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Arch. Min. Sci. **65** (2020), 2, 363-398

Electronic version (in color) of this paper is available: http://mining.archives.pl

DOI 10.24425/ams.2020.133198

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INSIGHT INTO A SHAPE OF SALT STORAGE CAVERNS

Salt caverns are used for over 70 years to store power sources and dispose of industrial wastes. The design of cavern shape and dimensions is still considered as a difficult engineering problem despite progress in geotechnical, construction and exploration methods. The rational design of cavern depends on mechanical parameters of rock salt and nonsalt rocks, stability conditions, safety requirements and stored material. However, most of these factors are related to geological factors like depth of cavern location, the geological structure of salt deposit, lithology of interlayers, petrology and mineralogy of rock salt and interlayers. The significant diversity in the geological conditions of different rock salt deposits contributed to the variety in shape and dimensions of salt caverns worldwide.

In this paper, the examples of caverns developed in various salt deposits are presented. The shape of these caverns and its relation to geological features is presented. The influence of geological factors on the formation of irregularities in a cavern shape is described. Moreover, the evaluation of storage caverns located in Polish salt deposits in a view of the aforementioned geological factors is performed. The information and analysis described in this paper provide input which can be useful in future plans connected with the development of underground storage in Poland.

Keywords: underground storage in rock salt deposit, geological features, shape of salt caverns, irregularities

1. Introduction

Salt caverns are used to store power sources, such as natural gas, LPG (liquid petroleum gas), oil, compressed air and hydrogen as well as dispose of industrial wastes and were considered for disposal of nuclear wastes. The underground storage in a salt cavern is a technology which has been used for over 70 years. Moreover, salt caverns are still an important source of brine and salt production.

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Canada is a pioneer in underground storage in salt caverns. The liquid hydrocarbons were stored in salt caverns at early World War II. In 1949,, underground storage facility for LPG was built in Texas (USA). Next, England stored the crude oil in salt caverns in the mid-1950s. A few years later in the early 1960s (Warren, 2006; Yang et al., 2015; Plaat, 2009), salt caverns were used for natural gas storage in Saskatchewan (Canada) and Michigan (USA). In Europe, gas storage began in the 1970s and the first underground stores in salt caverns were built in Kiel (Germany) and Etzel (France). Currently, the USA is a world leader in underground storage of oil and gas e.g. in Kansas there are 9 active storage facilities with 368 active storage wells and caverns (Kansas Department of Health and Environment, 2019). The largest number of storage caverns for oil and gas in Europe is located in Germany, according to SMRI (Solution Mining Research Institute) about 360 (Horváth et al., 2018). The underground storage in Poland has been developing and currently operates 22 caverns for gas and 12 for crude oil, petrol and fuel oil (Horvath et al., 2018; Zawisza, 2013; Król & Kuśnierz, 2019).

The first two caverns for compressed air energy storage (CAES) worldwide were commissioned in 1978 in Huntorf (Germany). In the 1980s the second compressed air cavern field was constructed in Alabama (USA). Another compressed air storage facility is planned in Larne (UK) and Texas (USA). The hydrogen storage caverns have been constructed in recent years in Saltholme (UK) and Texas (USA). Moreover, in Saltholme the same cavern field operates the cavern for nitrogen. Another nitrogen caverns are located in the Heiligerlee (Netherlands) and Wilton (UK) (Horváth et al., 2018).

The alkali wastes from local soda production were disposed in salt caverns since 1959 in England. The same method was used in the Netherlands and Mexico (Warren, 2006). The disposal of wastes from oilfields is widely utilised in the USA and Canada, e.g. in Alberta (Kukiałka, 2014, 2015, 2017) there are over 100 this kind of caverns (Horváth et al., 2018). Salt caverns were considered for radioactive waste disposal. However, it is a very complex issue because of long-term stability problems and high toxicity of wastes (Warren, 2006).

In comparison to other rocks, rock salt is distinguished by low permeability, specific mechanical properties, high solubility in water and a rather common occurrence (Lux, 2009; Warren, 2006). The progressive improvement in cavern design is related to continuous development in geotechnical assessment and exploration techniques, laboratory testing, numerical modelling, technical construction and practical experience (Lux, 2009). Engineering experience shows that rational design of salt cavern shape and dimensions improves safety and reduces negative effects. However, a design of salt cavern shape and dimensions is considered as a difficult engineering problem because it is influenced by many factors (Wang et al., 2013). These factors are related to mechanical parameters of salt and nonsalt rocks, safety requirements, geological and mining conditions and substance which is planned for storage or disposal.

Numerical modelling techniques are a powerful tool to design and simulate a cavern shape and predict the stability in the given geological and mining conditions. Moreover, numerical modelling and geomechanical testing are constantly improved, however, they are based on simplifying assumptions imposed by computational limitations, geometric simplifications and limited sampling. These techniques should be integrated with the geologic model and evaluation of geologic risk and their impact on cavern operations and integrity (Looff, 2017). From these reasons, a determination of the final cavern shape is a difficult problem and associated with the following factors: leaching method, depth of cavern location, the geological structure of salt deposit, lithology of interlayers, petrology and mineralogy of rock salt and interlayers. All these factors contributed to the significant diversity in the shape and dimensions of salt caverns located in various rock salt deposits all over the world. The shape of the salt cavern at the designing stage is idealised and projected by geometric solids, consequently, it rarely complies with a real shape resulted from leaching process (Cyran et al., 2018). In the case of salt caverns created for brine production from outgoing brine, the design criteria, including their shape, may not necessarily comply with requirement applied to storage caverns. However, these days controlled leaching is applied to production caverns and these caverns are converted to storage (Warren, 2006).

In this paper, firstly, the overview of requirements need to be fulfilled by salt cavern are presented. These requirements are limited by geological conditions as well as stored material. Geological factors influencing the cavern design and construction are described, and examples of cavern shapes based on available literature are presented. Secondly, an assessment of cavern shape concerning factors that contributed to formation of irregularities is performed with an emphasis on Polish salt deposits.

2. Salt caverns suitability for storage

Many requirements need to be fulfilled to make salt cavern suitable for storage. There are sufficient size/volume, short and long term stability, safety containment of the stored material (Plaat, 2009). Salt caverns used for natural gas storage can be also suitable for compressed air and hydrogen storage purposes (Ozarslan, 2012). The geometrical assumptions for salt cavern (shape, dimensions, volume) should be achieved in the solution mining process. All of them are designed with consideration of substance intended to be stored in the given geological and mining conditions. These conditions include the type of salt deposit (domal or bedded), depth of cavern location, the internal geological structure of salt deposit, lithology and mineralogy of salt and non-salt rocks. A wide diversity of listed factors results in the development of irregularities in a cavern shape that can affect cavern volume and stability.

2.1. Leaching methods

There are two basic leaching methods for developing and shaping the salt cavern (Fig. 1), namely direct and indirect (reverse) leaching (circulation). In the direct method, freshwater or unsaturated brine is pumped into the cavern through the inner leaching string (Fig. 1a). The freshwater flows (due to its lower density in comparison to the brine) and. The saturated brine is ejected to the surface through the annular space between the inner and outer leaching strings. In the indirect leaching method, the freshwater is pumped into the upper part of the cavern through the annular space between the inner and outer leaching strings. Then, while its concentration increases during leaching, it flows down to the bottom and is pumped out through the inner leaching string (Fig. 1b). The saturated brine is withdrawn through the inner leaching string (Warren, 2006; Kunstman et al., 2007; Ozarslan, 2012). The cavern shape with an enlarged top is likely to be formed as a result of reverse leaching. By direct leaching, more cylindrical caverns are formed. A protective blanket is used to limit leaching in a roof of the cavern. The blanket is a substance lighter than freshwater or unsaturated brine and does not dissolve the salt (Kunstman et al., 2007, 2009; Ozarslan, 2012).

Generally, a combination of both methods is applied during the leaching. A shape of the cavern is controlled by changing the depth of leaching strings, the depth of blanket and the rate and direction of circulation (Plaat, 2009). The salt caverns built for storage purposes are shaped

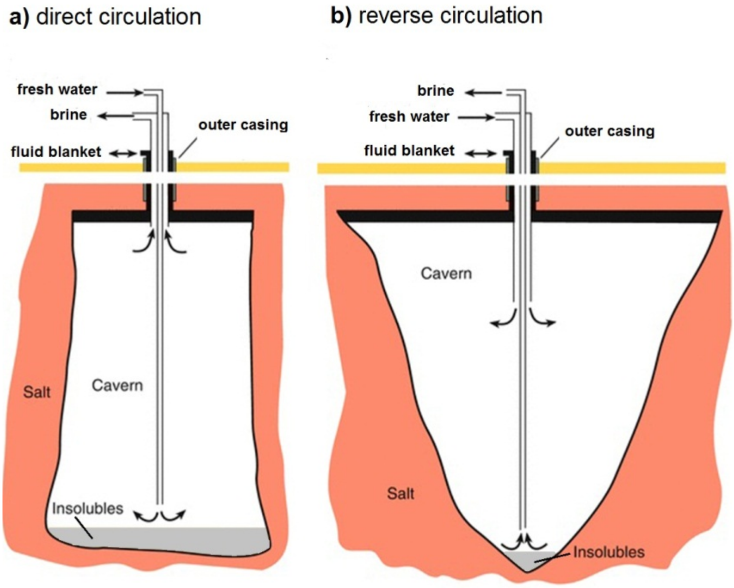

Fig. 1. Reverse and direct leaching of salt cavern (Warren, 2006)

by controlled solution mining techniques. However, a shape of caverns for brine production was rarely controlled, from this reason their conversion to storage purposes can be difficult.

2.2. Type of salt deposit

According to SMRI report (Gillhaus & Horvath, 2008), 286 cavern fields are located in bedded salt deposits and 145 in domal salt deposits worldwide. Most of the cavern fields for storage of LPG and crude oil are located in salt domes. They are the preferred location as the salt mass is large and homogenous what makes it easier to design cavern shape and volume (Warren, 2006). The best-known salt domes used for storage purpose are located in the Gulf Coast (USA) and north-western Europe. A planar shape of the salt dome is circular and elliptical, with horizontal dimensions in a range of few hundred meters to even 10 km. In vertical cross-section, the salt domes have a form of a plug, column, bulb, mushroom and vertical dimensions ranging from a few to 10 km (Nettleton, 1987). The thickness of salt beds in the salt domes ranges up to 800 m (Warren, 2006). Generally, in the USA operate 99 cavern fields with over 600 caverns built-in 48 salt domes. In Europe, Germany implemented 27 cavern fields with 150 caverns located in 14 salt domes (Gillhaus & Horvath, 2008).

The preferred cavern shape in the salt domes is a vertical cylinder several hundred meters high with a diameter of some 50-80 m (Fig. 2). Such caverns have a volume of 300 000 m^3 to even 700 000 m^3 (Plaat, 2009). The United States Strategic Petroleum Reserve include over 300 caverns located in salt domes (Fig. 2) in Texas and Louisiana (Sobolik & Ehgartner, 2006). In Germany, about 100 caverns for crude oil and petroleum products are located in salt domes. Two caverns for compressed air with a total volume of 310 000 m^3 (Fig. 3) are located in the same salt dome (Horváth et al., 2018). Another one was built in MacIntosh salt dome (Alabama, USA, Fig. 4).

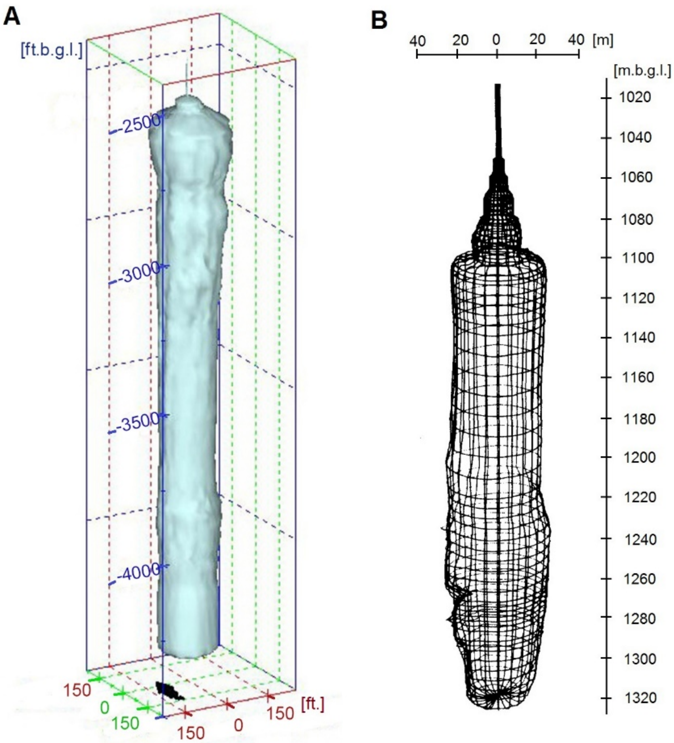

Fig. 2. Examples of caverns for oil and gas storage: A – Barbers Hill salt dome (Mont Belvieu) USA, crude oil, Texas (Cartwright & Ratigan, 2005), ft. – feet, 1 m = 3.281 feet; B – Petersen salt dome (Tastrup, Denmark) cavern for gas TO-9 (Petersen, 1986)

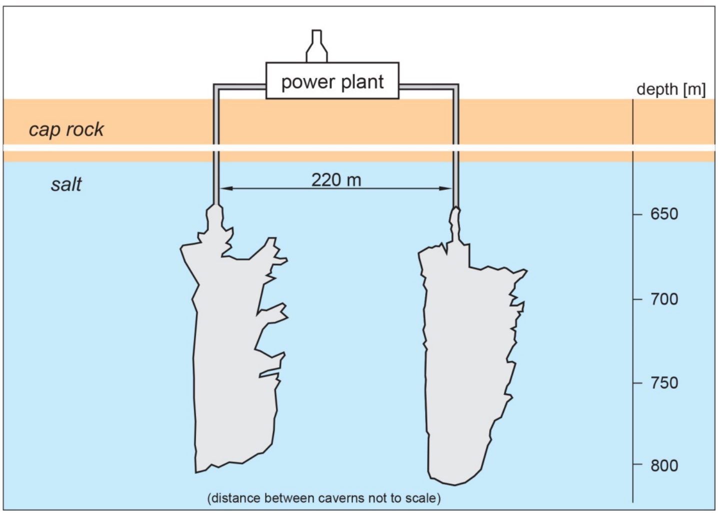

Fig. 3. Caverns NK I and NK II in CAES plant in Huntorf, Germany (Gillhaus & Horvath, 2008)

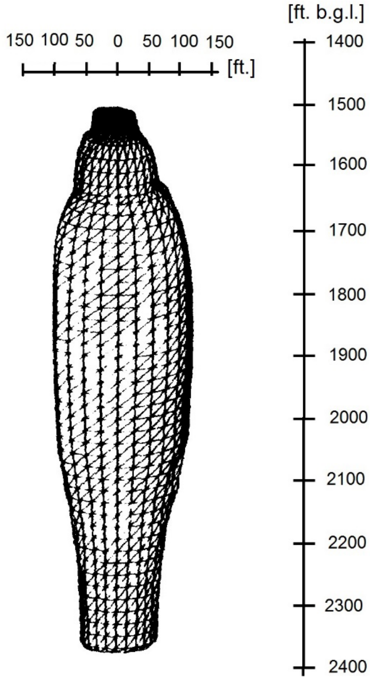

Fig. 4. Compressed air storage cavern in McIntosh salt dome (Mehti, 1991), ft. – feet, 1 m = 3.281 feet

Bedded salt deposits tend to be less vertically homogenous and consists of thinner (100-300 m) salt beds with interbeds of mudstone, sandstone, limestone, dolomite and anhydrite. Due to the limited thickness of salt beds, the geometry and volume of caverns can be maximized by a larger diameter to height ratio. Caverns in bedded salt deposit usually have volume in a range of 100 000 to 300 000 m^3 (Plaat, 2009). Caverns for natural gas storage were constructed in thin-bedded salts in the UK (Cheshire salt basin – NW England). The salt beds of Norwich halite formation are up to 250 m thick, including several layers of mudstone. The caverns have diameters between 80 and 100 m and heights between 60 and 80 m (Horváth et al., 2018). Another example is Chinese Jintan salt formation, in which underground gas store was built (Fig. 5). It is characterised by the thickness from 70 to 230 m and contains two interlayers of mudstones (Yang et al., 2015). Caverns for oil and gas storage constructed in multilayered bedded salt are built in Texas/Kansas (Hutchinson Salt). The salt beds of max. thickness of 160 m is interstratified with shale, gypsum and anhydrite. Bedded salt deposits in Alberta and Saskatchewan (Canada) in the Lotsberg salt formation and Prairie Evaporite formation are used to locate oilfield wastes like untreatable oil, oily sand, slops (Fig. 6), emulsions and other wastes that are created from upstream petroleum production. The Lotsberg salt formation reaches the thickness of 220 m with shale interbeds (Duyvestyn et al., 1998, Kukiałka, 2014; 2015). Another Prairie Evaporite formation is 180 m thick and contains interlayers of anhydrite, shale and carnallite (Reed & Green, 2012). However, the salt layers in bedded salt deposits can be extremely thick. As the example, in Etrez (France) caverns for gas are located in a bedded salt deposit where salt thickness reaches up to 1000 m (Horváth et al., 2018).

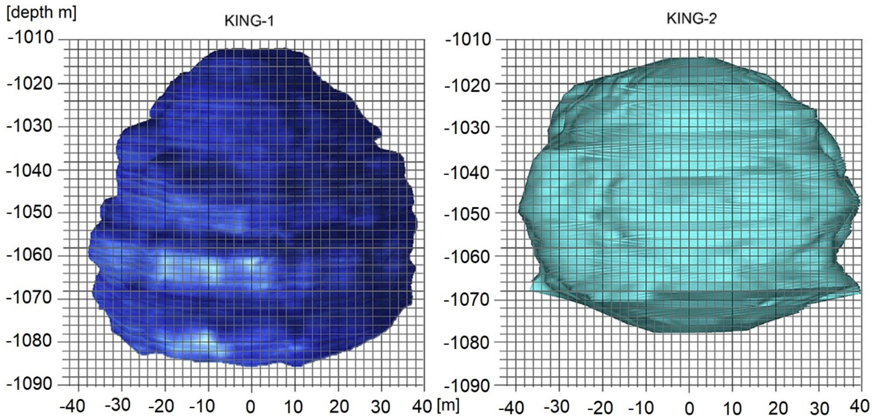

Fig. 5. Gas storage caverns in Jintan salt formation, China (Yang et al., 2016)

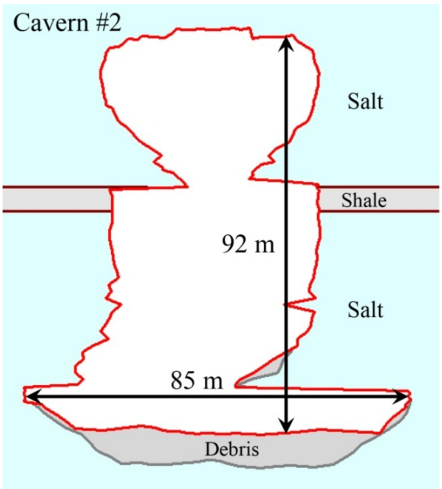

Fig. 6. Salt cavern for wastes from upstream petroleum production, Foster Creek facility near Cold Lake, Alberta, Prairie Evaporite formation (Reed & Green, 2012)

2.3. Depth of salt caverns location

The target depth for salt caverns location is between 400 to 500 m and depending on geological and mining conditions down to 2000 m (Fig. 7). The greater depth is related to ongoing salt creep and salt cavern size reduction (Warren, 2006). The depth of the cavern location is similar for both domal and bedded salt deposits.

Caverns for crude oil and natural gas or LPG in domal salt deposits are located at the depth from 600 to 1600 m (Lux, 2009). The depth range in bedded salt deposits is wider and include two intervals from 200 to 600 m and from 1000 to 1600 m. However, there are storage caverns built at the depth about 1800-2000 m.

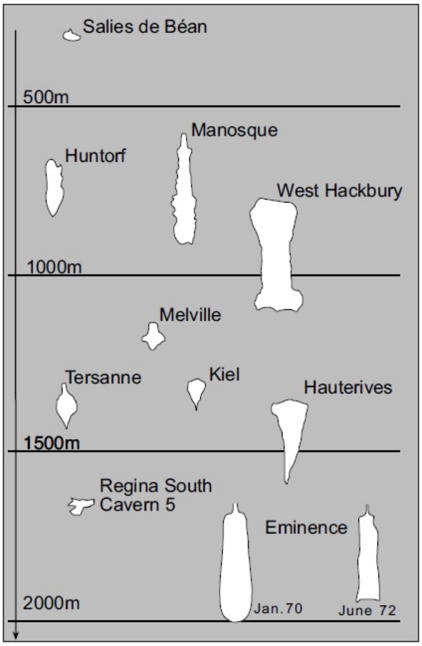

Fig. 7. Depth of various salt caverns (Warren, 2006; Berest et al., 2001)

In Etzel salt dome 75 caverns for oil and gas (Fig. 8) in volume between 250 000-700 000 m^3 were located at the depth of about 900-1200 m (Schweinsberg, 2012; Wiehl et al., 2006). The deepest storage field for natural gas storage was constructed in Hornsea/Atwick (UK) at the depth

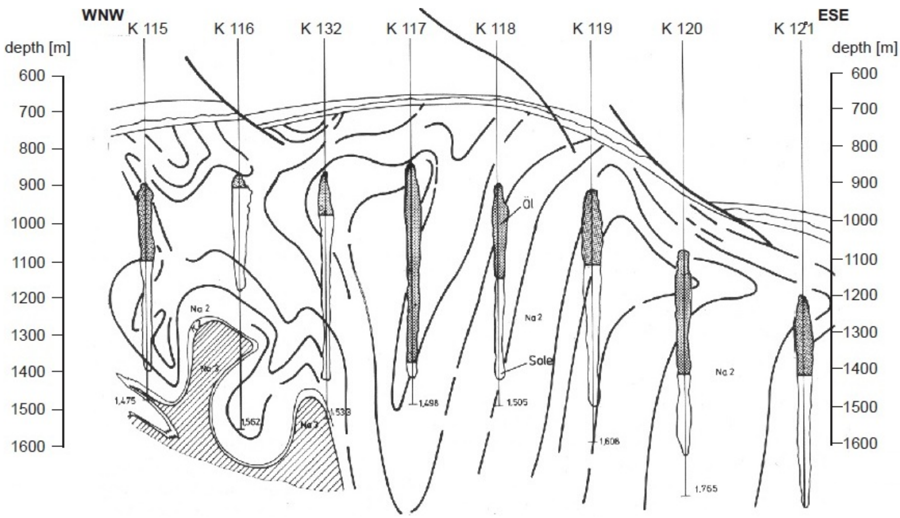

Fig. 8. Cross section through Etzel salt dome with caverns (Hentschel 1984; Gillhause & Horvath, 2008)

of 1,730 and 1,830 m below the ground and Hornsea/Aldbrough at the depth of 1800-1900 m in the bedded salt deposit (Evans & Holway, 2009; Beutel & Black, 2005). In Lesum salt dome operate 3 caverns for gas at depths between 1315 and 1780 m, their average volume is 600 000 m^3. Most of the storage caverns in Etrez (bedded salt deposit in France) are constructed in the salt unit which extends from a depth of 1200 m to over 1800 m (Fig. 9). At the largest cavern field for oil and gas in Epe (Germany) the storage caverns are located at the depth between 1000-1500 m (Fig. 10) in Zechstein Werra salt beds (Gillhaus et al., 2006). A high depth of caverns location is characterised for waste disposal in Canada. The Lotsberg salt formation at the depth of 1900 m and Prairie evaporates (1000-1600 m) caverns for wastes are operating (Fig. 11).

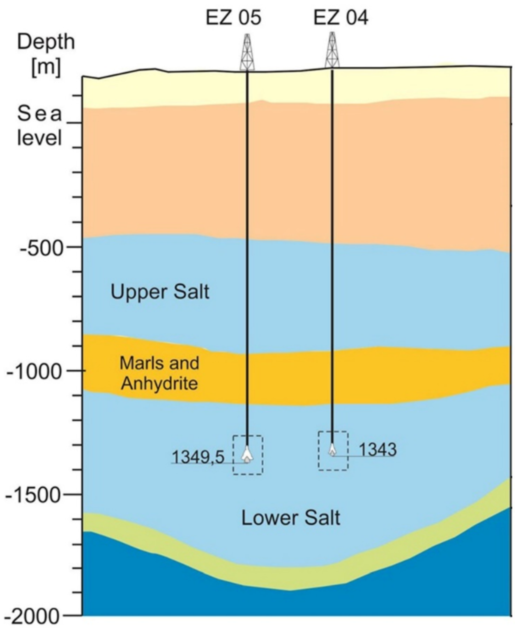

Fig. 9. Cross section through Etrez cavern field (Lasneret & Vernet, 1978; Horváth et al., 2018)

Caverns for nitrogen are located at various depths. In UK (Saltholme and Wilton) they operate at an average depth of 650 m. At the Heiligerlee brine field in Winschoten salt dome (Netherlands) a nitrogen cavern is located at the depth between 1000 and 1500 m. Compressed air energy storage (CAES) in Neuenhuntorf salt dome took place at the depth of about 650 m. In McIntosh salt dome (Alabama) the cavern for compressed air was located at the depth of about 450 m. In addition, caverns for hydrogen operate in Saltholme (UK) and in Texas (USA) at the depth of 950 m (Bergström et al., 2011).

2.4. Internal geological structure of salt deposit

The internal structure of salt deposits was studied for salt-mining or storage-related purposes. From this reason it was described based on observations from mine galleries and borehole data

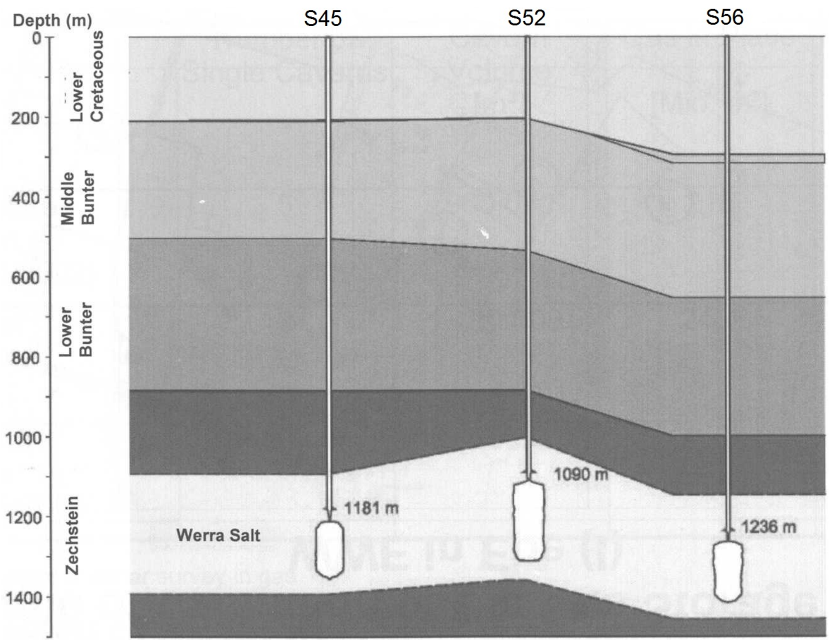

Fig. 10. Cross-section through Epe cavern field (Gillhause et al., 2006)

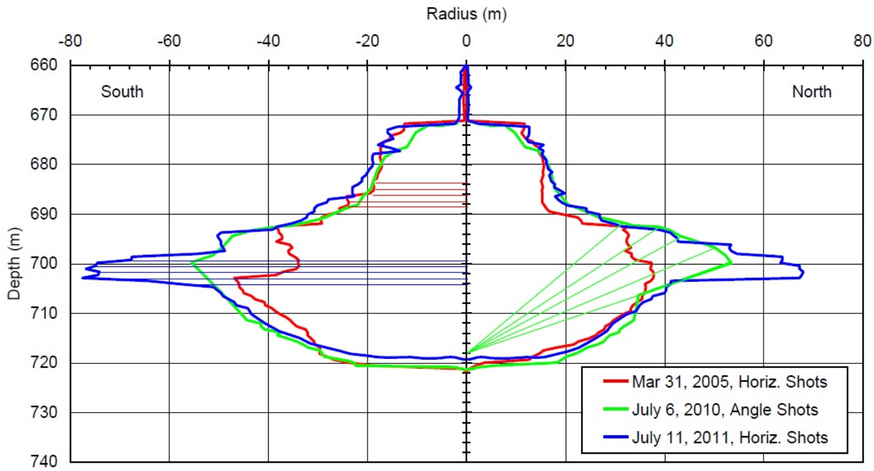

Fig. 11. Vertical cross-section of cavern 907A, Fort Saskatchewan, Alberta
(Cicchini, 2004, Gillhause et al., 2006)

(Richter-Bernburg, 1980; Jackson et al., 1995; Richter-Bernburg, 1987; Smith, 1996; Behlau & Mingerzahn, 2001; Schléder et al., 2007, 2008; Talbot & Jackson, 1987; Zirngast, 1996; Burliga, 1996; Smith, 1996). These studies showed the extremely complex internal geometry of salt bodies. However, detailed observations in salt mines workings and drilling cores revealed a variety of deformation structures on a wide range of scales (Gent et al., 2011). These deformations have an impact to salt cavern design, location within the salt deposit, leaching process, real cavern shape and volume.

The internal structure of salt domes is usually more complex than bedded salt deposits as a result of halokinetic movements. The salt mass in the salt dome is built of the whole sequence of salt series strata (Jeremic, 1994). The internal tectonics features in salt domes were described in details based on the Zechstein salt formation (Burliga, 1996; Behlau & Mingerzahn, 2001). The most typical are described below.

The salt beds in the salt domes underwent intense and steep folding with a very high wave amplitude, e.g. Richter-Bernburg (1980) described several examples of fold structures with amplitudes over half the height of the salt structures (Hofrichter, 1968; Muehlberger, 1968, Gent et al., 2011; Jeremic, 1994). Contrasting mechanical behaviour of salt layers to the barren rocks as anhydrite, dolomites, sandstone and shales resulted in the formation of boudins, shear zones and breccia. The anticlines cores are built of older salts piercing upward across the overlying younger sediments. Moreover, rock salt layers are often thinned in the anticline limbs. At the same time, the intercalating barren rocks are torn out, squeezed and pinched out. The edge of salt domes is a problematic area for cavern location. In these areas salt layers can be a complex melange with large blocks of salt detached from the main mass and blocks of barren rocks. The shear zones are met close to the edge of salt domes but their occurrence is not limited to the salt dome edges (Fig. 12). These zones occur also between differentially moving salt spines where the salt experiences increased shear stress due to differential salt movement (Looff, 2017; Looff et al., 2010a, 2010b). In the zones associated with the edge of the salt dome, the rock salt or barren rocks like shales and sandstones might be incorporated by shearing as slices (Jeremic, 1994). Moreover, an occurrence of anomalous salt is associated with shear zones (Kupfer, 1980; 1990, 1998). As described by Kupfer (1980, 1990) an anomalous salt is a rock salt that deviates from what was considered typical domal salt. Anomalous salt can be defined upon the basis of impurity content, structure, colour, or other features e.g. unusual colour, very coarse-grained, poikiloblastic or fri-

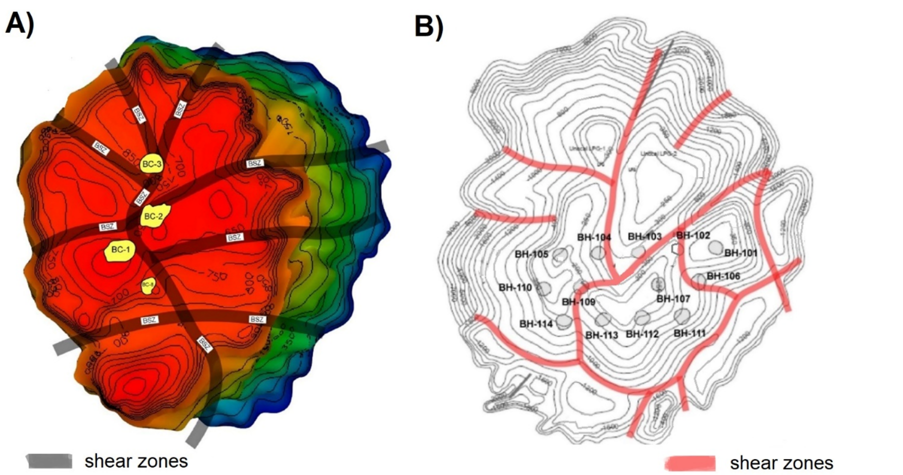

Fig. 12. Boundary shear zones in salt domes: A – Bayou Choctaw Dome, Louisiana; B – Big Hill Dome, Texas (Looff, 2017 modified)

able salt. These fabrics are associated with physical and mechanical properties like high creep rate, strength, or dissolution characteristics (Looff, 2017; Looff et al., 2010a, 2010b). The occurrence of anomalous salt and shear zones have a negative impact on salt caverns development and operation, e.g. anomalies in a cavern shape (Fig. 13), string damage (Fig. 14), preferred planes of dissolution (Fig. 15). This kind of deformations and anomalous salt was described in details for salt domes in the USA (Looff, 2017; Looff et al., 2010a, 2010b).

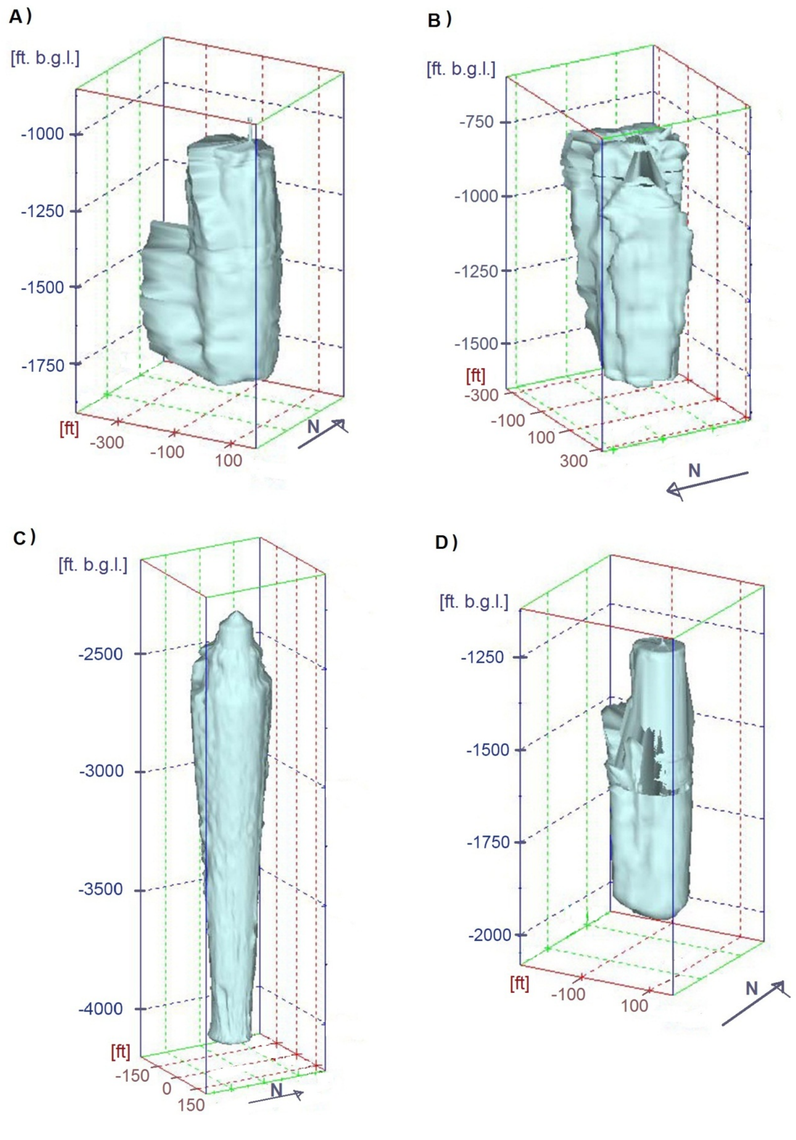

Fig. 13. Anomalous cavern shape related to shear zones: A – Bayou Choctaw Dome, Louisiana, cavern BC-1, B – Bayou Choctaw Dome, Louisiana, cavern BC-2, C – Big Hill Dome, Texas, cavern BH-106, D – Bayou Choctaw Dome, Louisiana, cavern BC-8 (Rautman & Lord, 2007 a, b), ft. – feet, 1 m = 3.281 feet

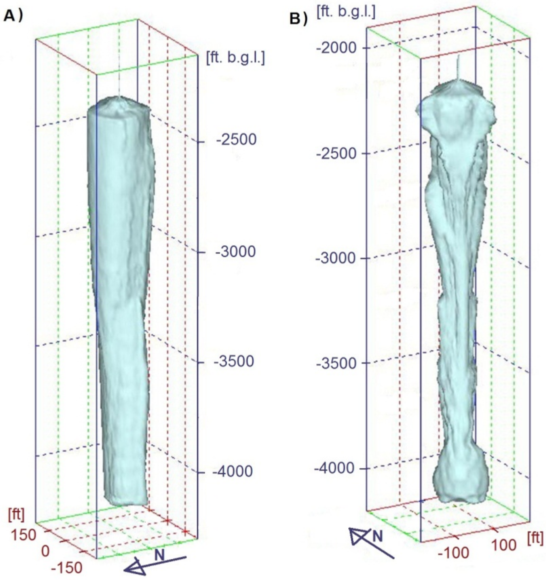

Fig. 14. Caverns where string damage was registered, located in shear zones: A – Big Hill Dome, Texas, USA, cavern BH-114; B – Bryan Mount Done, Texas, cavern BM-114 (Rautman & Lord, 2007 b, c), ft. – feet, 1 m = 3.281 feet

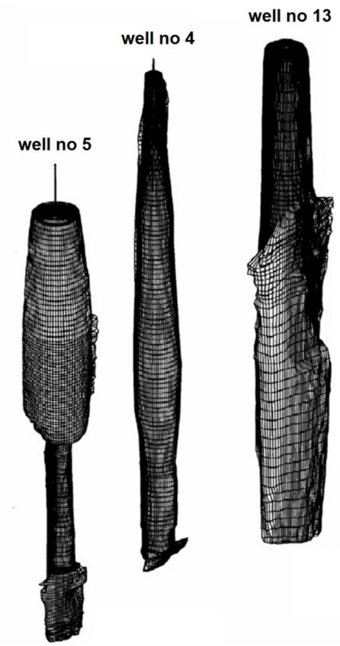

Fig. 15. The plane of preferred dissolution that intersects the caverns, Barbers Hill salt dome Louisiana, Enterprise East facility (Cartwright & Ratigan, 2005)

The internal structure of bedded salt deposits may be affected by sedimentary and tectonic processes. The complex internal structure of bedded salt deposit can be described based on a flexural form resulted from intensive tectonic movement or salt beds that occur as a lens or fingering shape. A fingering shape is formed due to salt beds pinch-out which is controlled by the evaporation process and sedimentation mechanism of the basin (regressive and transgressive phases) and this shape is associated with the periphery of salt deposits. The complex flexural form represents a large salt body, sometimes with multi-salt facies (Jeremic, 1994). The Carpathian province in Poland contains salt deposits with a complex flexural morphology. The salt beds were intensively folded, thrusted and compacted over a short distance (Poborski & Skoczylas-Ciszewska, 1963; Garlicki A, 1979). The internal structure of these deposits is complex and similar structural features like in salt domes are met. Folds of rock salt beds are irregular with asymmetric limbs and high amplitude. A thickening of the salt in the fold bends is observed. The lithostratigraphic sequence of a layer is disturbed. Folding is less intensive in salt beds with an admixture of barren material and intercalations. The reverse faulting and breccia associated with shearing are met. Rock salt piercing through discontinuities in the claystone, sandstone and anhydrite interlayers. Moreover, blocks of barren rocks in a size from several cms to meters are met within the salt beds (Cyran, 2008).

2.5. Lithology and mineralogy

Evaporite deposits are composed dominantly of a various proportions of halite, anhydrite, gypsum, K-Mg minerals and other minerals. Rock salt strata consist predominantly of halite with the admixture of other minerals. The following minerals occur as an admixture in rock salt beds: anhydrite, gypsum, carnallite, kainite, langbeinite, bischofite, polyhalite, sylvite, kieserite, clay minerals, quartz ect. Rock salt encompasses fundamental textural properties of sedimentary rocks like grain size, shape and fabric (packing and orientation). It is characterized by thin bedding and lamination and lateral continuity of beds and laminae (Boggs & Boggs, 2009). For instance, the layering in salt beds consists of darker anhydrite-rich bonds separating the purer salt. Other minerals like anhydrite, silts or clays can be mixed with halite and dispersed inside the halite grains or enclosing the halite grains. Non-salt layers composed of mudstone, claystone, sandstone, dolomite, anhydrite, shale, calcareous sandstones and K-Mg salts may interbed with the salt beds. The thickness of non-salt layers and their quantity within the salt beds vary in different salt deposits. Moreover, salt beds may contain the different size of non-salt clasts distributed irregularly or forming the breccia (Warren, 2006; Jeremic, 1994).

The geomechanical properties of the salt layers vary greatly because of the mineralogical composition, petrological features, diagenetic and tectonic history (Zhang et al., 2014). The leaching process is related to a content of insoluble minerals like anhydrite and dolomite in rock salt or more soluble like carnallite or bischofite (Warren, 2006). Thus, a detailed recognition of salt beds petrology is crucial in planning a leaching process, cavern shape and stability analysis.

Cavern shape irregularities result from the occurrence of less or more soluble layers intersecting cavern edge. With less soluble interlayers within salt beds is a tendency to form ledges, bevels and “waists” or “necks”. The interlayers of silt mudstone, silt sandstone and argillaceous (Fig. 16) are frequent in Jintan salt formation in China (Li et al., 2018. Wei et al., 2016). The claystone interlayers characterized by various thickness in the rock salt profile (Fig. 17) are known from Northwick Halite Formation in UK (Charnavel et al., 2015). The occurrence of interbed consists of shale and anhydrite layers (Fig. 18) is met in Prairie Evaporite formation in

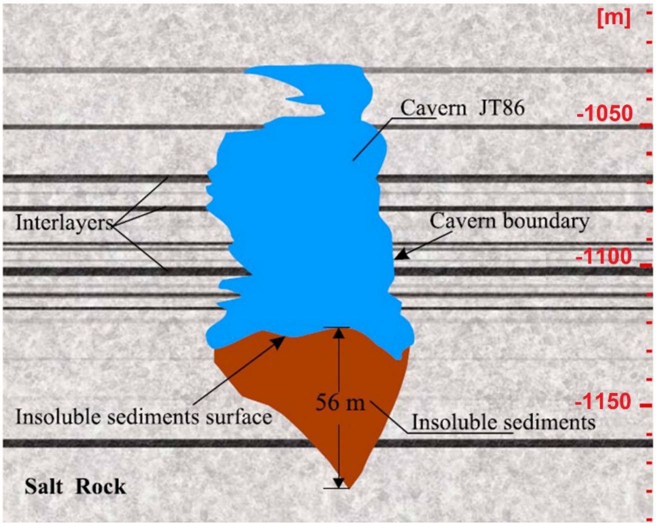

Fig. 16. Insoluble interlayers of cavern JT86, Jintan UGS in Jiangsu province, China (Li et al., 2018)

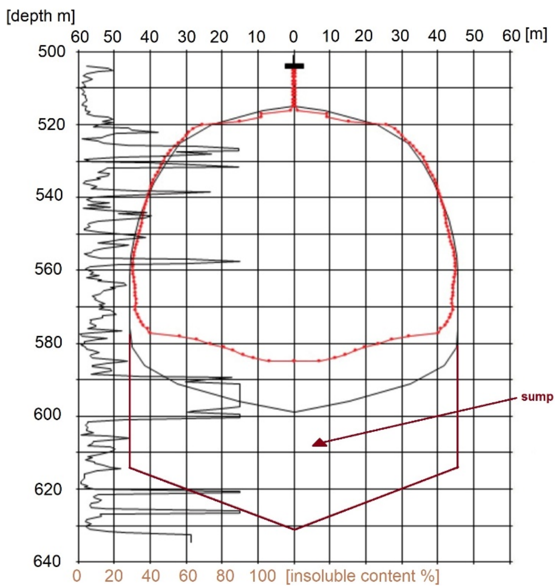

Fig. 17. Insoluble content in profile of cavern H315 in Cheshire, UK (Charnavel et al., 2015)

Canada (Reed & Green, 2012). The broken interlayers may collapse and fall on the floor of the expanding cavern, consequently a cavern bottom raises and decrease its volume (Li et al., 2017; Charnavel & Lubin, 2002). Otherwise, faster leaching of more soluble beds may lead to cavern enlargement in one direction. Rapid solution of these interlayers can leave behind blocks of less soluble halite, which are likely to collapse (Warren, 2006). Moreover, impurities throughout the salt beds can occur in the form of laminas or dispersed inside of salt grains. The variable distribution of impurities (mainly clays, sand and anhydrite) throughout the salt beds (impurity content 3.29-5.78%) and their impact on cavern shape (Fig. 19) is known from Bryan Mound salt dome, Texas, USA (Munson, 2008; Looff, 2017).

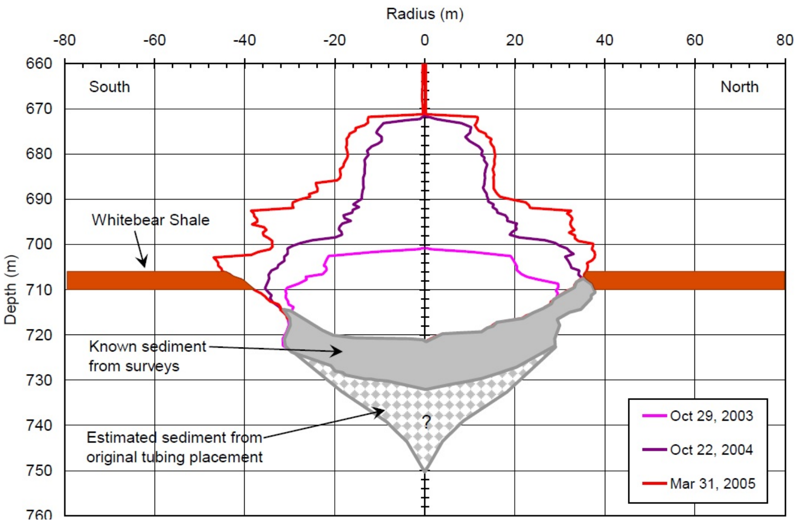

Fig. 18. Layer of insoluble shale and anhydrite in Cavern #1, Foster Creek facility near Cold Lake, Alberta, Canada (Reed & Green, 2012)

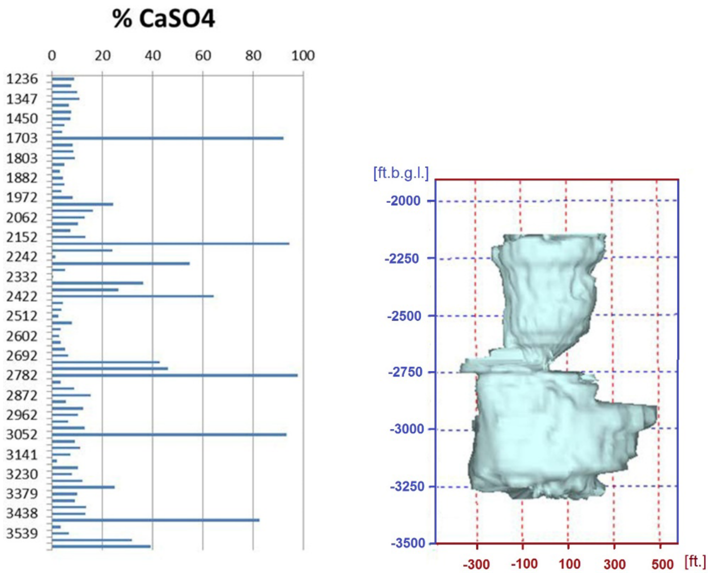

Fig. 19. Impact of anhydrite content on a shape of BH-5 cavern, Bryan Mound salt dome, Texas, USA (Hansen et al., 2016), ft. – feet, 1 m = 3.281 feet

Not only the composition but also internal fabric of salt beds can influence a cavern shape, development, and long term operation and integrity of storage cavern (Loof et al., 2010b). The term fabric refers to all components that feature a rock salt both primarily related to sedimentation process and originated as a result of deformation or recrystallization. Such fabric includes textural items like size, shape and arrangement of grains, structure, preferred orientation. The character of salt fabric can vary significantly within a salt deposit, cavern field and even within a single well. However, it is unclear how and what extend variations in salt fabric actually impact cavern development and operation (Loof et al., 2010a; Loof, 2017).

As an example of these fabrics, the occurrence of very coarse-grained halite in Big Hill salt dome can be mentioned. This halite contributes to a high creep rate (Fig. 20), moreover this part of the salt dome is associated with the shear zone. In addition, an occurrence of anomalous salt is associated with shear zones (Kupfer, 1990, 1998). This kind of salt can be defined by impurity content, structure, colour and fabrics e.g. internal flow banding, better solubility, grains elongation in one direction.

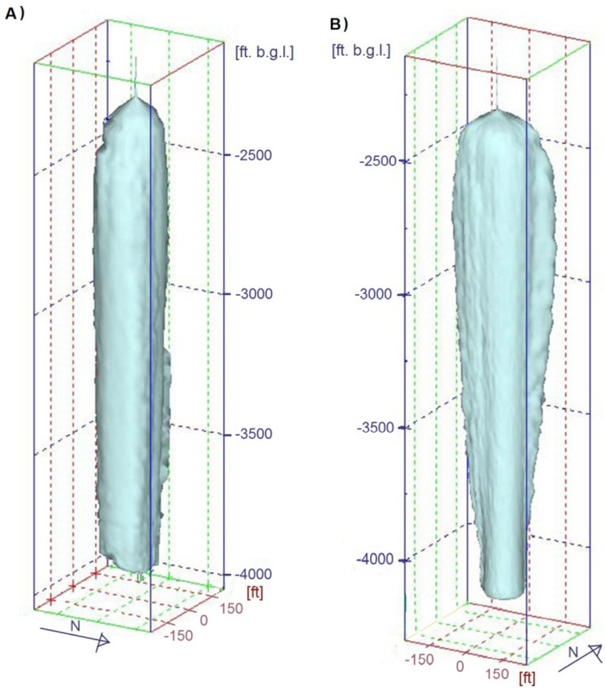

Fig. 20. Caverns located in very coarse grained halite beds, Big Hill Dome, Texas, USA (Rautman & Lord, 2007b): A – cavern BH-103, B – cavern BH-108, ft. – feet, 1 m = 3.281 feet

3. Cavern shape in relation to geological factors

Geological factors described in the foregoing sections have an impact on the formation of irregularities in a cavern shape. A detailed description of the irregularities and their connection with the internal structure of salt deposits, lithology and mineralogy of salt layers and non-salt interlayers as well as internal fabrics of salt beds in Polish salt deposits is presented in this section. Storage caverns selected for this analysis are located in Góra salt dome (central Poland) and in Mechelinki salt deposit (Northern Poland). In both salt deposits, underground storage facilities are operating. In Góra salt dome the oil and fuel is stored but in Mechelinki salt deposit, the underground storage of natural gas has been performed. Moreover, some factors that have an impact on cavern shape are described on the example of exploitation caverns from Mogilno salt dome. In Mogilno salt dome the underground store for natural gas is operating, however, the operator refused access to storage caverns data. All salt deposits belong to Zechstein salt series which comprise the area of central and north-western Poland and is a part of Zechstein basin extends in Western and Central Europe (Peryt, 1987).

3.1. Geology, lithology and internal structure of salt deposits selected for analysis

3.1.1. Góra salt dome

The solution mining and salt production in Góra salt dome is carried out since the 1960s. In 2002 twelve exploitation caverns were converted to the storage of oil and fuel. The salt dome raised from the depth of about 6 km in a dislocation zone and pierced through Mesozoic and partially Cenozoic sediments. It is in a shape of column extended in the lower part with almost vertical walls and probably inclined towards N. In horizontal cross-section the salt dome is an ellipse elongated in NW-SE direction with the dimensions of 1000 m and 900 m (Fig. 21). The salt mirror occurs at the depth of 101-110 m below surface and salt beds belong to Zechstein cyclothems from PZ2 to PZ4. Generally, the thickness of the salt sequence reaches about 1000 m, but rock salt layers range from about 30-300 m. The salt beds are homogenous and average NaCl content ranges from 96 to 97%. The salt dome is covered by the caprock of thickness from 34 to 116 m. It is overlaid by Pleistocene and Holocene silts, sands and mads of thickness 30-100 m (Czapowski et al., 2009 a i b).

The internal structure of Góra salt dome was recognized on a basis of drilling cores till the depth of 1750 m. Generally, the evaporate beds were strongly folded and characterized by steep, even vertical dip as a result of halokinetic and halotectonic processes. The Older Halite (Na2) with intercalations of the Older Potash (K2) and Transition Beds (Na2K + K2) dominate in the upper, middle and southern part of the dome (Fig. 20). The coarse-grained halite is characteristic for the southern part of the dome. The northern and north-west area of the dome built evaporates of PZ3 and PZ4 cyclothems, folded together with PZ2 sediments. The Older Halite probably pierced through the younger sediments of PZ3 and PZ4 and pushed them towards the N, NE and NW (Biernat & Wichowska, 2011; Wichowska, 2019). The blocks of Main Anhydrite (A3) range several meters that are probably part of one layer were recognized in the NW border area of the dome. The Younger and Older Potash layers were strongly folded and as a result, their thickness was reduced. Most of the anhydrite layers were broken and divided into blocks ranged from a few cms to several m in size (Wachowiak, 2017).

The Older Halite (PZ2) beds are characterised by the lowest impurity content (about 97% NaCl). The Younger Halite (PZ3) and the Youngest Halite (PZ4) occur mainly in the northern and north-western part of the salt dome and are interlayered with K-Mg salts. The main factors that influence on a cavern shape are layers and laminas of K-Mg salts and anhydrite characterised by a various thickness from a few cms to several m and a steep dip of salt layers up to 800. Moreover, the anhydrite occurs in a form of breccia in rock salt and as anhydrite sand in rock salt layers. Clay minerals, carnalite, sylvine, kieserite are admixture in halite crystals. The layers and packets of very coarse-grained salt are met.

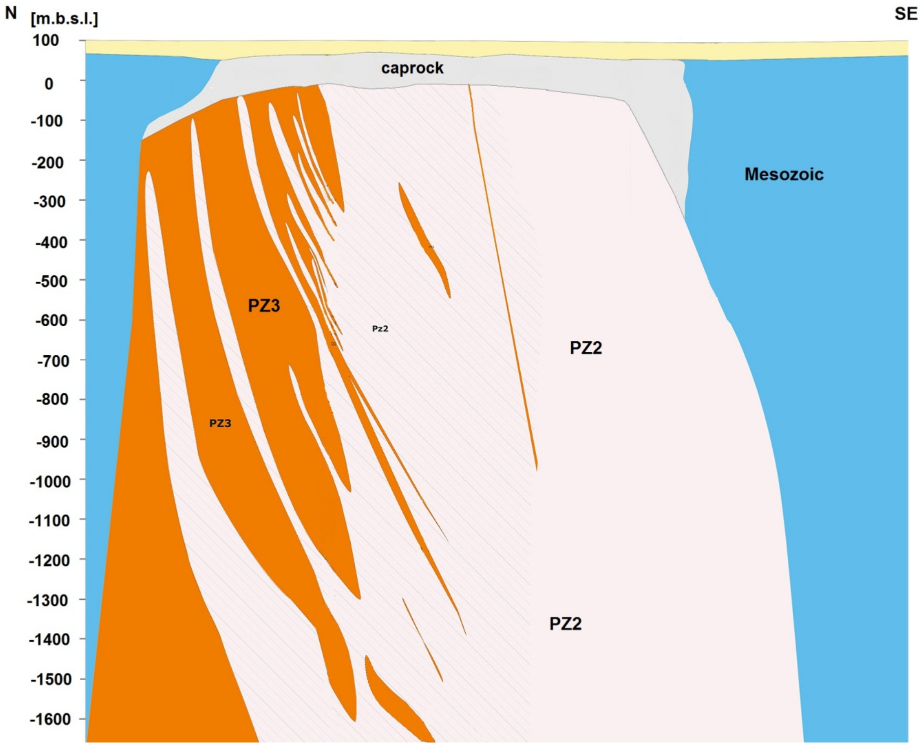

Fig. 21. Geological cross section through Góra salt dome (Wichowska, 2019 modified)

3.1.2. Mogilno salt dome

Two firms are operating in the Mogilno salt dome, consequently, the salt dome was divided and documented as two deposits: south-eastern part – Mogilno I and north-western part – Mogilno II. The salt production by solution mining was carried out in since 1986. Currently, the solution mining is conducted only in the SE part of the Mogilno I. In the Mogilno II storage caverns for gas have been built since 1997 (Wachowiak et al., 2012). Both salt deposits are located in the Mogilno salt structure, which is 7 km wide and 30 km long. This structure is underlain by a very thick salt pillow. In the central part of this structure salt pierced through the Mesozoic and partially Cenozoic sediments and Mogilno salt dome was formed. The Mogilno salt dome is about 8 km long and up to 1 km wide. It is elongated in NW-SE in accordance with the run of the Mogilno structure. The walls of the dome are vertical, only the eastern wall is less steep. The dome widens in the lower part (from the depth of 800 m below the surface). The dome is covered by the caprock which thickness ranges from 100 to 160 m (Fig. 22). The caprock is overlaid by Quarternary sands and clays in a thickness of 8-90 m. The Oligocene and Miocene sediments cover mainly the NW part of the dome and their thickness range from 20 to 160 m. There are represented by muds, clays and sandstone. The salt mirror occurs at the depth of 210-600 m below the surface. The salt series is built of PZ2 to PZ4 sediments (Wichowska, 2013).

The internal structure of the Mogilno salt dome is recognized based on the drilling cores. The structure is very complex because the evaporate layers were strongly folded, steeply even vertically inclined and overturned. The lithostratigraphic units are reduced or repeated within the vertical profile (Fig. 21). The central part of the deposit builds strongly folded layers of the Older Potash (K2), Younger Halite (Na3), Brown Zuber (Na3t) and evaporates of PZ4 cyclothems. These sediments are surrounded by the Older Halite (Na2), Transition Beds (Na2K) with Older Potash (K2) and Main Anhydrite (A3) interlayers (Wichowska, 2013; Tadych et al., 2014).

The salt beds are represented by layers of the Youngest Halite (PZ4), Younger Halite (PZ3) and the Older Halite (PZ2) that are strongly folded and inclined. The repetition and reduction of the lithostratigraphic units are observed in the vertical profiles. The salt beds are characterised by a high lithological variability from pure homogenous rock salt to "zuber" (clay salt) or salty claystone. The main impurity in salt beds is anhydrite which occurs as the layers of thickness

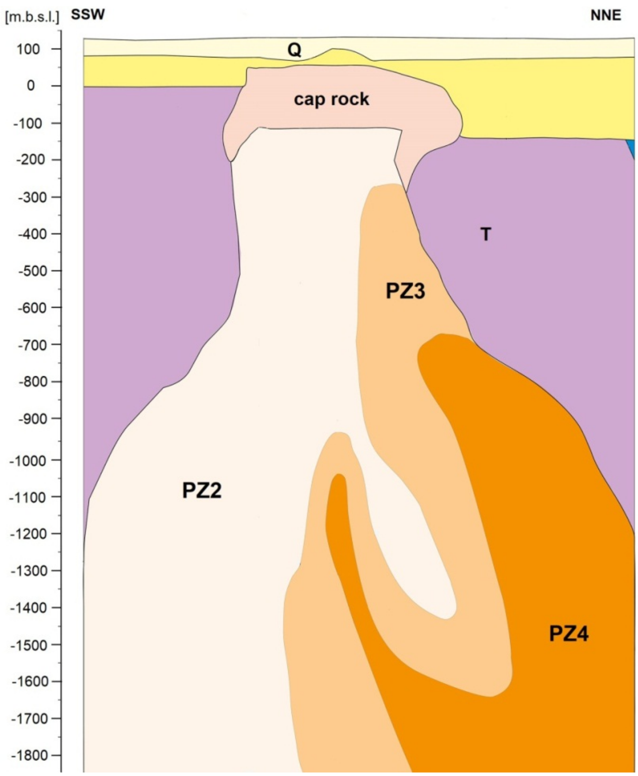

Fig. 22. Geological cross section through Mogilno salt dome (Wichowska, 2013 modified)

from several cms to a few meters, laminas and blocks. The interlayers of claystone, "zuber" (clay salt) and K-Mg salts are met in salt beds. Moreover, K-Mg salts, clay minerals and anhydrite are admixtures in halite crystals. All these features contribute to the formation of cavern shape. The thick layers of K-Mg salts belonged to Na2K, K2 and K3 as well as layers and packets of recrystallised salts are considered as the most adverse factors in the cavern leaching process.

3.1.3. Mechelinki salt deposit

The Mechelinki salt deposit is situated in the northern part of the Gdańsk bay, where the salt beds thickness is the highest (Czapowski et al., 2007; Lankof et al., 2016). The salt deposit is in a pentagonal shape and comprises an area of 6.4 km^2. The salt beds occur at the depth from 946.2 m to 996.1 m below sea level (b.s.l.). The thickness of salt beds changes from 123.6 m to 285.9 m. The salt beds are underlain and overlain by anhydrite layers (the lower anhydrite – A1d and the upper anhydrite – A1g) with thickness ranges from about 1.5 to 20 m. The rock salt beds interlay with two anhydrite interbeds with a thickness reaching 0.5 m. The salt beds lie concordantly on the lower anhydrite (A1d) and dip at the angle of max. 10° to SSE. The following stratigraphic units of the PZ1 cyclothem underlie the salt beds and the lower anhydrite: Kupferschiefer (T1), Zechstein Limestone (Ca1) as well as the Rotliegend sediments (mainly sandstone and conglomerates) and the Silurian sediments (Fig. 23). The salt beds and the main anhydrite are covered by the sediments of the PZ2 and PZ3 cyclothems, mainly limestones, sulphates and silts which overlie the salt beds. The Zechstein sediments are overlain by the Triassic sandstones, clays and claystones, Jurassic sandstones and sands, Cretaceous muds and Cenozoic clays and sands (Czapowski et al., 2007). The salt beds are undisturbed, fine- and medium-grained with impurities of anhydrite which occur as the laminae (thickness of 1-8 mm) or admixture in halite grains. The rock salt is homogenous with NaCl content varying from 96.7 to 97.8%. The thin (from a few to 20 cm) layers or packets of very coarse-grained halite are met.

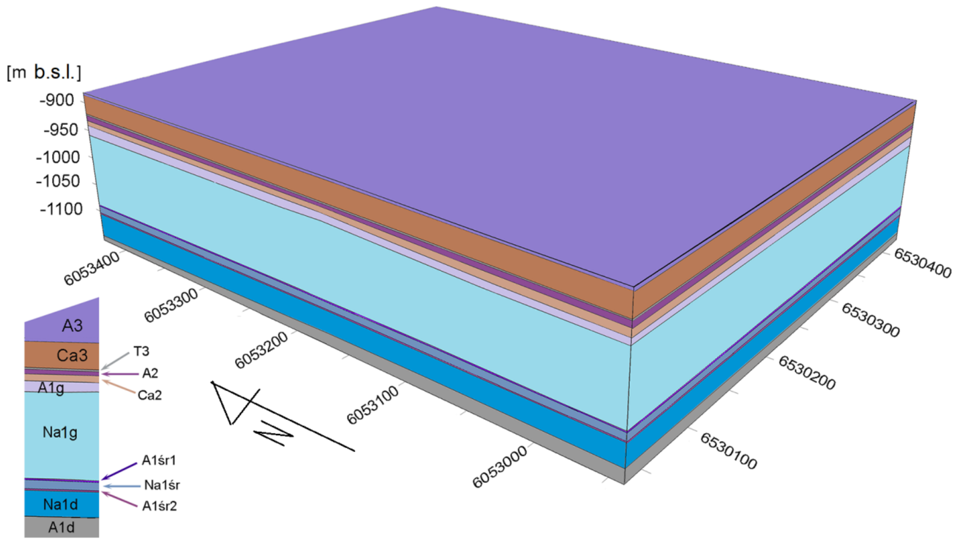

Fig. 23. Geological cross section through Mechelinki salt deposit (Cała et al., 2018)

3.2. The shape of cavern in a light of geological factors

The internal structure of salt deposits described in the previous section were considered in a cavern placing inside the salt deposits. Caverns were located in these parts of deposits where salt beds are undisturbed or slightly disturbed, thick and homogenous. For instance, the areas with strongly folded salt beds, brecciated anhydrite layers and thick layers of K-Mg salts were omitted in the Góra salt dome. The underground storage in Mechelinki salt deposit took place in this part where salt beds are thick and the most homogenous. In other parts of this deposit, the admixture and interlayers of polyhalite occur.

Taking into account that a cylindrical shape is considered as the most efficient in keeping stability (Staudtmeister & Rakhar, 1997; Sobolik & Ehgartner, 2006; Onal, 2013), a design of the presented caverns were based on this assumption. Typically for the salt dome, the caverns in Góra and Mogilno are very high and characterise by a small diameter in comparison to their height. In bedded salt deposits a cavern diameter is larger, in some extreme cases, like caverns leached by two wells, even larger than their height (Wei et al., 2017; Jie et al., 2020). In Góra salt dome the salt beds, documented to a depth of 1700 m, are a part of the three cyclothems (PZ2-PZ4), consequently, their thickness in the production wells reach up to 1200 m. Typically for the halotectonic origin, the salt beds in salt domes were enriched as a result of halokinetic movements. The salt beds in Mechelinki salt deposit were deposited and occur in the same location as a layer. This layer is up to 200 m thick and represents one Zechstein cyclothem PZ1. A diameter is related to the required capacity taking into account cavern stability constraints. The dimensions of caverns are strictly connected with a depth of salt beds location. The top of caverns in the Góra salt dome was located at depth ranges from 300 to 450 m but in Mechelinki deposit from 1000 to 1050 m below the ground level. In addition, the depth below 2000 m is related to ongoing salt creep and salt cavern size is reduced (Warren, 2006). It was calculated for cylindrical cavern (diameter/height ratio 2), designed accordingly to the salt beds thickness, that convergence increases significantly below a depth of 1200 m and this effect accelerate with a depth (Onal, 2013). Thus,.

The role of lithology and petrological diversity in the formation of irregularities is visible in a shape of caverns G-6 and G-10 located in S and SW part of the mining area. Both caverns were solution mined in the 1970s and operated in the Góra salt dome firstly as production cavern. Next, they were converted into storage purposes (G-6 in 2002 and G-10 in 2015). The available geological data for these caverns include core lithological description and geochemical analysis of core samples. The contents of chemical elements in a single depth interval is compared with an average content calculated for the depth range characteristic for each cavern e.g. for cavern G-6 the average content of chemical elements were calculated for the depth range 380-1200 m b.g.l.

The cavern G-6 is in the shape of a column, typically for the salt domes. There are some irregularities in a cavern shape (Fig. 24). The cavern is about 820 m high and extends from a depth of 380 m to 1200 m b.g.l. The average diameter is 50-60 m. The various petrological types of rock salt were indicated in G-6 core, from fine-grained to very coarse-grained (halite crystals 3-6 cm), pure rock salt and with the admixture of anhydrite and clays. However, the cavern was leached in rock salt layers without interlayers of another evaporates. The maximal diameter is related to the zones of its enlargement. In these zones, the symmetry of the cavern is disturbed. The most clearly marked in a vertical cross are two depth intervals 540-570 m.b.g.l. and 720-750 m.b.g.l. (Fig. 24). In the first interval, the diameter is enlarged to 87 m in SSW

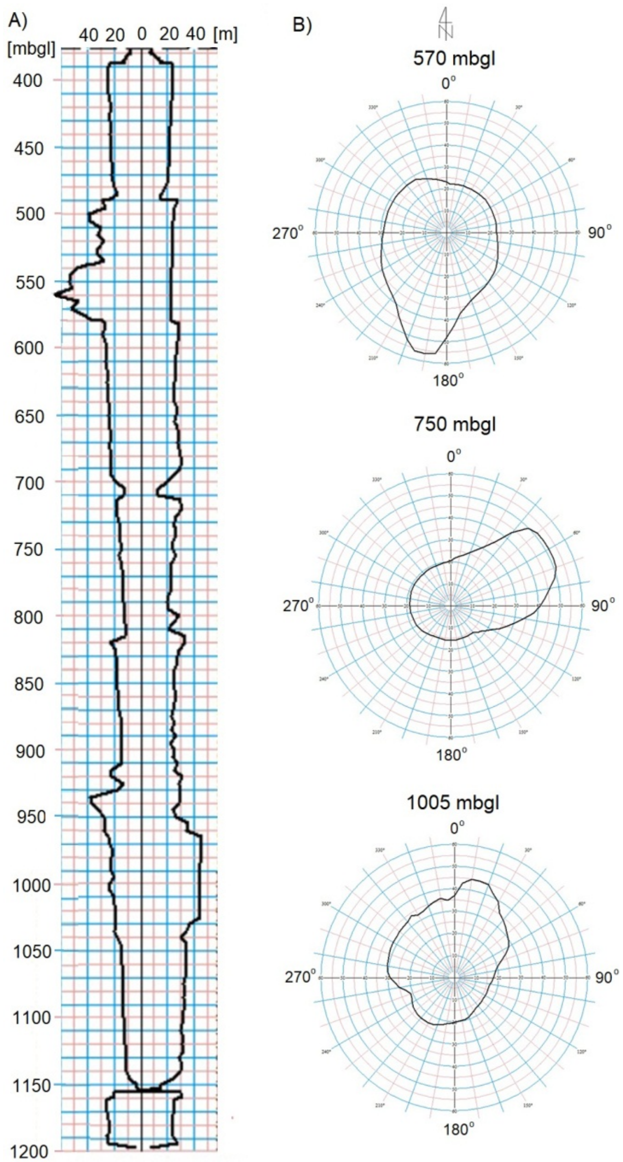

Fig. 24. Cross sections through G-6 cavern: A – vertical cross section, B – horizontal cross sections (based on echometric survey data Wichowska, 2019)

direction and it is the maximal value of the diameter. In the second depth interval, diameter ranges from 68-78 m and is enlarged in NE direction. Very coarse-grained rock salt (crystals in size of 1 cm, some even up to 5-6 cm) interlayered with middle and fine-grained rock salt laminated by anhydrite occur in these intervals. Laminas are very steep from 750 to vertical. In the second interval chemical analysis shows an increase in the content of max. Mg – 0.320%

(average for the cavern is 0.048%), max. Ca – 3.58% (average for the G-6 cavern is 0.618%) and insoluble content – 9.200% (average for the G-6 cavern is 0.992%) (Fig. 25). This increase is related to thin (0,5 m) anhydrite layers at a depth of 743.6-744.1 m b.g.l. that deep at 750. Another section where a cavern diameter is enlarged is at a depth of 970-1020 m b.g.l. (Fig. 24). In this interval, a diameter reaches 65-75 m and symmetry in horizontal cross-sections are shifted in NE direction. The layers of fine and middle grained rock salt occur in this interval. The salt is white clear to grey and dark, bituminous. In chemical analysis there is an increase in Mg content – 0.810% (average for the G-6 cavern is 0.048%) and K content – 0.064% (average for the G-6 salt interval is 0.026%) (Fig. 25). This interval may correlate with Transitional Beds (Na2+K) that occur similar depth range in adjacent cavern G-39 (Czapowski et al., 2009). Besides, three waists are marked in a vertical cross-section. These zones are related to the following depth intervals: 480-490 m b.g.l and 700-710 m b.g.l. and middle grained grey and dark grey rock salt with steep vertical laminas of anhydrite sand (Fig. 24). However, chemical analysis showed an only small increase in insoluble content (1.100%) in the first interval (Fig. 25). They are related to leaching stages. The grey colour of rock salt in this cavern is not associated with clay minerals but is related to anhydrite dispersed into the halite crystals (Cyran et al., 2016). In addition, in a cavern shape, many smaller irregularities are related to specific rock salt fabrics.

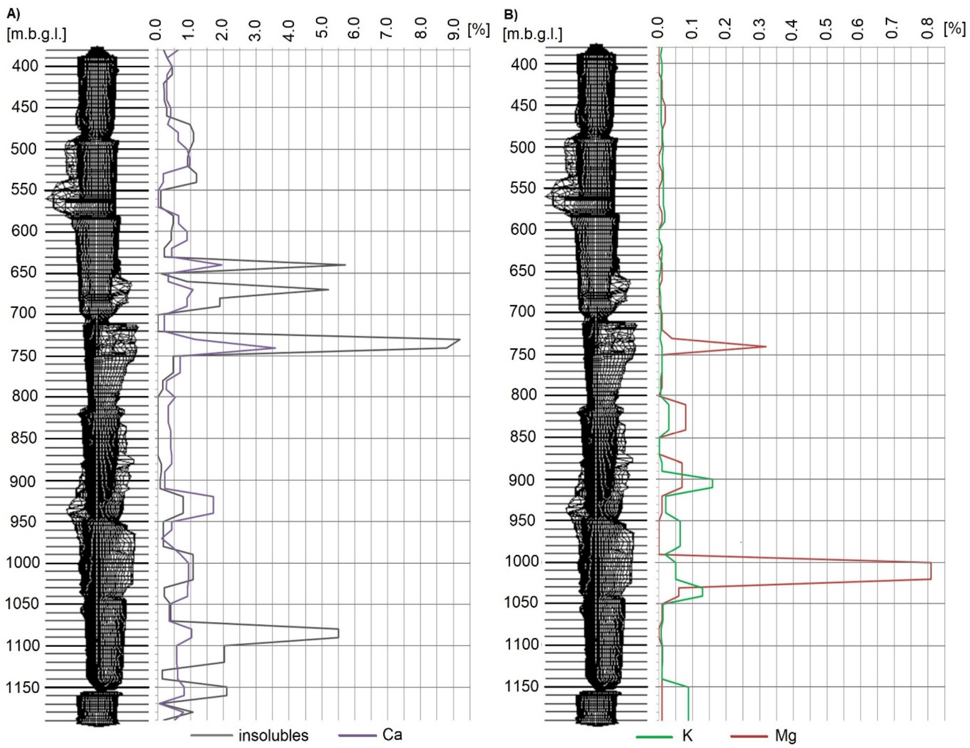

Fig. 25. The 3D shape of G-6 caverns in correlation with chemical analysis
(based on Wichowska, 2019)

The shape of G-10 cavern is the elongated cylinder, asymmetrical in the lower part. It is more regular and smaller than cavern G-6. The cavern roof is located at a depth of 350 m (including 50 m long neck) and bottom at 886 m b.g.l. The rock salt in G-6 core is homogenous (without interlayers of other evaporates), mainly middle grained white, light grey, grey with several interlayers of fine-grained rock salt with the admixture of anhydrite sand. The average diameter is 47-50 m but there is one depth interval where the diameter is enlarged 690-710 m b.g.l. (Fig. 26). In this interval, the diameter is enlarged to 55 m in SW direction and it is the maximal value of the diameter. Middle and fine-grained rock salt laminated by anhydrite sand at the angle of 800 occurs in this interval. Chemical analysis shows only an increase in the content of Ca – 0.950%

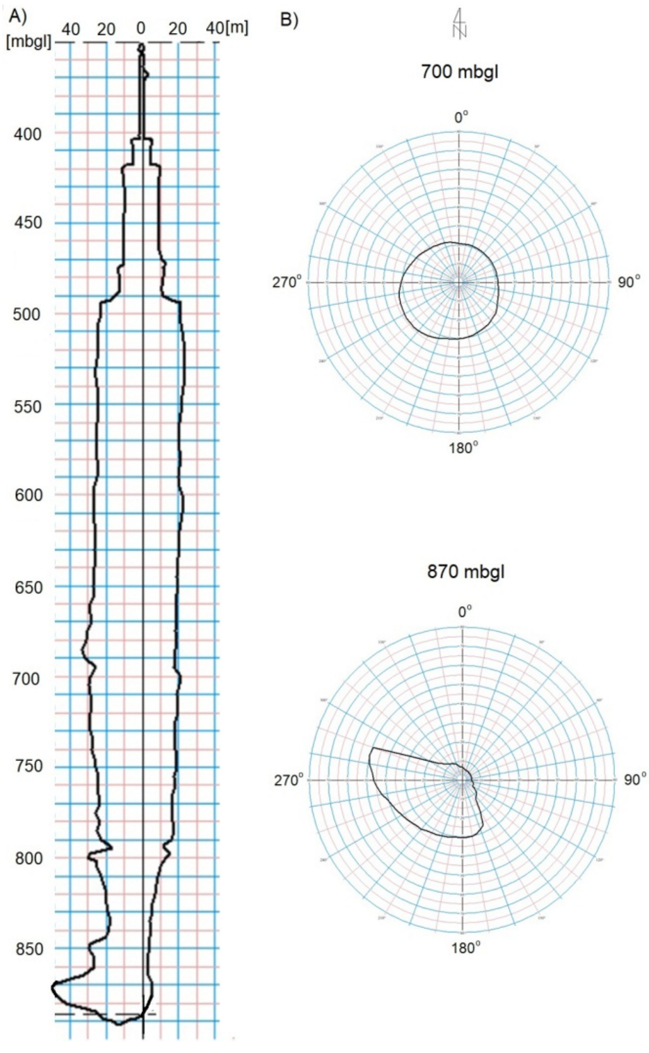

Fig. 26. Cross sections through G-10 cavern: A – vertical cross section, B – horizontal cross sections (based on echometric survey data Wichowska, 2019)

(average for the G-10 salt interval is 0.571%) (Fig. 27). In a vertical cross-section another but smaller irregularity is visible at the depth of 790-810 m b.g.l. (Fig. 26) In this interval, the same type of rock salt as described above occurs andCa content is 0.550% (Fig. 27). The lower part of the cavern (from a depth of 850 m.b.g.l.) is characterized by disturbed symmetry in SW and W direction. In this interval, the rock salt is homogenous, middle grained, white to grey without visible admixtures. The chemical analysis showed increased in the content of K in a range of 0.007-0.019% (average for the G-10 cavern is 0.005%) (Fig. 27). The grey colour is not associated with clay minerals but anhydrite dispersed into the halite crystals similarly to G-6. There are several irregularities in a cavern vertical cross-section in the depth interval between 500 and 600 m b.g.l. but lithological characteristic describes typical middle grained white and grey rock salt. At the depth of 580-600 m b.g.l. (Fig. 26) the core was washed out although there was no major increase in the K or Mg content. In G-10 profile the crystalline halite layers are below the cavern bottom from the depth of 928.4 m.b.g.l.

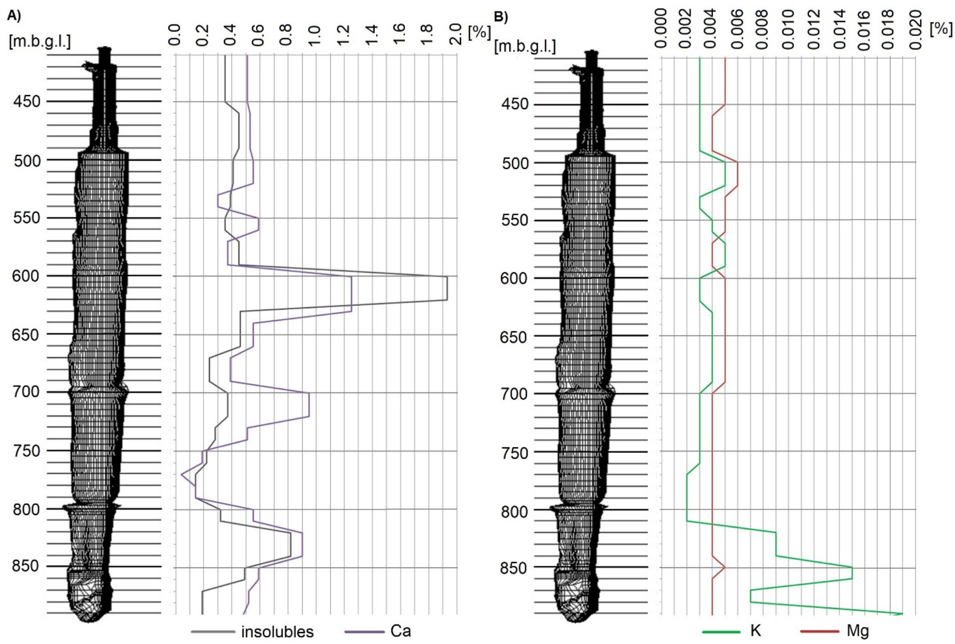

Fig. 27. The 3D shape of G-10 caverns in correlation with chemical analysis
(based on Wichowska, 2019)

Both described shapes of caverns have some irregularities formed during the leaching process. They correlate with the lithological type of rock salts like very coarse-grained (crystalline) rock salt with crystals above 1 cm and the presence of rock salt with steep laminae of anhydrite or anhydrite sand. The very coarse-grained (crystal) rock salt (3-6 cm) in form of several centimetres thick layers and packets occur in Mechelinki salt deposit. The Oldest Halite is interlayered with two anhydrite layers (A1śr1 and A1śr2) in a thickness of up to 0,5 m. The occurrence of crystalline halite packets and layers is the most frequent under the anhydrite interlayer A1śr2

(Fig. 28). The crystalline halite is underlain and overlain by middle (2-5 mm) and fine (below 2 mm) grained rock salt laminated by anhydrite. The laminae spacing range from 20-30 cm, in some parts reach even 20 laminas per meter. Rock salt layers and anhydrite laminae lay almost horizontally (0°-5°). Crystalline packets occurrence contributed to enlargement in cavern diameter, for instance in cavern K-8 at the depth of 1100-1120 m b.g.l. and K-9 at the depth of 1110-1125 m b.g.l. (Fig. 28). These enlargements are directed in SW according to the dip of the salt beds. The occurrence of two anhydrite interlayers is related to waists in a cavern shape (Fig. 28).

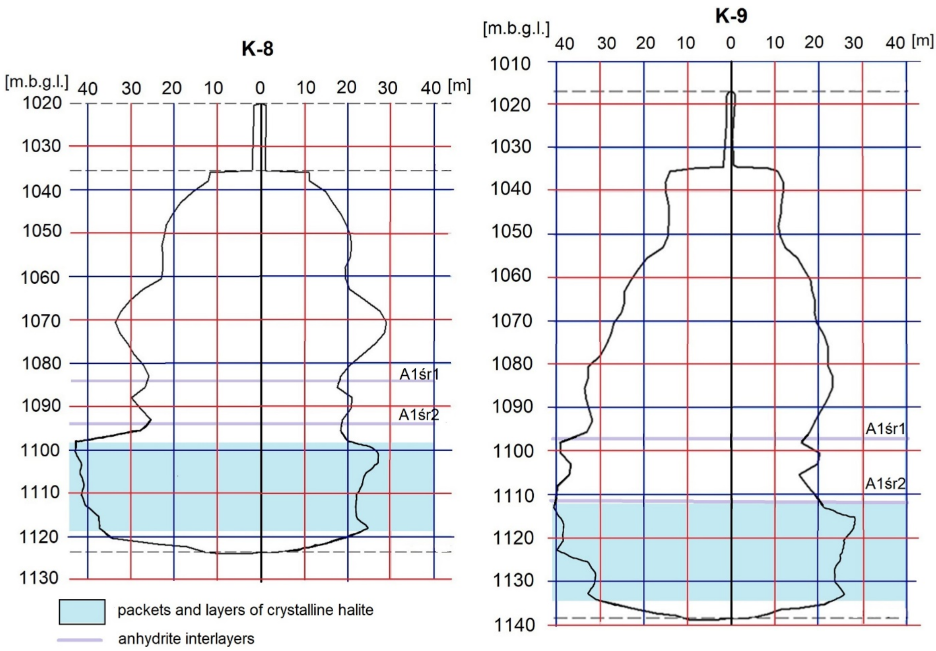

Fig. 28. Vertical cross section through caverns in Mechelinki salt deposit
(based on echometric survey data Brańka et al., 2014)

The lithological and petrological diversity of salt series is reflected in a shape of caverns in the SE part of Mogilno salt dome (mining area Mogilno I). Caverns M-28 is located in the S part of the mining area and M-34 in the NE part. Both caverns have a much smaller volume than in Góra salt dome because of larger impurities content and more complex geological structure of the deposit. The available geological data for these caverns include core lithological description and geochemical analysis of core samples. The contents of chemical elements in a single depth interval is compared with an average content calculated for the depth range characteristic for each cavern, e.g. for cavern G-6 the average content of chemical elements were calculated for the depth range 380-1200 m b.g.l.

The M-28 cavern is characterised by quite regular cylindrical shape, enlarged in the middle and lower part. It was solution mined from 2009 and is still in the extraction phase. The cavern extends from the depth of 1590 to 1900 m b.g.l. and its average diameter is 45-50 m. It was located in beds of the Youngest Halite Na4 (PZ4 cyclothem), below layers of the Brown Zuber

(Na3t) and Pegmatite Anhydrite (A4). In a vertical cross-section, two intervals of diameter enlargement distinguish at the depth of 1630-1660 m b.g.l. and 1825-1850 m b.g.l. (Fig. 29). The horizontal cross-sections show that diameter enlargements in these intervals are directed in NW. In both intervals occur light orange and pink, form middle to very coarse-grained (up to 1.5 cm) rock salt overlaid and underlaid by middle grained salt laminated mainly by anhydrite and anhydrite sand and clay minerals as well as K-Mg salts. However, lamination is steep (650 to 800) and distributed every about 30 cm or rare. In the first interval, the chemical analysis showed (Fig. 30) an increase in insoluble content – 19.837% (average content for the cavern is 2.329%) and K content (0.186%) slightly above average (0.167%). In the second interval, there are more laminas of K-Mg salt. The chemical analysis shows (Fig. 30) increase in Mg – 0.156% and K – 0.208% (average for the cavern is 0.041% Mg and 0.122% K). In the upper part of the second interval, there is a 2 m thick layer of salt with high impurity con-

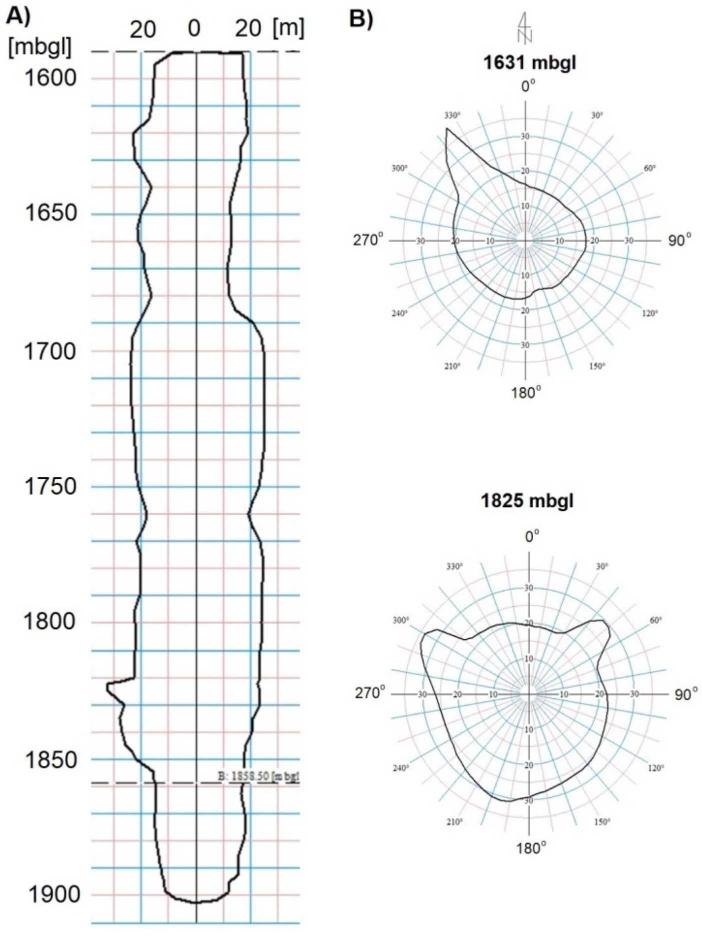

Fig. 29. Cross sections through M-28 cavern: A – vertical cross section, B – horizontal cross sections (based on echometric survey data Wichowska, 2013)

tent 12.359%. In the lower part of the cavern, at the depth range between 1870-1880 (Fig. 30), a major increase in Mg content (0.516%) is noticed. This interval is associated with the layer of K-Mg salts.

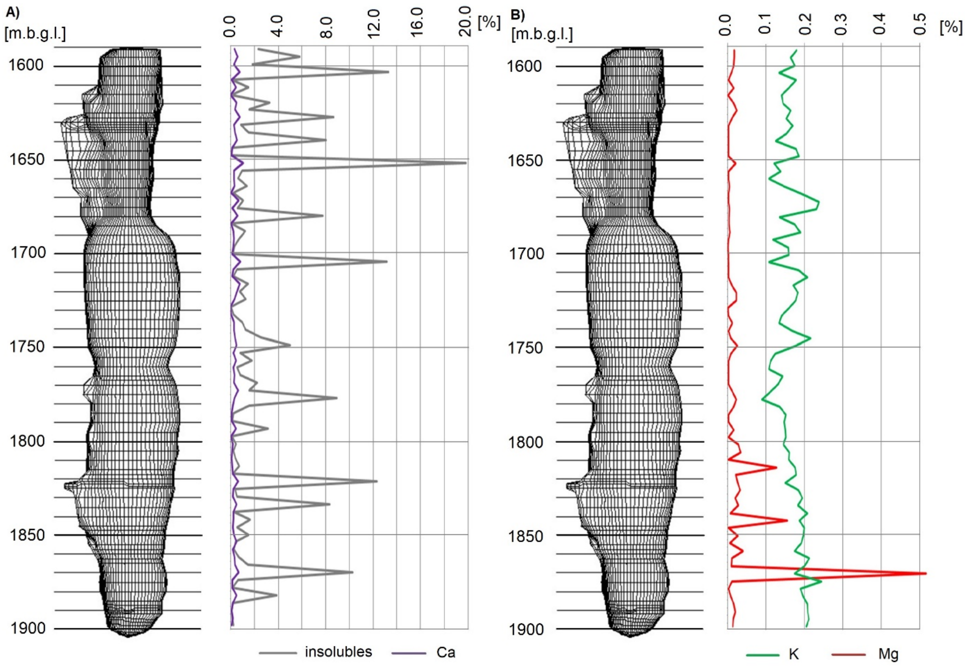

Fig. 30. The 3D shape of M-28 caverns in correlation with chemical analysis
(based on Wichowska, 2013)

The cavern M-34 was leached in salt beds of PZ3 and PZ4 cyclothems and consists of two parts divided by Brown Zuber (Na3t) layers. The solution mining started in 2011 and is still in the leaching phase. The lower part extends at the depth of 1635-1742 and the upper from 1489 to 1579 m b.g.l. A shape of a lower part is very irregular and asymmetric, narrowed in the middle part. This part of the cavern was leached in alternately layered Brown Zuber (Na3t) and the Younger Rock Salt (Na3), and three anhydrite layers up to 1.8 m thick. All these beds belong to PZ3 cyclothem. The rock salt is highly impure with an admixture of clay minerals. There are two intervals of diameter enlargement: in cavern roof 1630-1648 and 1680-1700 m b.g.l. (Fig. 31). The diameter enlargement is directed to SE in the first interval and SW in the second interval. The average cavern diameter range from 35 to 42 m but in the first interval is enlarged to 60 m, in the second to 46 m. These intervals are related to pure coarse-grained orange salt with packets of crystalline halite. Salt is laminated by steep anhydrite layers in a cavern roof but in the second interval, the anhydrite layer 0.3 m thick occur. The chemical analysis showed the insoluble content of 81.424% for the first interval and 41.458 % for the second (the average insoluble content for a cavern is 8.490%) (Fig. 32). In the depth interval 1680-1690 m b.g.l. there is an increase in Mg content – 0.742% (the average for a cavern is 0.263%) (Fig. 32). The upper part of the M-34 cavern is in an inverted cone shape with irregularities in the upper part. This part of the cavern was leached in mainly middle and coarse-grained rock salt (the Youngest Halite Na4) with an admixture of anhydrite, K-Mg salts and clays. However, the insoluble content is much lower than in the lower part of the cavern (2.994%). In the upper part (1510-1530 m b.g.l.) the irregularities in vertical cross-section are visible. They are associated with low admixture content and confirmed by chemical analysis. Rock salt is laminated by K-Mg salts (laminas several cms thick) and anhydrite (laminas from a few mm to 20 cm thick) and anhydrite sand at the angle of 45-50°.

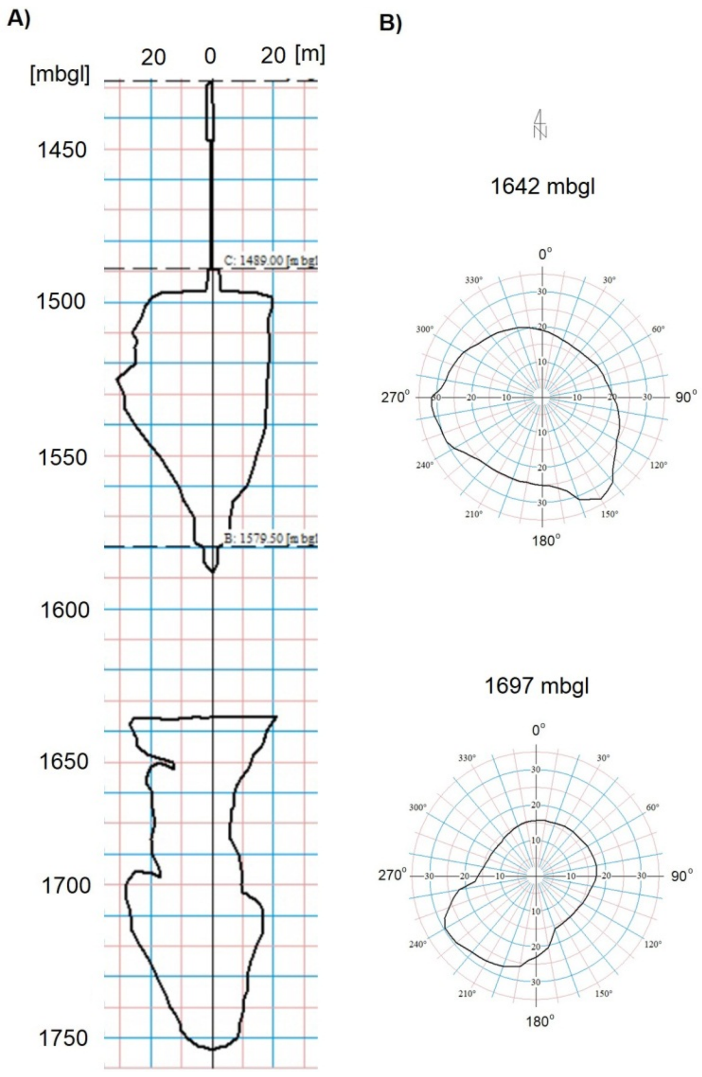

Fig. 31. Cross sections through M-34 cavern: A – vertical cross section, B – horizontal cross sections (based on echometric survey data Wichowska, 2013)

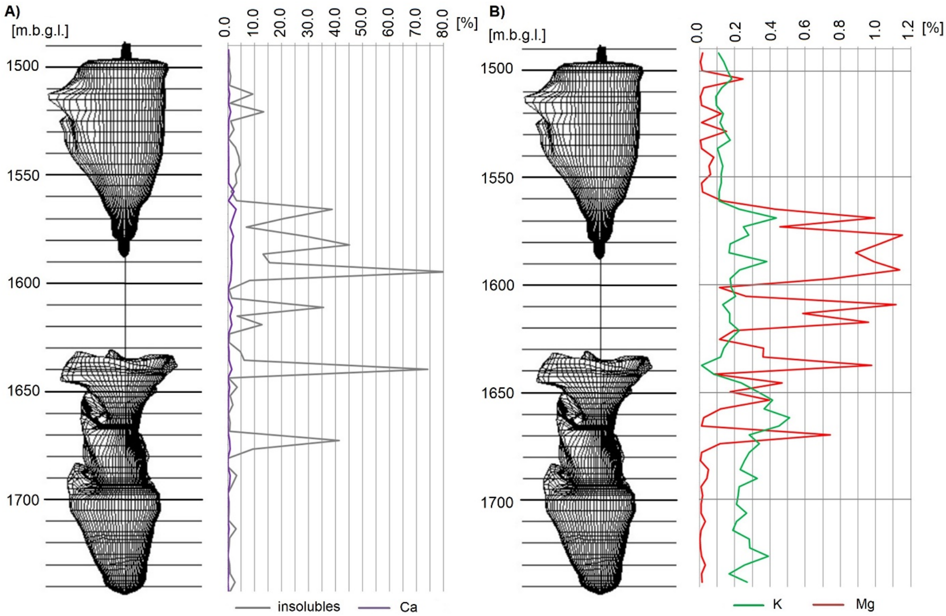

Fig. 32. The 3D shape of M-34 caverns in correlation with chemical analysis (based on Wichowska, 2013)

4. Discussion

The cavern dimensions and storage capacity depend on many factors like mechanical parameters of salt and non-salt beds, stability conditions, safety requirements and storage. The geological factors described in this paper are another group included in this list. They have to be considered in a cavern design and stability analysis. Most of these factors like depth of cavern location, the internal structure of deposit and lithology are defined based on the borehole and core data as well as basic chemical analysis. Their impact on a cavern shape is well recognized in engineering practice, for instance, the presence of interlayers composed of more soluble minerals like K-Mg salts or less soluble like anhydrite or clays results in the formation of irregularities in a cavern shape. As an example can be taken the anhydrite interlayers that contribute to the formation of waists in a cavern in Mechelinki salt deposit. Another example is the presence of Transitional Beds (Na2+K) in Góra salt dome (Czapowski et al., 2009) displayed by an increase in Mg and K content and associated to the formation of irregularities (enlargement) in a cavern shape.

However, there are other factors like petrological features and internal fabrics of salt beds that influence the cavern shape. They can be considered in different scales: mesoscales (visible in core) like lamination, grain size and distribution, and microscales (visible under a microscope) like cleavage, fluid or solid inclusions. The detailed role of these features in irregularities formation require further research. For instance, the presence of very coarse-grained (crystal) halite in the form of layers and pockets contributes to enlargement in a cavern diameter. This effect was observed in Góra salt dome and Mechelinki salt deposit. In Góra salt dome crystal halite occurrence is associated with rock salt from fine to middle grained laminated by very steep

(750-900) anhydrite or anhydrite sand. In Mogilno salt dome the laminae were more diversified because they consist of anhydrite, anhydrite sand, clays and K-Mg salts and deep at the angle of 650-800. This type of salt was described e.g. in Barbers Hill salt dome or Bryan Mount and was associated with the shear zone between salt spines (Loof, 2017; Loof et al., 2010a 2010b). In Mechelinki salt deposit, the crystalline halite occurs in the form of packets. The laminae occur with different quantities and dip at the angle of 0°-15°. Taking into account the undisturbed structure of Mechelinki deposit their connection with shearing is slightly possible. However, the detailed characteristics of this type of rock salt and their impact of irregularities formation in a cavern shape require deeper analysis.

Another issue is the form of impurities occurrence. The K-Mg salts contain different amounts of minerals like kieserite, sylvine and carnallite. These minerals occur in the form of laminae, layers and admixture in halite crystals. For instance, in analysed caverns in Góra increase in K and Mg content is related to the formation of irregularities and disturbance in cavern symmetry. However, the presence of these minerals was not detected in the core samples. In Mogilno salt dome in analysed caverns, the K and Mg content was higher than in Góra caverns. Nevertheless, the petrological diversity of salt beds and admixture of anhydrite and clays caused that role of K and Mg content in irregularities formation is less visible. In both domes occurs grey salt which is not related to clays admixture but increases in anhydrite content. Layers of this salt are related to waists formation in a cavern shape. The admixture of anhydrite dispersed in halite grains contributes to a decrease of solubility.

In addition, described petrological features can be considered in a context of prediction of the final cavern shape and this shape impact on stability conditions. However, factors related to the stability issues like mechanical and rheological parameters of salt beds and non-salt interbeds are also related to the petrological issues. Consequently, they influence on long-term operations in storage caverns.

5. Conclusion

The global demand for energy has been growing rapidly. Salt caverns offer a promising option for underground storage of different energy sources. Their large storage capacity, low permeability preventing the sealing of the stored medium and eventual environment contamination, availability of salt deposits as well as flexible operation scenario with relatively short injection and withdrawal cycles made them an attractive solution for growing energy demand and provide energetic security. The expected growth in energy consumption will contribute to the development of underground storage in salt caverns. This development will result in an improvement of caverns design, including cavern shape, assessment of geological conditions and exploration of geological features. The progress in design, exploration and construction techniques can potentially bring positive results like increase in caverns storage capacity and cavern location in geological conditions currently considered as difficult or not prospective.

Acknowledgement

Author would like to thank IKS Solino for making the data available for analysis and publication. Author would like to give special thanks to Joanna Tadych and Jacek Drogowski for help in collecting data for this paper.

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