Salt Mines at Bochnia and Wieliczka

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Marine Miocene deposits are present in southern Poland and cover the area of the entire foreland of the Polish Flysch Carpathians, extending without interruption from Silesia, through the Cracow region to the Paleozoic massif of the Kielce region to the north and to the eastern state boundary. The thickness of the discussed deposits varies greatly ranging from a few hundred metres in the western and northern parts to over 3000 m in the eastern part of the Carpathian foreland (Fig. 1).

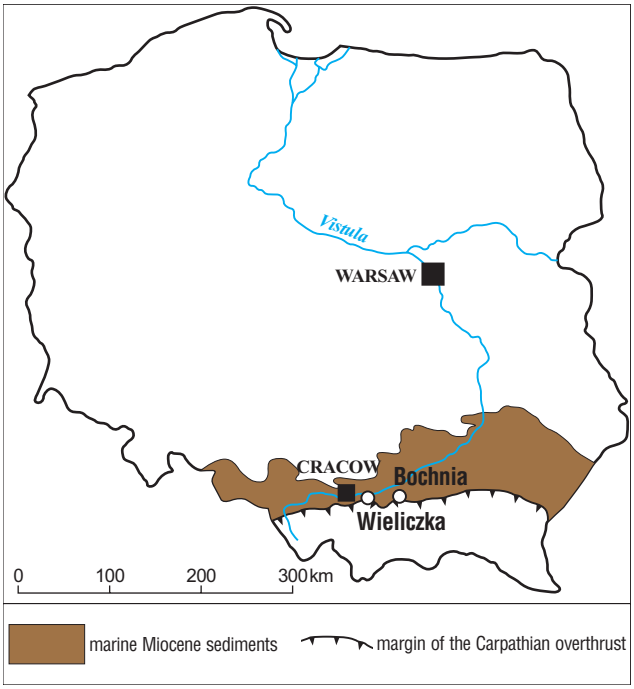

Fig. 1. Extent of marine Miocene deposits in Poland (after Garlicki, 1974; modified)

The marine Miocene consists of clays, sands and evaporites. The evaporites comprise only a small part of the vertical profile of marine sediments, but they are widespread in the sedimentary basin and thus form an important marker bed. The Miocene salt-bearing formation containing the evaporite horizon belongs to the Badenian (stage M4) and is subdivided into 3 members:

- ❏ Skawina Beds (underlying evaporites),
- ❏ Wieliczka Beds (evaporites),
- ❏ Chodenice Beds (overlying evaporites).

The Skawina Beds range in thickness from a few meters up to 150 m. They are usually represented by marly claystones and marly, clayey shales, and less frequently by siltstones with cement composed partly of evaporites. Within these beds numerous intercalations of chemically deposited dolostones occur, as well as abundant carbonized plant remains.

A transition to overlying evaporites is gradual, with slow increase of chloride and sulphate minerals. The thickness of the Wieliczka Beds range from 40 m to about 200 m, with an eastward increase in thickness. In normal profile of evaporites five cyclothems can be distinguished. The youngest cyclothem is present only in the central part of the sedimentary basin. In general, each cyclothem begins with claystones or clayey-anhydritic rocks, with abundant admixture of silt and carbonized plant fragments, followed by anhydritic claystones of nodular and banded structure, which in turn are followed by clayey-anhydritic shales that are fine-laminated and thinly banded. The uppermost part of each cyclothem consists of rock salt layers, except for some profiles of the youngest, fifth cyclothem, where the uppermost section is developed as anhydrite, instead of salt. In the Badenian basin between Wieliczka and Bochnia the intensity of chemical sedimentation was never high enough to cause the precipitation of potassium-magnesium salts.

The Chodenice Beds (overlying evaporites) are usually developed as sandy, marly, clayey shales, with numerous dolostones intercalations in the lower part and tuff intercalations in the upper part. The total thickness of the Chodenice Beds varies from 100 m to about 1000 m.

The youngest Badenian formation (Grabowiec Beds) is developed as sands and sandstones. These strata are fairly undisturbed and in the area adjacent from the north to the salt mines at Bochnia and Wieliczka overlie discordantly clayey rocks of the Chodenice Beds (Figs. 2, 9).

Within the Wieliczka Beds, three facies have been distinguished:

- ❏ carbonate — littoral facies comprising organic limestones, mixed carbonate and detrital rocks;
- ❏ sulphate facies, comprising anhydrite-gypsum and sulfur-bearing deposits;
- ❏ chloride facies, containing rock salt with anhydrite and clay-anhydrite rocks.

The areal extent of the chloride facies is smaller than the other one. In the Upper Silesia the chloride facies covers an oval shaped area and is surrounded by the sulphate facies. Farther east, along the Carpathian boundary, chloride facies extend from Wieliczka to Tarnów and occur in the vicinity of Pilzno and Przemyśl (Garlicki, 1974, 1979).

In the Badenian salt-bearing formation of the Carpathian foreland two main units can be distinguished, namely an autochthonous unit and overthrust one (the latter sometimes is called an allochthonous element). In the substratum of both Miocene units, the Mesozoic strata developed as marls and limestones have been stated in the western part of the Wieliczka deposit and north of the Bochnia mine. During the Late Miocene, strata in the allochthon were folded in front of the Carpathian nappes and thrust

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from the south over the autochthon. These tectonic features can be observed in numerous cross-sections through the marginal zone of the Miocene in front of the Carpathian thrust belt in Poland. As a result of these intense disturbances in the overthrust unit, one can observe recumbent folds passing into imbrications, strong deformations of salt layers resulting in increase and decrease of their thickness, and even coarse breccia composed of salt clay with blocks of rock salt. The final stage of these disturbances was an uplift of folded strata to the surface. This was the origin of the Miocene salt deposits, among others at Bochnia and Wieliczka (Figs. 2, 9).

The Miocene salt deposits were the cradle of the Polish mining industry. In the vicinity of Bochnia and Wieliczka the first traces of salt production go back to the Neolithic period (ca 3500 BC). In the earliest times salt was obtained there by roasting and boiling to dryness salt brine obtained from the natural surface salt springs and brine wells. Boiling kettles from the tenth and eleventh centuries were discovered during recent archaeological excavations. Written documents show that as early as the eleventh century there was a great brine producing centre at Wieliczka (called *Magnum Sal* in Latin). Rock salt, however, was discovered several years later. Surface salt springs and shallow wells must have become depleted quickly. In the course of deepening the brine wells rock salt was discovered in Bochnia about 1248 and at Wieliczka in the second half of the 13th century. By the 13th century rock salt mines operated at Bochnia and Wieliczka (Jodłowski et al., 1988). These salt mines were the King's property and were administered by managers designated by royal orders. During medieval history of Poland, the salt mines were the main source of income to the royal treasury. On the other hand both mining towns were granted special royal privileges, which established their leading position in the country for several hundreds years. In 1978 the Wieliczka Salt Mine was included by UNESCO in the first list of the World Cultural and Natural Heritage. In 1994 it was recognized by state's authorities as a Polish historical monument. Few years later in 2000, the Bochnia Salt Mine was also recognized as a historical monument of Poland.

It is worth mentioning that Bochnia and Wieliczka Salt Mines (from the Middle Ages known as *the Cracow Saltworks*) are the oldest still operating factories in Poland. Of course, their main tasks nowadays are quite different than those carried out during passed 800 years.

Bochnia

Geological setting of the Bochnia salt deposit has been presented in several publications (Poborski, 1952; Garlicki, 1968). The best description accompanied by numerous cross-sections and maps one can find in the monograph by Poborski (1952).

In the vicinity of Bochnia, in front of the Carpathians, two Miocene anticlines occur (Fig. 2). The main, northern fold is called the Bochnia anticline, whereas the parallel, southern is called the Uzbornia anticline. Cores of these anticlines are built up of flysch sediments which indicate that the evaporites of Bochnia were deposited upon flysch sediments. The salt deposit is situated in an almost vertical northern limb of the Bochnia anticline, about 40 km east of Cracow. The length of the deposit is about 7 km; the width varies from some dozen metres to 200 m. The deepest part of the mine is about 460 m. Westward continuation of the Bochnia salt deposit, about 6 km long, has been discovered in the years 1956–1968 in localities: Łapczyca, Moszczenica, Siedlec and Łężkowice. The internal structure of these deposits reveals some features similar to the Bochnia deposit. In vertical profile four cyclothems have been distinguished, comparable with those in other salt deposits.

Part of the deposit recognized at Łężkowice used to be exploited between years 1968–1990 using the method of leaching salt beds with water through boreholes from the surface. Generally, production of salt in the Bochnia mine was finished in 1990.

The inner tectonics of the Bochnia deposits reveals a unique accumulation of steep folds of high amplitude. Such intense folding was connected with a partial tectonic squeezing of certain limbs of folds resulting in plastic translocation, shearing of salt off more rigid rock layers, accumulation of salt in fold bends, and finally piercing of fold bends by the salt mass. In some cases bigger accumulations of salt took place due to thinning out of the barren beds (separating the salt beds in an undisturbed profile). The richest part of the deposit mainly composed of middle salts, was situated at the depth about 200–450 m below surface, generally between the first and tenth mine levels.

Within lithostratigraphic profile of the deposit following rocks can be distinguished (from the bottom):

- ❏ basal anhydrite
- ❏ lower zuber
- ❏ southern salts
- ❏ shaley marly claystone
- ❏ upper zuber
- ❏ anhydritic claystone

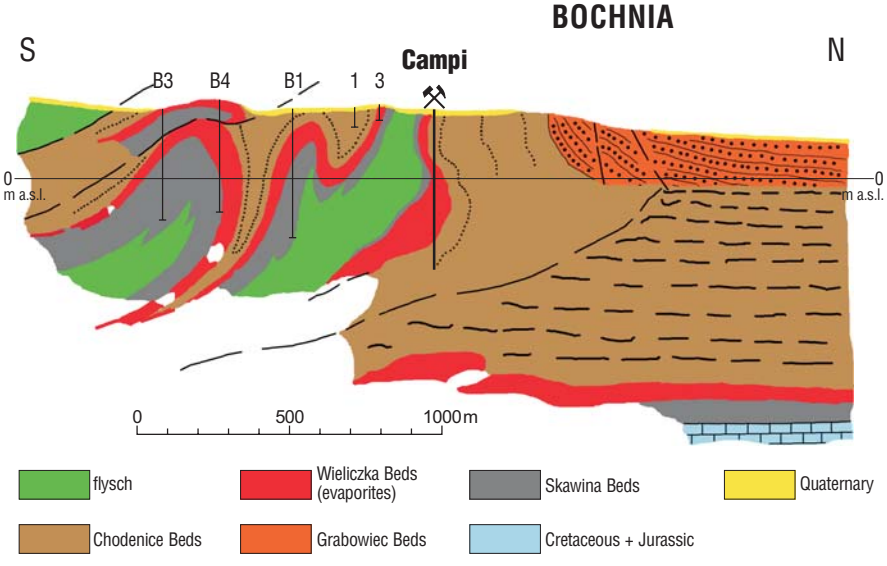

Fig. 2. Cross-section through the shaft Campi (after Garlicki, 1968; modified)

Fig. 3. Shaft Campi. Figs. 3, 5 photo by K. Stompór

Fig. 5. St. Kinga chapel

- ❏ argillaceous anhydritic shale with beds of crystal salt
- ❏ middle salts
- ❏ anhydritic claystone
- ❏ northern salts
- ❏ shaley marly claystone
- ❏ top anhydrite

The primary thickness of these sediments was about 70 m and they may be well correlated with five cyclothems distinguished in the Wieliczka salt deposit (Garlicki, 1968, 1979).

An access to the mine took place through several shafts: Floris, Gazaris, Regis, Sutoris, Campi, Trinitatis. Currently operate two main output shafts: Sutoris and Campi (Fig. 3). Both shafts are connected by several mine working levels. In the western part of the mine there is also an intake shaft Trinitatis.

In the Bochnia Salt Mine there are numerous artifacts of old mining from the 17th to 19th centuries. Of particular interest are chapels, old chambers and galleries carved out in salt which are situated in the upper part of the mine. Some wooden tools and appliances from Bochnia have become a part of permanent exhibition in the underground museum in Wieliczka. Since 1993 the touring route in the Bochnia salt mine was arranged between two main shafts: Sutoris and Campi. These two shafts are connected by longitudinal gallery of the first mine level called August. The level founded at the beginning of the 18th century is situated at the depth of 212 m below the surface, reaching the length of 3 km. Section open to tourists, over 2 km long, leads through old workings: galleries, crosscuts and internal shafts in the mine.

Some of these workings are protected by the wooden lining and filled up with barren rocks. To the touring route have been included old mine workings of the neighboring parallel levels (Wernier, Lobkowicz and Sienkiewicz). The main objects of the touring route are chambers: Wernier, Christian, Stanetti, Rabsztyn, St. Kinga and Ważyn) as well as galleries and cross-cuts, mine staircases, wooden hauling gears and other tools, sculptures and paintings. In old cross-cuts natural geological forms have been preserved (Fig. 4).

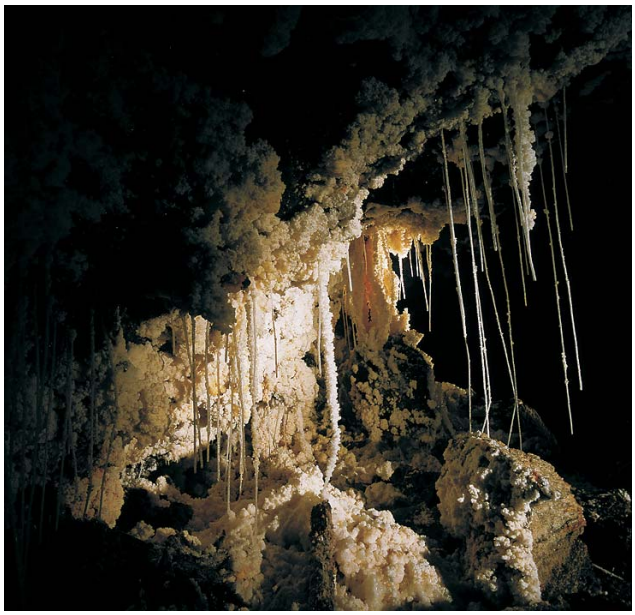

Fig. 4. Stalactites in a cross-cut section. Level Lobkowicz. Figs. 4, 6 photo of the Bochnia Salt Mine

Fig. 6. Ważyn chamber

Fig. 7. Wooden slide and steps heading into Ważyn chamber. Figs. 7, 8 photo of the Bochnia Salt Mine

On the level August, after 1747 was built the largest chapel in the Bochnia mine and dedicated to St. Kinga (Fig. 5). It is about 31 m long, 21 m wide; an average height is 5 to 6 m. The chapel is furnished with two altars and several sculptures carved both in wood and rock salt. On the walls and ceiling very distinct features of salt tectonics are exposed.

On the level Sienkiewicz (about 250 m below the surface) after 1697 in several stages the Ważyn chamber was developed (Fig. 6). In recent years this chamber was remodeled with the use of modern mining machinery; it is about 300 m long and adapted to the functions of a sanatorium, recreation, sport and social events. The subterranean sanatorium with a unique microclimate is an ideal place for treatment of respiratory diseases, bronchial asthma, and allergies. The sanatorium provides to the visitors overnight stays and such medical facilities as equipment for inhalations. A stable temperature inside the Ważyn chamber is 14 to 16 °C. Direct access from the August level to the Ważyn chamber provides connecting shaft equipped with a lift for visitors. Another access to the Ważyn chamber is also possible by dip heading furnished with steps and wooden slide for children (Fig. 7).

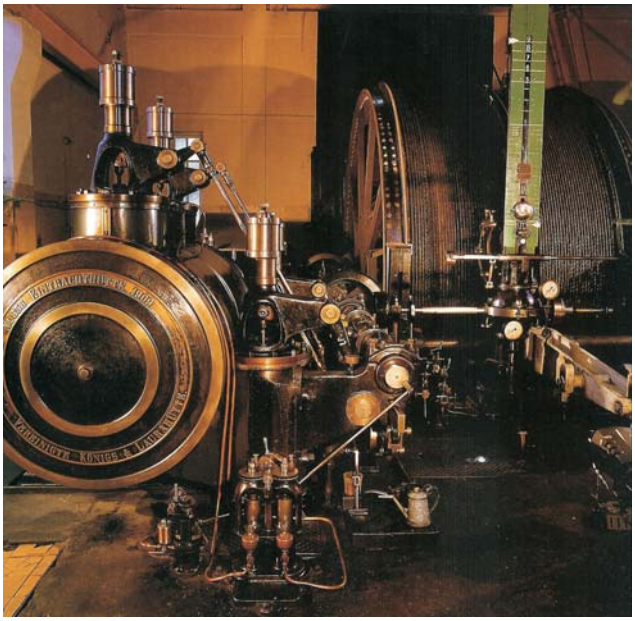

Fig. 8. Old steam winding engine of the shaft Campi

A special attraction furnished for the visitors is underground trip along the August level between two shafts (Sutoris and Campi). The train on rails is hauled by the battery-powered locomotive. It is said that it is the only case in the world with the train passing through the central part of the church (it means through middle of the St. Kinga chapel).

On the surface, close to the shaft Campi there is exposed steam engine for many years operating in the shaft. It was manufactured in 1909 in Silesia and has been preserved in excellent technical condition up to now (Fig. 8).

During last few years the number of tourists visiting the Bochnia mine has been increasing gradually. In 2007 the number of visitors already exceeded 130 000 persons.

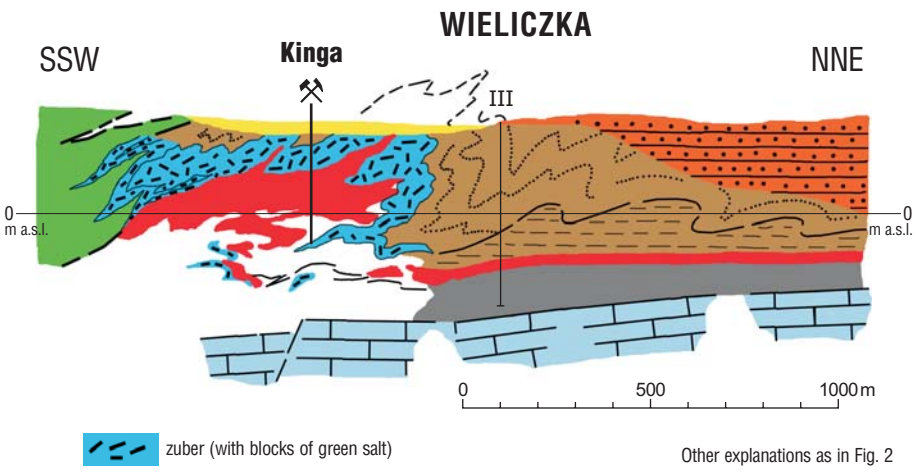

Fig. 9. Cross-section through the shaft Kinga (after Garlicki, 1968; modified)

Wieliczka

Geological structure of the Wieliczka salt mine has been already described in numerous papers (Gaweł, 1962; Poborski & Skoczylas-Ciszewska, 1963; Garlicki, 1974, 1968; Kolasa & Ślączka, 1985; Ślączka & Kolasa, 1997; Bukowski, 1997). The most comprehensive publication is that of Gaweł (1962), in which numerous detailed cross-sections have been presented. The salt deposit at

Fig. 10. Shaft Daniłowicz. Figs. 10, 11 photo by A. Grzybowski

Wieliczka situated 13 km south of Cracow, is 1 km wide, about 6 km long, over 425 m deep, and consists of two essential parts (Fig. 9). The upper one is developed in the form of coarse breccia (*boulder deposit*) composed mainly of salty clays (*zuber)*, with blocks of coarse-grained salt, called green salt. These blocks of irregular shape and various thicknesses in some places reach an extension of more than 150 m. Some authors (Kolasa & Ślączka, 1985; Ślączka & Kolasa, 1997) have stated that the boulder deposit was formed due to submarine gravitational slumps and flows (olistostrome), developed on a tectonically active basin slope. This part is supposed to be the facies equivalent of the lower one. The lower part of the deposit is developed as a complex of salt layers strongly folded, deformed and thrust over one another, being usually called *stratified* or *bedded* part of the deposit. Within the lower part of the Wieliczka salt deposit three main anticlines have been distinguished (southern, central and northern). They are elongated northwards, reduced in thickness and form a kind of scales (imbricated folds) piercing up into the boulder deposit. East of the Daniłowicz shaft the northern scale is transformed into a domal structure of the Crystal Caves. The salt layers of the stratified deposit are interbedded with anhydrite and anhydritic clays. In this part of deposit occur considerable complexes of the shaft salt and spiza salts, which used to be very important subjects of exploitation up to the 20th century. From the south, flysch deposits in the form of tongue-shaped wedges are squeezed into the inner part of the salt deposit (Garlicki, 1974). Western part of the Wieliczka salt deposit called Barycz, about 1 km wide and 2 km long is separated from the underground mine by 200 m wide safety pillar. During 1923–1998 there took place exploitation of salt by leaching salt through boreholes carried out from the surface, whereas the Wieliczka salt mine stopped an output of salt in 1996.

Reconstructed normal stratigraphic profile of the stratified part of the deposit is as follows (from the bottom):

- ❏ anhydritic claystones and siltstones,
- ❏ the oldest salts (varigrained with admixture and intercalations of clay, silt and sand);
- ❏ salty sandstones and siltstones, partly conglomeratic;
- ❏ set of green layered salts (numbered I–V), intercalated with anhydritic claystones;
- ❏ shaft salt (coarse-grained salt devoid of mineral admixtures but containing traces of gaseous hydrocarbons);
- ❏ lower spiza salts (or spizum salts);
- ❏ central intercalation (anhydritic claystone);
- ❏ upper spiza salts (both lower and upper spiza salt are coarse-grained, banded, with intercalations of sandy anhydritic clays);
- ❏ claystones, siltstones and sandstones, anhydritic in the upper part.

The primary thickness of this sequence was about 70 m. The lowermost part of the profile (including the oldest salts) corresponds to the first and second cyclothems recognized within autochthonous unit of evaporites. Green layered salts, shaft salt and lower spiza salts belong to the third cyclothem, whereas the fourth cyclothem contains the upper spiza salts. At the bottom of evaporites and within the lower part of the green layered salts three thin tuff intercalations have been distinguished, being the important marker beds (Garlicki & Wiewiórka, 1981).

Historical salt mine at Wieliczka consists of two parts:

- ❏ touristic route, comprising galleries, chambers, and other mine workings occurring from the first to third level (from 64 m to 135 m below the surface);
- ❏ exhibition of underground museum located on the third level.

The first part is managed and subordinated to the governmental join-stock company Salt Mine Wieliczka, the second is administered by the Cracow Saltworks Museum, representing Ministry of Culture and National Heritage.

The Wieliczka Mine has several shafts (Daniłowicz, Kinga, Kościuszko, Regis, Górsko) and mine working levels, from the first situated at 64 m below surface to the last one at the depth of 327 m. In the upper part of the mine the old exploited area comprises a network of chambers and galleries the total length of which exceeds 200 km. In this part of the mine an original underground touring route and museum have been arranged. The touring route (about 2 km long) starts at main touristic shaft Daniłowicz (Fig. 10) and leads to the depth of 135 m (third mine level) passing through galleries staircases, artificial lakes, chambers, and chapels carved out of salt blocks during the 17th to 20th centuries. The underground museum has several sections showing both the history of salt mining in Poland and geology of the Wieliczka salt deposit.

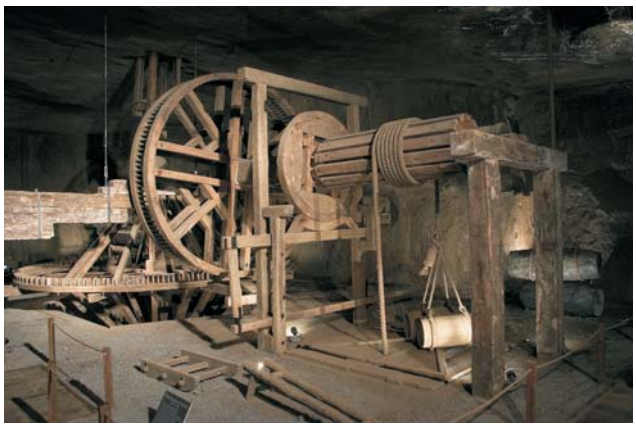

Fig. 11. Horse-powered treadmill. Polish type

Fig. 12. St Kinga chapel. Figs. 12, 13, 14 photo by A. Grzybowski

The large exhibition of Muzeum Żup Krakowskich (the Cracow Saltworks Museum) situated in chambers: Russeger, Maria Teresa, Miejska, Kraj, Karol and Modena on the third level of the mine, presents various methods of salt extraction, safety systems, outstanding works of sacred art, geology of salt and sulfur deposits in Poland, results of archaeological excavations in the vicinity of Wieliczka, history of salt industry in southern Poland, old mining mechanisms and equipment for transport and many others.

Among mining equipment of special interest are various types of horse-powered treadmill (Fig. 11) and a wide scope of tools used in salt mining.

In geological section a great attraction are Permian color salts, specimens of big crystals and numerous fossils well preserved inside the rock salt.

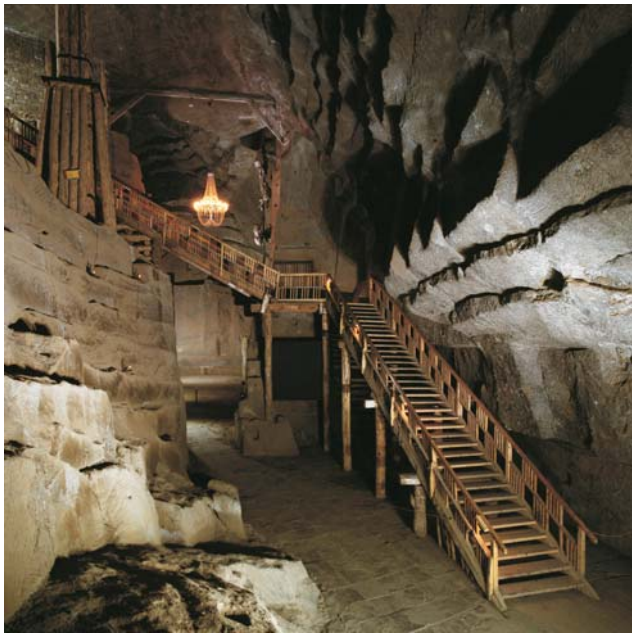

Fig. 13. Saurau chamber

One of the largest and most beautiful is the chapel of St. Kinga founded at the depth of 101 m (Fig. 12). It is 54 m long, 18 m wide and 12 m high. The walls of the chapel are decorated with sculptures and bas-reliefs representing Biblical scenes (e.g. *The Flight to Egypt*, *Herod's Sentence*, *The Slaughter of the Innocents*, *The Miracle at Cana of Galilee*, *The Last Supper*).

On the main altar of the chapel there is exposed monumental sculpture of St. Kinga carved out in translucent salt and the background of the figure is made of pure large salt crystals (taken from the Crystal Caves). The floor of St. Kinga chapel is one uniform flat plane of salt, with secondary carved channels in form of separate tiles. Interior of the chapel is illuminated by chandeliers made of pure crystals of salt.

Besides St. Kinga chapel there are many famous chambers and namely: St. Anthony, Drozdowice, Michałowice, Weimar, Warszawa, Saurau, Pieskowa Skała, J. Piłsudski, E. Barącz, S. Staszic, N. Copernicus. Chamber Saurau is an example of conservation works using modern technologies in order to preserve this object of old mining for the next generations (Fig. 13). Some chambers have been filled up with saturated brine and equipped with special illumination (light and sound). Among the largest underground workings of the Wieliczka mine Warszawa chamber is worth mentioning, situated at the depth of 125 m. It is intended for cultural and sport events with accommodation for about 1000 persons.

Fig. 14. Wall of the Crystal Cave

At the depth of ca 80 m there occur unique Crystal Caves. During the 18th and 19th century intense mining works were carried out in order to explore new salt reserves in the eastern part of the mine. Special attention was paid to seepages and outflows of fully saturated brine. Protecting works against water influx hazard resulted in the discovery of complex system of fissures and cavities in the Upper and Lower Crystal Caves. At the end of the 19th century the chamber Baum-Schwind was discovered. There occurred very pure and large crystals of halite (Fig. 14). Their edges sometimes reach about 50 cm (Alexandrowicz, 2000).

For the youngest visitors there have been arranged sets of sculptures carved in rock salt presenting dwarfs, legends, fables, famous persons etc.

Fig. 15. Group of geologists inspecting underground exposures. Spiza salts, chamber Wałczyn, first level. Photo by S. Klimowski

Over 50 years ago, some 200 m underground, a sanatorium for patients with bronchial asthma and allergic diseases has been established. The microclimate in the chambers left after extractions of salt produces excellent effects and sensational curing results.

Since the Middle Ages the salt mine in Wieliczka has been visited by many famous citizens of Poland as well as foreigners. Their signatures are exposed in many documents and Visitors' Books.

Each year over one million tourists visit the Wieliczka Mine, which is one of Poland's top touristic attractions.

An integral part of the Cracow Saltworks Museum is the Saltworks Castle (called *Saline Castle*), erected on the surface, which used to be the historic seat of the Saline Authorities from the 13th to 20th century. Currently it houses the Cracow Saltworks Museum with its offices, exhibition rooms, collections and library. There are permanent and temporary exhibitions in the Castle. There commonly take place such special events as conferences, workshops, shows, games and concerts. The Saltworks Museum is also a scientific institute taking care of underground exhibitions, carrying out research and editorial activities.

Final remarks

In the underground workings of both salt mines students of the University of Science and Technology (AGH) carry on their field exercises in surveying, mining, geology and underground mapping. Some big chambers in the Bochnia and Wieliczka salt mines are the places of sport tournaments (e.g. championships in basketball, tennis, handball, volleyball, football) or such scientific and social events as conferences, seminars, symposia, meetings, classes for pupils of schools, temporary exhibitions and fairs. For these purposes some chambers have been specially equipped with facilities (conference rooms, projectors, screens, panel discussion rooms, cafeterias and even banquet halls). Besides regular group of tourists, sometimes special trips for those connected with mining professions are guided to selected places of interest (Fig. 15).

In order to preserve these mines for the future generations, continuous long lasting and very expensive maintenance works are required. Unfortunately, due to these works many interesting geological exposures must be cover up by the wooden lining.

Both chapels of St. Kinga at Bochnia and Wieliczka offer unforgettable experiences to visitors, but they also serve religious purposes. Every year solemn masses are celebrated in these churches, at least on Christmas Eve, on the St. Kinga's Day (24th July) and on St. Barbara's Day (4th December).

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