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Lithostratigraphic and Bromine Profile of the Zechstein Salt Series In the Area of Borehole M-29 of the Mogilno Salt Dome

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Abstract

The M-29 exploratory borehole and operating well is located on the Mogilno I deposit in the south-eastern section of the Mogilno Salt Dome (Fig. 2). It was drilled down to the depth of 1,751 m in 2014. The borehole penetrated the evaporites of the Upper Permian (Zechstein) and a sequence of clay-mudstone-sand formations of the Lower Triassic. 11 lithostratigraphic members of the Zechstein salt series, belonging to cyclothems PZ-2, PZ-3, and PZ-4, were separated in the core subjected to our analysis. The salt deposit of the borehole M-29 area had been formed tectonically. The borehole cuts through a deep syncline, filled with the sediments of cyclothems PZ3 and PZ4. The syncline is limited on the ceiling and floor sides by anticlines composed mainly of Na2 rock salt. As a result of the uplift of the two anticline intrusions, the salt layers became strongly folded and formed very steeply. The borehole pierces through the same members several times. Many divisions are reduced in thickness or completely wedged out. No ceiling layers of cycle PZ-4 or evaporites, being older than Older Halite (Na2), were found in the profile.

As a result of halokinetic and tectonic deformations, the salt layers became extremely folded and steeply arranged. The layer dip varies from 35° to 90°, mostly 60-80°. Numerous changes of the dip angle and multiple folding are demonstrated by the fact that the borehole often penetrated the same members.

Key Words: salt deposits, Zechstein (Late Permian), Zechstein evaporites, Zechstein stratigraphy, salt cyclothems, Mogilno salt dome.

Streszczenie

Otwór badawczo-eksploatacyjny M-29 jest zlokalizowany w południowo-wschodniej części wysadu solnego Mogilno, na złożu Mogilno I (Ryc. 2). Został on odwiercony w 2014 r. do głębokości 1751 m. Otwór nawierca ewaporaty późnego permu (cechsztynu) oraz kompleks utworów ilasto-mułowcowo-piaszczystych dolnego triasu. W analizowanym rdzeniu wydzielono 11 ogniw cechsztyńskiej serii solnej cyklotemów PZ-2, PZ-3 i PZ-4. Złoże solne w rejonie otworu M-29 jest uformowane tektonicznie. Otwór przewierca głęboką synklinę, wypełnioną osadami cyklotemów PZ3 and PZ4. Synklina ograniczona jest od stropu i spągu antyklinami, zbudowanymi głównie z soli kamiennej Na2. W wyniku wypiętrzenia tych dwóch intruzji antyklinalnych warstwy solne zostały silnie sfałdowane i zalegają bardzo stromo. Otwór przewierca kilkakrotnie te same ogniwa. Wiele wydzieleń jest zredukowanych lub całkowicie wyklinowanych. W profilu nie stwierdzono warstw stropowych cyklu PZ-4 i ewaporatów starszych niż Starszy Halit (Na2).

W wyniku deformacji halokinetycznych i tektonicznych warstwy solne są silnie pofałdowane i zalegają bardzo stromo. Upad warstw waha się od 35 do 90°. Najczęściej jednak wynosi 60-80°. Otwór przewierca wielokrotnie te same ogniwa ze względu na częste zmiany kąta upadu i przefałdowania.

Słowa kluczowe: złoża soli, cechsztyn (późny perm), ewaporaty cechsztyńskie, stratygrafia cechsztynu, cyklotemy solne, wysad solny Mogilno.

Introduction

The Mogilno salt dome is an element of a large tectonic unit: the anticline structure of Mogilno (Sokołowski, 1966;

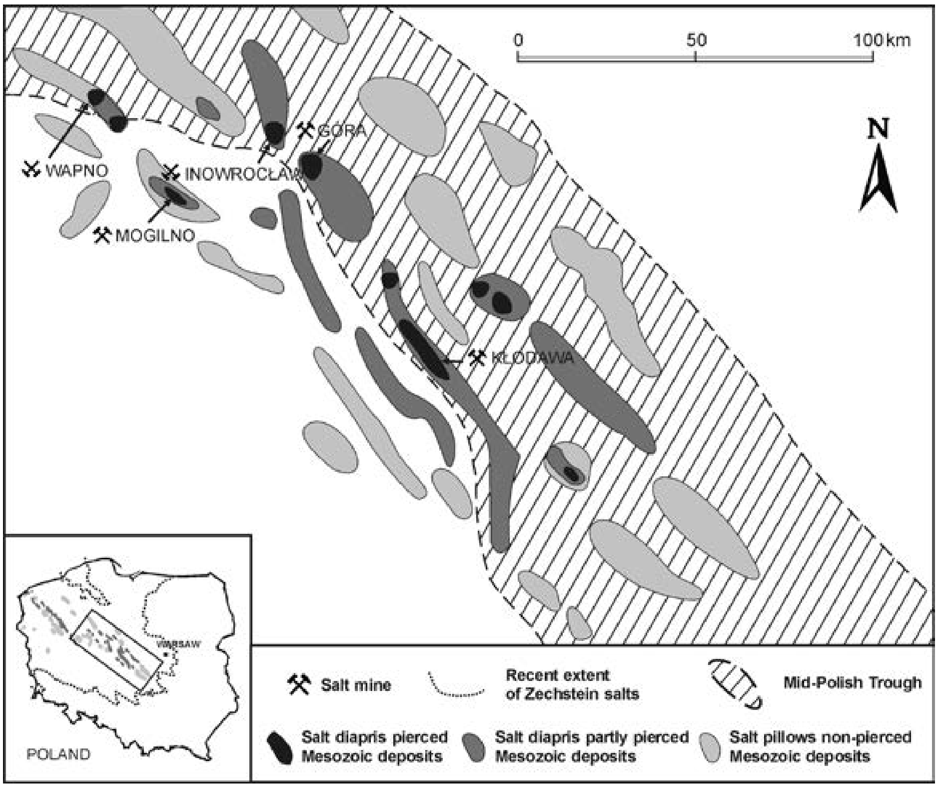

Fig. 1. Distribution of salt structures in the central part of the Mid-Polish Trough (from Garlicki & Szybist, 1986; Dadlez at al., 1998, Wachowiak at al., 2012)
Ryc. 1. *Rozmieszczenie struktur solnych w centralnej części Bruzdy Środkowo-Polskiej (wg: Garlicki & Szybist, 1986; Dadlez i in. 1998, Wachowiak i in., 2012).*

Dadlez, 1997), situated within the Kuyavian-Pomeranian Wall (Fig. 1). The structure is elliptic, with the NNW-SSE elongation (Krzywiec, 2006), whose longer axis is ca. 30 km long and the shorter one ca. 7 km long (Dadlez et al., 1998, 2002; Mizerski, 2014). In the north-western part of the structure, Zechstein salts completely pierce through the Mesozoic cover on the area of ca. 8 km by ca. 1 km, creating the core of the Mogilno salt dome. The salt mirror of the diapir is located at 210-600 m below the ground. It is covered by a gypsum cap and filled with Tertiary and Quaternary sediments (Wilkosz, 2001, 2006). Mining operations currently continue on the Mogilno salt dome. Salt is extracted by the solution method down to 1,750 m. In the NW portion of the salt dome (Mogilno II deposit, Fig. 2), salt is leached with the intention to produce caverns designed for underground storage of natural gas (KPMG Mogilno, Mogilno Underground Cavern Natural-Gas Storage Facility). In the SE section (Mogilno I deposit), the IKS Solino S.A. conducts salt and brine extraction for industrial purposes. To recognize the geological structure of another section of the Mogilno deposit and to continue salt extraction, several more exploratory boreholes and operating wells were drilled recently (2014-2015). On the basis of the core material, initial lithostratigraphic characteristic was made and bromine content was determined and selected trace elements (Wachowiak, 2015).

Methodology

Cartographic Works and Sampling

Mapping and sampling of the rock salt originating from the borehole M-29 core was carried out in the salt-core warehouse of the Mogilno Salt Mine. The core material of the interval from 310 to 1751 m USL (under the surface level) was used in the process. Maps was drafted in the scale of 1:100. Macroscopic descriptions of the core were recorded, with particular attention paid to such structural and textural and characteristic lithostratigraphic features of the rocks as e.g. lead levels, correlation layers etc. 107 samples, weighing ca. 1 kg each, were collected from ca. 1,441 m long core section. 11 types of rocks, making up 11 lithostratigraphic members, were sampled. Sampling density, varying from 1 to 30 m, depended on lithological changeability and the dip angle of layers.

Laboratory Tests

Samples were delivered to the "Geosalt" Laboratory in Kraków where they were cleaned and crushed into ca. 10-50 mm fractions. Next, 200 g of representative material was separated from each sample by the quartering method for subsequent tests. Each of the 200 g samples was grinded in an agate mortar down to the fraction of 0.1-1 mm. After careful mixing of the grinded samples, 50 g were weighed from each sample, with the intention to determine chloride $[Cl^-]$ and bromide $[Br^-]$ contents. Determinations were carried out in the Hydrogeochemical Laboratory of the Department of Hydrogeology and Engineering Geology of the AGH University of Science and Technology in Kraków. Chlorides and bromides were determined in water extract (ca. 5 g of the sample per 100 ml of distilled water). Chlorides were determined by the argentometric method, in accordance with Polish Standard PN-ISO 9297: 1994. Bromide was determined by the mass spectrometry method, in accordance with the following Standards: PN-EN ISO 17924-1: 2007 and PN-EN ISO 17924-2: 2006, using a Perkin Elmer ICP MS „Elan 6100" spectrometer, with inductively excited plasma.

Based on chloride and bromide contents, the bromide-chloride coefficients [Br*1000/Cl] was calculated and a bromide-chloride profile of the M-29 borehole salt rocks was drafted, as presented in Fig. 3. To check the correctness of the calculations, also the Br^- contents, expressed in mg/kg, were entered.

Results

The M-29 exploratory borehole and operating well is located on the Mogilno I deposit in the south-eastern section of the Mogilno Salt Dome (Fig. 2).

It was drilled down to the depth of 1,751 m. The borehole coordinate is located at the altitude of 144 m ASL (above the sea level). Within the 0-230 m interval, the borehole penetrates Quaternary clays and mudstones and Tertiary clay, sands, and brown coal formations, as well as the clay-anhydrite-gypsum cap. At the depth of 230 m, the salt mirror of Zechstein salt series was identified. At the depth of 421 m, the borehole cut the salt-dome border and a fragment of clay-mudstone-sand layers of the Lower Triassic (T1). At the depth of 526 m, the borehole entered the salt-dome border again and continued within the salt series down to the borehole's end.

11 stratigraphic members of the Zechstein salt series, belonging to cyclothems PZ-2, PZ-3, and PZ-4, were separated in the analyzed core material as follows:

1. Older Halite (Na2) of cyclothem PZ2
2. Older Potash (K2) of cyclothem PZ2
3. Lower Younger Halite (Na3d) of cyclothem PZ3
4. Younger Potash (K3)
5. Upper Younger Halite (Na3g) of cyclothem PZ3
6. Anhydrites A, B, C
7. Brown Zuber (Na3t) of cyclothem PZ3
8. Underlying Halite ($Na4_0$) of cyclothem PZ4
9. Pegmatite Anhydrite (A4) of cyclothem PZ4
10. The Youngest Halite (Na4) of cyclothem PZ4
11. Red Zuber (or Hematite Zuber, Na4t)

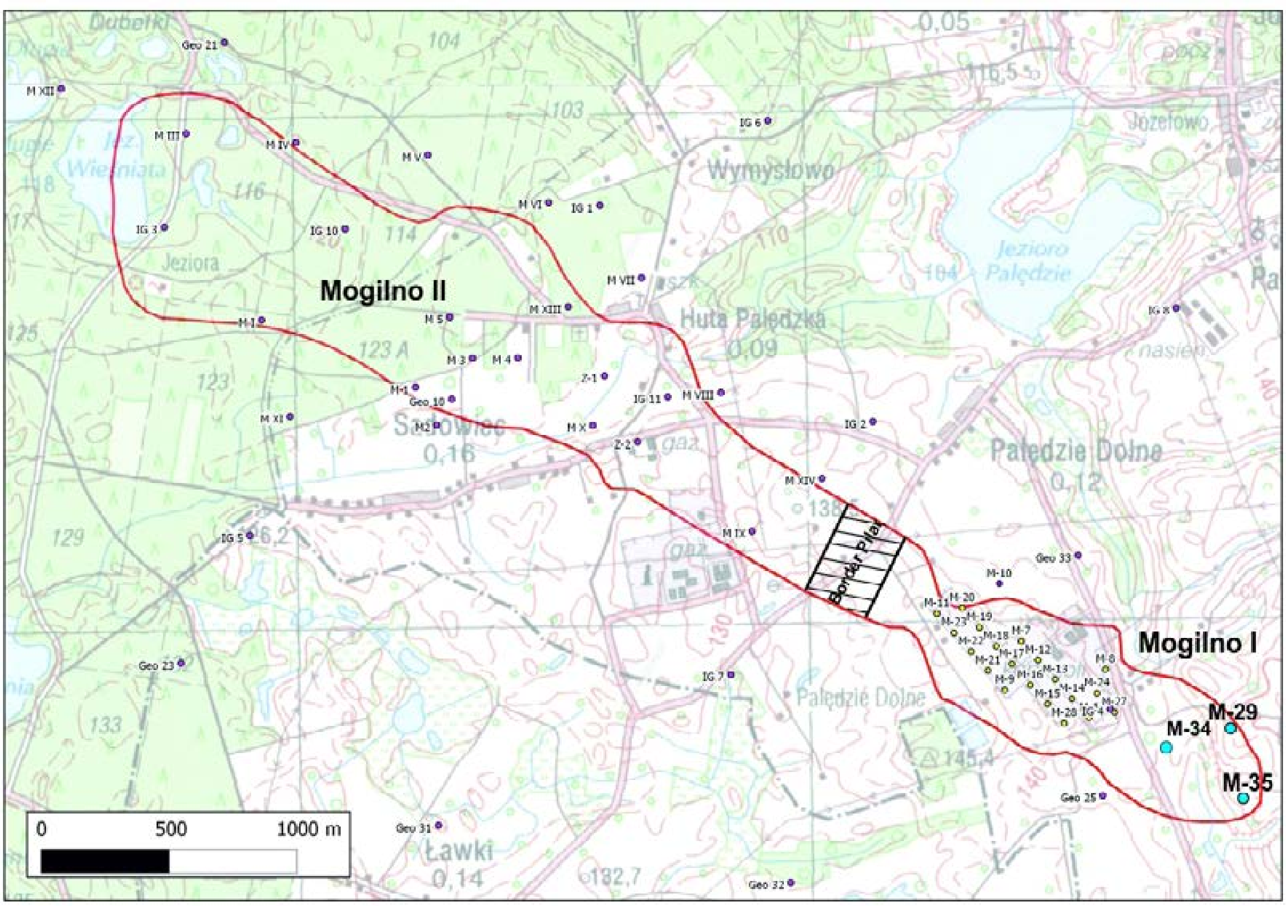

Fig. 2. Localization of borehale No M-29 against Mogilno I salt deposite.
Ryc. 2. *Lokalizacja otworu M-29 na tle złoża Mogilno I.*

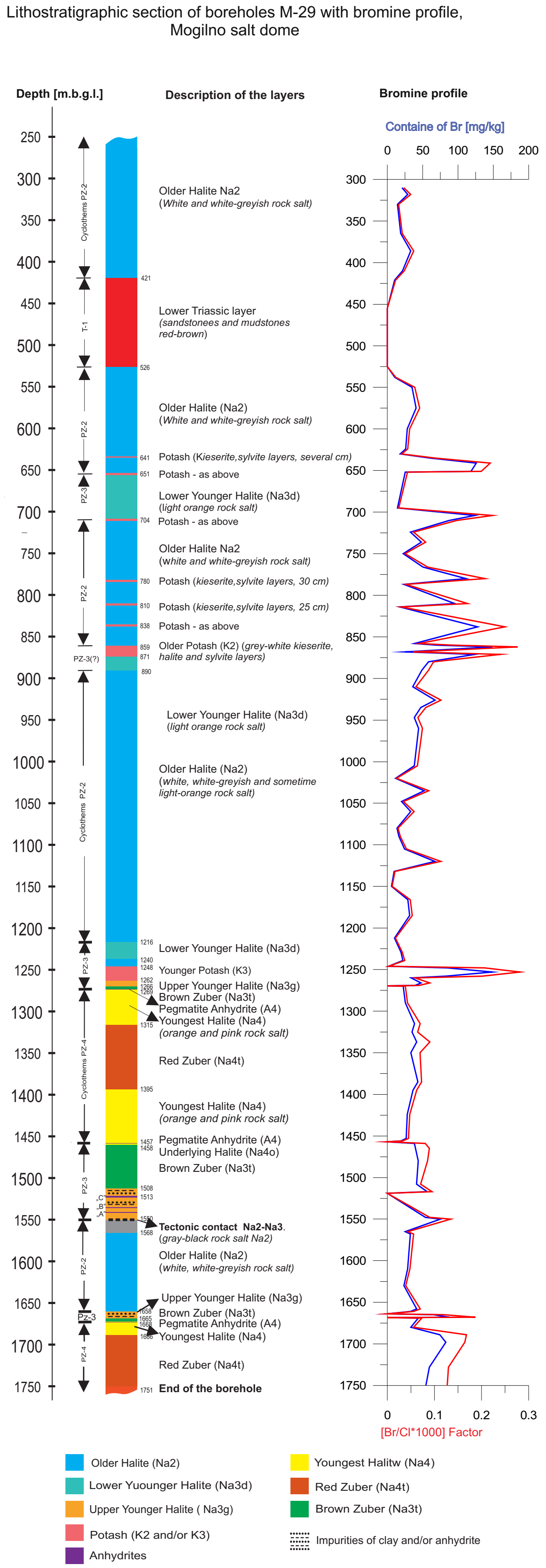

Fig. 3. Lithostratigraphic profile of borehole M-29. Mogilno salt dome. Mogilno I salt deposit.

Ryc. 3. *Profil litostratygraficzny otworu M-29. Wysad solny Mogilno. Złoże Mogilno I.*

Based on our mapping and detailed lithological and bromide-chloride analysis of the tested rocks, a lithostratigraphic profile of borehole M-29 was provided (Fig. 3). Our lithostratigraphic interpretation was based on the positions of particular divisions in larger lithostratigraphic sequences.

Lithostratigraphic Member Characteristics

• **Older Halite (Na2)**. Older Halite was found in sample cuttings down to the depth of 230 m and next down to 306 m in the core. Na2 salt continues in the salt dome down to 1216 m. However, at 421 m, the borehole left the salt dome and penetrated the Lower Triassic sediments at 421-526 m. Then, the borehole entered older rock salt again. In the interval of 641-871 m, rock salt displays interbedding of K-Mg salts which are clearly marked in the bromide profile. In addition, the older rock-salt layers are located at 1,550-1,658 m. The respective member was tectonically formed. No interval showed any lithostratigraphic sedimentation borders, i.e. Basal Anhydrite (A-2) or Stinking Shale (T-2), within the floor layer; similar to Older Potassium salt (K-2), or grey Salt Silt (T-3) in the ceiling of the member. The rock salt in question is white, milk-white, grey-white, and with yellow-orange hue locally. In the interval of 1550-1568 m, salt assumes dark grey to black colours on the tectonic contact areas with the cycle PZ-3 formations. Next, the colour fluently alters to grey-white and white. The rock structure is heteroblastic, from very fine to coarse blastic and crystal locally. Halite blasts/crystals represent the diameter from 0.2 mm to several centimetres. Na2 salts usually display well-ordered, layered texture, with dark streaks of anhydrite sand laminations.

The interval and the borders of the Older Rock Salt Na2, interbedded with K-Mg salts, are clearly distinct on the bromide profile (Fig. 1). The bromine content varies from 5.9 to 87.4 mg/kg in pure rock salt Na2, while the bromide-chloride coefficient is ranging from **0.01** to **0.15**. High bromine contents occur close to the contact area between rock salt and K-Mg salt interbedding.

• **Older Potash (K2)** occurs in the 859-871 m interval. Considering the layer dip of ca. 70-80°, its actual thickness does not exceed 2-3 m. In addition, thin inserts of about a dozen of centimetres each, being rather epigenetic, were found within Older Salt (K2) at various depths. Identification of the location is not, however, certain owing to the lack of correctly arranged neighbouring lithostratigraphic members in both ceiling and floor. The rock is composed of intermittent laminae of grey-white kieserite, dark grey halite, and orange sylvine and/or carnallite. The rock's structure is heteroblastic, with well-ordered and layered textures. Actual bromine content is hard to determine in the salts in question owing to a considerable degree of core weathering and partial dissolution of bromine-bearing chlorides (sylvine and/or carnallite). Nevertheless, the salts are clearly distinct in the bromine profile due to high bromine content (from 69.4 to 148.7 mg/kg), which is higher than that of rock salt.

• **Lower Younger Halite (Na3d)** occurs in two depth intervals: 651-704 m and 1,216-1,240 m. That lithostratigraphic member is not fully developed and tectonically formed as it does not have natural lithostratigraphic contacts with the neighbouring layers. Salt Na3d creates intermittent light orange and orange-pink layers of highly pure salt and light orange salt, with the admixture of silt minerals and dispersed anhydrite sand. The rock's structure is fine and medium-sized blastic (with 1-10 mm blasts) and its layered texture is disordered or poorly ordered. The bromine content varies from 14.3 mg/kg (**0.02**) to 25.3 mg/kg (Br/Cl coefficient: **0.04**) and the content is typical for that division.

• **Younger Potash (KUpperLower Younger3)** was found at the depth of 1,248-1,262 m. That member is astratigraphic in that interval. Higher floor layers border tectonically Older Halite (Na2). Lower ceiling layers display a correct stratigraphic border with Upper Younger Halite (Na3g). Younger Potash is made up of intermittent layers of grey-white kieserite and dark grey halite, with the admixture of anhydrite and sylvine. The rock's structure is heteroblastic, from very fine (<1 mm in kieserite laminae) to medium-sized and coarse blastic (2-10 mm) in rock salt. The rock texture is well-ordered and layered. Similarly to Older Potash, it is hard to determine the actual bromine concentration in those types of salts, owing to a considerable degree of core weathering and partial removal of potassium chlorides. Nevertheless, the salts are clearly distinct in the bromine profile due to high bromine content (from 82.6 to 148.4 mg/kg), being higher than that in the neighbouring layers.

• **Upper Younger Halite (Na3g)**. The layers of ceiling younger rock salt occur in the 1262-1266 m and 1508-1550 m intervals. The Na3g salt layers are strongly reduced in thickness in the higher interval. The Na3g member has a tectonic contact with Older Rock Salt Na2 (lack of K-3 potash layers) in the lower interval. However, the same has a natural stratigraphic border with the Brown Zuber (Na3t) formations in the ceiling. That member is represented by light orange, grey-orange, and brown-red-grey salt layers, with the admixture of clay, anhydrite, and potash. The presence of potash among the upper younger rock layers is caused by both primary sedimentation and secondary tectonic maceration of those layers during the salt-dome formation. The rock's structure is fine and medium-sized blastic, with ordered laminar and layered texture. The bromine content varies from 33.7 mg/kg (Br/Cl coefficient: **0.06**) to 75.2 mg/kg (Br/Cl coefficient: **0.13**) in those salts and it is clearly higher than that in lithologically similar layers of member Na3d. High bromine concentrations are associated with the admixture of potash.

• **Anhydrite layers (A, B, and C)** occur within Upper Younger Rock Salt (Na3g). They form 3 anhydrite layers, with the thickness from several to several dozen centimetres each (up to 50 cm each), usually accompanied by thin (5-15 cm) potash layers on the ceiling side. Those were found in the M-29 borehole profile only at the depths of 1513, 1518, and 1537 m. Anhydrites under discussion are grey-white, with compact and very fine blastic (<0.5 mm blasts) structure and disordered texture. Anhydrite rocks are incrusted with halite grains.

• **Brown Zuber (Na3t)**. It creates a thinner complex at the depth of 1,458- 1,508 m, which seems to be completely developed, with a correctly arranged layer sequence. The Brown Zuber (Na3t) layer borders the Upper Younger Halite (Na3g) member in the floor and the Underlying Halite ($Na4_0$) layer in the ceiling. The ceiling border is also the border of cycles PZ3 and PZ4. In addition, Brown Zuber (Na3t) occurs in two complexes, strongly reduced in thickness, at the depths of 1266-1269 m and 1665-1668 m. The Brown Zuber member is composed of clay-salt rocks. Their main components are halite, chlorite, and illite. The proportions of those components are varying and much diverse. What is a characteristic feature of the Brown Zuber formations is the grey-green hue of the clay substance (from chlorite); rock salt shows colours from pale orange to brown-orange. The rock's structure is heteroblastic, with disordered texture. Brown Zuber is characterized by high bromine contents, from 39.2 to 87.3 mg/kg (Br/Cl ratio: **0.07-0.19**).

• **Underlying Halite ($Na4_0$)**. It occurs at the depths of 1269.5, 1457.5 m, and 1668.5 m. The stratigraphic locations of that member are correct in all intervals. The formation borders the Brown Zuber (Na3t) rocks in the floor and Pegmatite Anhydrite (A-4) in the ceiling. The layer's thickness is from several to several dozen centimetres. The rock salt is pale pink and pale orange, laminated with irregular anhydrite interbedding and smudges. The layer's structure is fine and medium-sized blastic, with ordered laminar and smudge texture. The bromine content amounts to ca. 38 mg/kg.

• **Pegmatite Anhydrite (A-4)**. It was found at the depths of 1269.5, 1456.5, and 1668.4 m. Its stratigraphic locations are correct in all intervals. It borders Underlying Halite ($Na4_0$) in the floor and the Youngest Halite (Na4) member in the ceiling. Pegmatite Anhydrite occurs in the form of an irregular layer, with the thickness from several to 60 cm. It is a grey-white or grey rock, with a very fine blastic structure (<1 mm blasts) and disordered texture. Bromine content was not examined. The occurrence of the A-4 anhydrite layer with Underlying Halite ($Na4_0$) is important for correlation reasons since it determines the borders between cyclothems PZ3 and PZ4.

• **Youngest Halite (Na-4)**. It occurs in two thick complexes in the 1269-1315 m and 1395-1457 m intervals at the depth of 1668-1686 m, where the layer thickness is tectonically reduced. In the first two repeating intervals, one can observe lithologically complete formations of that member in correct stratigraphic locations. The formation borders the Pegmatite Anhydrite (A-4) layer in the floor and the Red Zuber (Na4t) member in the ceiling. However, the layers are arranged astratigraphically in the upper and the lowest intervals. The bromine content in the Na4 member varies from 19.3 mg/kg (Br/Cl coefficient: **0.03**) to 43.8 mg/kg (Br/Cl ratio: **0.07**).

• **Red Zuber (Na-4t)**. It creates two thicker clay and salt rocks in the 1,315-1,395 m interval and from the depth of 1,686 m to the end of the borehole. The Na4t member is developed incompletely in both upper and lower intervals. The floor border in the upper interval, at the depth of 1,395 m, is stratigraphically compliant. There is a lithologically "fluent" transition from the orange rock salt of Youngest Halite (Na4) to Red Zuber (Na4t) rocks. However, there is a tectonic contact again with pink and orange salts of member Na4 in the ceiling of that interval. Layer inversion occurs in the lower section of the borehole. The layers of member Na4t and the neighbouring ones are arranged astratigraphically. At the depth of 1,686 m, there is a lithologically "fluent" transition from the orange rock salt of member Na4 to Red Zuber rocks. Farther on, the borehole penetrates younger and younger sediments of member Na4t down to the depth of 1,751 m (end of the borehole). In that interval, the Red Zuber member seems to be formed most completely, although its ceiling rocks were not drilled through (similarly to other drillings in that section of the deposit). Red Zuber is composed of clay and salt rocks in various proportions of such main components as halite, chlorite, illite, and carbonates. Halite grains/crystals are grey-white and orange turning up to red-brown. The clay substance is red-brown and/or grey. The rock represents heteroblastic structure, with mostly disordered texture, and it is well-arranged and layered locally. The bromine content in Zuber Na4t varies from 36 mg/kg to 82.8 mg/kg. Such concentrations are typical for that division and also much lower than those of the Brown Zuber rocks.

Conclusions

• The M-29 borehole was drilled to a depth of 1,751 meters. Drilled the Zechstein salt series of cyclothems PZ2, PZ3, PZ4 and complex clay-mudston-sandy rocks of Lower Triassic (T1), at the north-eastern border of the dome in the interval 421 m - 526 m.

• The lithostratigraphic profile obtained after research indicates that the borehole penetrates a deep tectonic syncline, filled with salt rocks of cyclothems PZ3 and PZ4. The syncline is limited from the ceiling by an anticline made up of the cycle PZ2 evaporites creating a thicker rock salt complex interbedded with potash. Those formations extend from the salt mirror down to the depth of 1,248 m. A less thicker "tongue" of the Na2 salt anticline, with the apparent thickness of ca. 100 m, pierces through the PZ3 and PZ4 salt layers at the depth of 1,550-1,658 m. As a result of the occurrence of those two tectonic intrusions by Older Halite (Na2) salts, the rocks of younger cyclothems PZ3 and PZ4 were extremely deformed and reduced in thickness in many sections. They are often arranged astratigraphically. Rocks more plastic, such as potash were often completely obliterated, with their epigenetic remains penetrating neighbouring layers.

• As a result of halokinetic and tectonic deformations, the salt layers became extremely folded and arranged steeply. The layer dip varies from 35° to 90°, mostly 60-80°. Frequent changes of the dip angle and multiple folding are demonstrated by the fact that the borehole often penetrates the same members.

• Many lithostratigraphic members were developed incompletely:

- Older Halite (Na2), Older Potash (K-2), and Lower Younger Halite (Na3d): lack of stratigraphically correct contacts with the neighbouring members in both floor and ceiling.
- Upper Younger Halite (Na3g): lack of stratigraphically correct contact with the neighbouring members in the floor.
- Red Zuber (Na4t): lack of ceiling layers.

• In contrast to the central and north-western part of the deposit (Wachowiak et al., 2012), in the southern part, including in the region of M-29 borehole, there are no floor rocks of cyclothem PZ-3 occur in the profile: Gray Pelite (T-3), Platy Dolomite (Ca-3), or Main Anhydrite (A-3). Since those rocks were rigid, they were probably torn apart by the uplifting salt Na2 anticlines and they presently lay at deeper sections of the salt dome.

• No older evaporites than Older Halite (Na2) were identified in the profile.

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