine, Transcarpathian Basin, Ukraine (Kityk *et al.* 1983; $n = 7$); 10, all data, East-Slovakian Basin ($n = 32$ samples);

Genesis of Zbudza Evaporitic Formation

The redeposition processes generally played a very important role during the deposition of evaporites and, while resedimented gypsum and anhydrite occurrences are well known (e.g. Hardie & Eugster 1971; Parea & Ricci-Lucchi 1972; Schreiber *et al.* 1976; Schlager & Bolz 1977; Rouchy *et al.* 1995; Warren 1999; Peryt 2000; Roveri *et al.* 2001; Manzi *et al.* 2005), resedimented halite deposits are less commonly noted (e.g. Schreiber 1986; Ślączka & Kolasa 1997). Salt breccia (employed as a morphological term) is more often interpreted as a result of tectonic deformation, additionally the influence of tectonic processes (recrystallization, foliation) is readily causes loss of primary sedimentary structures of halite.

The salt-bearing succession in the Zbudza Formation contains much evidence of sedimentary origin and a considerable part of the studied halite was mechanically redeposited.

1. Both halite clasts (angular and rounded/partly dissolved with zoned, cloudy features) dispersed within the salt–clay matrix and accompanied with clasts (pebbles) of marls, sandstones and claystones and fine-medium clastic quartz (Fig. 9a), so they all were deposited by sedimentary process.
2. In vertical section common salt to siliciclastic units/sets are visible with normal and reversed grading, with erosional lower contacts and an upward increase in the content of siliciclastics and clay (Fig. 9b).
3. Salt/halite rudites–psamites units are interbedded with layers (up to several metres thick) of sandstones with gravels and claystone, having normal grading, erosionally scoured lower contacts, lignite fragments and

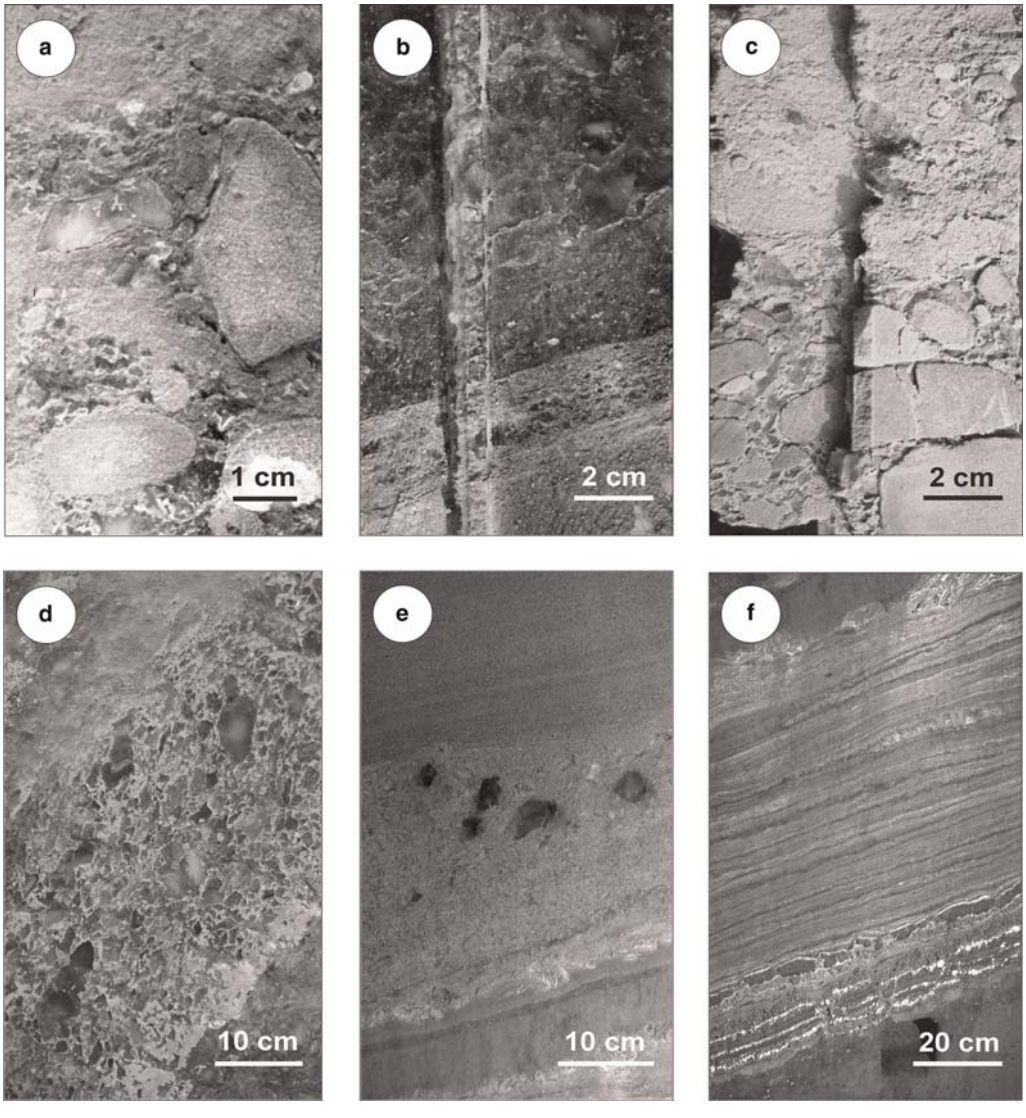


Fig. 9. Photographs of chosen examples being evidence of redeposition within Zbudza Fm. (**a**) Clasts of 'milky–clouded' halite dispersed within the salt-clay matrix and accompanied with clasts of marls and sandstones, Zbudza Fm, P-8, depth 612 m. (**b**) Erosional contact between halite with reverse grading and siliciclastic arenite, Zbudza Fm, P-7, depth 584 m. (**c**) Conglomerate with normal grading, pebbles about 10 cm in diameter, interbeds from Zbudza Fm, P-8, depth 610 m. (**d**) Layer of matrix-supported halite–rudite and monomictic breccia with large clasts of cloudy and chevron halites. Spiza salt. Gallery Kunegunda, first level in the Wieliczka Salt Mine. (**e**) Wavy laminated halite–arenite with the large rounded halite monocrystals in the centre. Spiza salt. Gallery Lichtenfeltz in the Wieliczka Salt Mine. (**f**) Fine laminated Spiza salt with the discontinuous layer of anhydritic siltstone in the lower part. Gallery Lichtenfeltz in the Wieliczka Salt Mine.

x-bedding, evidence of high dynamic transport and the intensive coarse sediment input (Fig. 9c).

4. Tectonically induced features observed in the form of vertical or oblique fractures and veins infilled with secondary clear halite, and as markedly inclined salt-clastic units but typical tectonic breccias are rare and occur locally in the top of the succession.
5. In the studied wells the deposits of the Zbudza Formation and also the over- and underlying sediments are only slightly inclined without features of intensive tectonic displacement

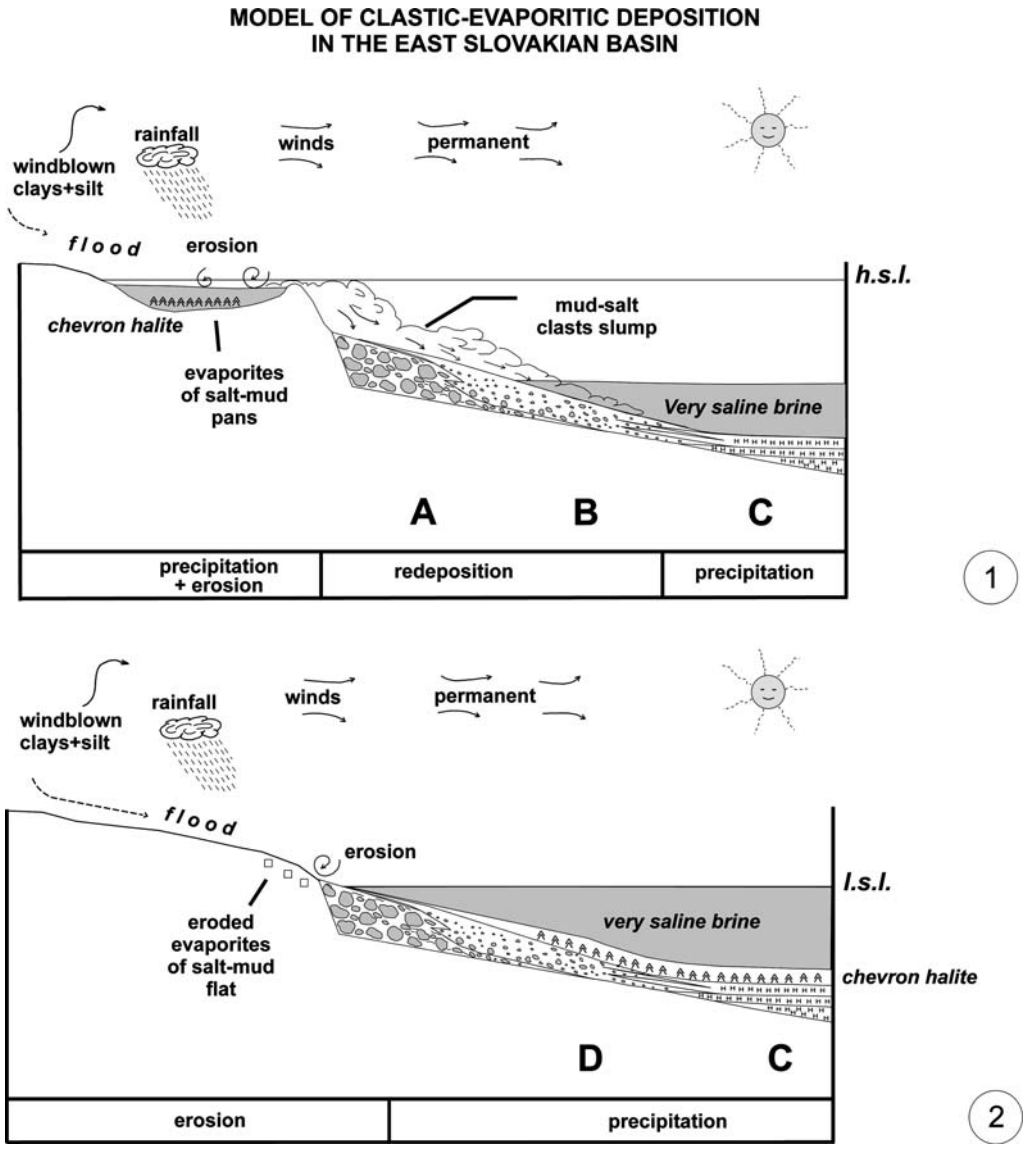


Fig. 10. Deposition model of salt facies as interpreted from deposits that comprise the Zbudza Formation. (**1**) High water level phase; (**2**) low water level phase; (A–D) salt facies described in the text.

and rebuilding, the zones of distinct tectonic transformation were found more commonly to the south of the studied profiles and are clearly related to the regional tectonics generated by the Zaluzice and Michalovce fault zones.

The Zbudza evaporites were produced mainly by repeated redeposition/recycling of chlorides precipitated from parent brines of a salt basin of variable/lowered salinity (comparable to brines of a salt basin in the outer Carpathian foredeep). Brine salinity fluctuation was due to periodic high continental influx (siliciclastics and floral input). We found that the mixed clastic–evaporitic deposition in the Zbudza area (East Slovakian Basin), was controlled by frequent tectonic and seismic phenomena and pulses of elevated terrigenous supply, producing the repeated slump sediments with dominant A (proximal mass flow) and B (distal flow) salt types (Fig. 10). These deposits

were separated by primary salt units (facies C and D) that precipitated *in situ* from bottom brines during calm periods.

Most of the clastic material composing the evaporitic deposits (redeposited halite–rudites and halite–arenites) and siliciclastics were probably transported from the intensively eroded coastal mud-salt flats framing the basin, but these facies had not been preserved in the sections due to post-depositional tectonics and erosion. Submarine fans and slope slumps, with the clastic salts as the main component and only partly transformed by diagenetic and tectonic processes, were described in the Spiza Salt Series from the Wieliczka salt deposit in the Polish Carpathian Foredeep (Ślączka & Kolasa 1997). Features analogous to the previously described salt types, as described above, were noticed in the galleries of the Wieliczka mine (Fig. 9d–f). In the Wieliczka salt deposit a lateral gradual decrease in the quantity of halite clasts and crystals, the replacement of halite–rudites by finer halite–arenites (Fig. 9e), as well as the more common presence of finely laminated rock beds (Fig. 9e) were noted in the east, west and north directions outside the deposit centre. This suggests a lateral transition from the axial to the distal fan portions.

The repeated cyclicity (cycles I–V) probably reflects varied tectonic activity of the basin margins, that mechanically remobilized the sediments from marginal salt pans, flats and adjacent uplifts, and could be correlated with cycles in the Wieliczka Formation from Carpathian Foredeep.

Analysis of redeposited material and facies succession in the well profiles located nearby the Zbudza salt deposit (Slávik 1967*b*) showed that the area of basinal salt facies was framed by the sulphate zone, producing a series of anhydrite–siliciclastic layers several metres thick.

Conclusions

The Middle Badenian evaporites of the Paratethetys area, present at the Langhian/Serravallian boundary were studied in the East Slovakian Basin (an intermountain depression having a horst-and-graben structure, located in the Inner Carpathians). In this area they were developed as an economically valuable salt-bearing series (Zbudza Formation), identified in several exploration wells.

The Zbudza Formation (100–140 m thick) is composed of pure to clayey halite beds up to 75 m thick, interbedded with siliciclastics (laminated siltstones and claystones, sandstones and conglomerates with carbonized flora remains) and nodular anhydrite. The chlorides are of four main diagnostic types: (A) coarse halite–rudites to salt breccia, being deposited by mass flows; (B) halite–arenites, deposited due to current and/or wave mobilization of halite crystals; (C) salt/clay with parallel to wavy rhythmites, interpreted as chemical precipitates from brines of fluctuating salinity; and (D) chevron halite layers, formed *in situ* due to a halite bottom growth.

The sedimentary succession that makes up the Zbudza Formation was subdivided based on lithological, geochemical and log data into five units, recording the cyclicity of evaporites deposition. Several cycles begin with laminated claystone layers (cycles II and IV), locally with nodular anhydrite interbeds (cycle I at the bottom) or with the anhydrite beds (cycle V at the top), reflecting the refreshment of basin brines (input of fresh marine and/or continental waters).

The middle cycle (III) began with coarser siliciclastic beds (sandstones to conglomerates), deposited by slumps of clastic material along the basin margin. These deposits represent subaqueous fan sediments, produced due to intensive erosion of emerged basin margins (Bukowski *et al.* 2003). Outside the supposed fan axis the sediment thickness and clast size diminish, replaced by a series of fine gravels and siltstones (e.g. P-6 well). The siliciclastics appear to reflect the period of maximum tectonic activity in the entire region, and their character and position within the Zbudza Formation profile is comparable to the sub-salt sandstone series typical of the Wieliczka Formation in the Carpathian Foredeep (Bukowski 1997).

Slope slides and associated mass flows of unsorted material, removed from coastal mud-salt flats, were responsible for deposition of halite–rudites (type A), accumulated in the axial part of formed subaqueous fan. Further redeposition of finer clastics by diluted distal mass flows and wave currents have produced the halite–arenites (type B), composing the distal fan part. Interbeds of salt/clay rhythmites and primary halite beds (type C), produced during the calm periods of dominant chemical precipitation and suspension drop, complete the evaporate succession of the cycle, illustrating a climatic fluctuations development of slope slumps. The high level of remobilization of both bottom and shallow water sediments, interpreted as a result of increased tectonic activity along basin margins, was observed in the third cycle, dominated by coarse clastics.

The youngest, fifth cycle was characterized by the specific succession of matrix-supported halite–rudites and breccias, called the 'zuber' series. This zuber zone apparently resulted from a single mud flow, triggered by tectonic movements on the basin margin. Comparable but thicker zuber rocks are common in the Wieliczka Formation within the Carpathian Foredeep, documented in the salt

deposits at Wieliczka and Bochnia (e.g. Kolasa & Ślączka 1985; Czapowski & Bukowski 2002).

Geochemical data indicate an upward increased in the terrigenous content of the salts of the Zbudza Formation, reflecting fluctuating but generally greater clastic supply to the basin, moving up the section. Fluctuating but low, on average, bromine content in halites – (up to 36 ppm), sulphur and oxygen isotopic composition of anhydrite interbeds and chemistry of primary fluid inclusions in halite (especially low SO_4 concentrations found in fluid inclusions) give evidence that the parent brines for the salts were of low concentration, depleted in sulphates and highly diluted by fresh/continental waters. The extremely low bromine (as low as 5.8 ppm) confirms that secondary brines obtained from dissolution of earlier primary salts by marine waters and non-marine/continental waters suggest a common source for deposition of Zbudza evaporites

Lithological and geochemical features of Zbudza salts are comparable with features of salts that make up the age-equivalent Wieliczka Formation in the Carpathian Foredeep, so the mechanisms of their formation and observed cyclicity, clearly controlled by tectonic activity, is the valid causitive agent within both the intra- (Zbudza area) and the extramountain (Carpathian Foredeep) basins.

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