The complex hydrogeology of the unique Wieliczka salt mine

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A b s t r a c t. The salt mine in Wieliczka is a mining plant which is unique on the worldwide scale, which has been developing since the Middle Ages until the present times. The high geological complexity of bedrock in the vicinity of the mine, which is associated with the Carpathians orogeny, determines the high level of complexity of local hydrogeological conditions. At present, about 260 l/min of water discharges into the mine, which is considered very high as for a salt mine. 86% of that amount comes from three major inflows, i.e. WVII-16 (from Fornalska II chamber), WVI-32 (from Z-32 chamber) and WVI-6 (from Z-28 chamber). These seepages cause threats to the mine, not only due to their large volumes but also due to high quantities of salt that is leaching from the rock mass. The most troubled area in the Wieliczka salt mine, from the hydrogeological viewpoint, is the northern border, where salt deposits are in contact with strongly dislocated sandstones via a gypsum-clay layer. These sandstone deposits comprise not very productive aquifers that, to some degree, are isolated from one another.

Keywords: *rock salt, hydrogeology, water catastrophes, Wieliczka Salt Mine*

The Wieliczka Salt Mine is a world famous cultural and historical monument, with unique sculptures and bas-reliefs that were sculpted in rock salt by numerous artists between the 17th and the 20th century. It is for the beauty and uniqueness of the interiors of remarkable post-exploitation chambers that the salt mine in Wieliczka is visited by over a million tourists from all over the world each year.

In parallel to that, the Wieliczka salt mine is one of the best known mining corporations in the world. Its technological uniqueness is based on 700 years of continual mining experience that started in the 13th century and continues until now. Salt pits of the Wieliczka salt mine are situated at seven operational levels that reach 330 m deep and are 350 km long. The rock mass consists of a Tertiary salt formation that has been densely cut through by numerous mining pits, pavements and chambers. The total number of chambers left opened after the salt extraction amounts to 2000, and their total volume is estimated at ca. 7.5 mln m^3. The complex of some 300 chambers and some 50 km of pavements between them constitute a legally protected heritage site. It is estimated that during the 700 year long history of the salt mining business in Wieliczka, some 50 mln tonnes of this produce have been extracted. The Crystal Caves (Groty Kryształowe) are one of many exceptional geological features of the Wieliczka salt mine. These are two chambers, called the Upper and the Lower, of a capacity of 1000 m^3 and 706 m^3 respectively, where walls and roofs are covered with natural salt crystals, often having their ideal shape (Fig. 1). The Crystal Caves were discovered at the end of the 19th century during salt mining in the eastern fringes of the mine. Due to high protection offered to natural formations of salt crystals, visiting the site is very restricted (Brudnik et al., 2000).

The salt mine in Wieliczka is an especially interesting place for hydrogeologists. Due to the complex geological structure of the mine, which was recognised during the mining of the successive pits, and mainly as a result of human errors (while mining), the natural isolation of the salt bed was broken and several large seepages were induced. The total groundwater inflow to the Wieliczka mine, during normal mining conditions, is very high and amounts to ca. 15.6 m^3/h (260 l/min). In comparison, in the neighbouring and only slightly less famous salt mine in Bochnia, the total groundwater inflow is estimated at nearly two orders of magnitude less, that is ca. 0.44 m^3/h (7.3 l/min).

During its entire history, in difficult geological mining conditions there were frequent geological catastrophes in the mine, which were associated with subsiding roofs of shallow post-extraction chambers and groundwater inflow to the mine. There are few well documented cases of groundwater leaks into the mine from the past 140 years; however, one of the most dangerous ones occurred not that long ago, in 1992.

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The large density of mining pits within the salt bed and the large number of research studies undertaken to counteract natural threats to the mine allowed for very precise identification of hydrogeological conditions in the vicinity of the salt mine in Wieliczka.

History of the salt mine in Wieliczka

The salt mining industry in the vicinity of Wieliczka has a very long history. The beginning of the salt making in this area is dated to the middle Neolithic time, that is 3500 B.C. At that time, salt was extracted from saline springs, which, due to salt making operations, lost their salinity or disappeared. It is likely that rock salt deposits were discovered in the Middle Ages, during deepening of saline wells. Since then, exploitation of rock salt beds started (Kolasa, 1990).

The oldest document dealing with the salt mining industry in Wieliczka is the royal charter by King Kazimierz I, from 1044 A.D., in which the salt mine is referred to as *Magnum Sal*, which means the Great Salt. Old evidence of the salt mining industry in Wieliczka comes from a foundation charter for the monastery in Tyniec from 1105, which comes from the times of King Bolesław Chrobry (996–1025), when salt was extracted by salt making and by mining. In the Middle Ages, the king had a monopoly over salt mining and its distribution, the salt being the basic product used for conserving food, including meat. Salt mining works were then undertaken by private entrepreneurs who had special tools and well qualified employees. These businessman were taking on themselves all risks associated with the investment and the only way they could recover their funds was by finding a salt bed. When a new salt bed was found, the king took over the new mine and paid an investment fund back to the investor, including a rent charge, and used to appoint the entrepreneur an important staff member within the mine's hierarchy. In the 14th century, when King Kazimierz Wielki ruled the country, income from the Wieliczka salt mine provided some 30% of national revenue. These funds covered the costs of building the Wawel Royal Castle in Cracow as well as allowing funding and providing means of support to the Royal Academy (the initial name of the Jagiellonian University). The *Kazimierzowski Status*, dated 1368, which was considered a legal act at that time, included a detailed description of rules for salt extraction, its trade as well as responsibilities and privileges of different groups of workers employed by the Wieliczka salt mine. Throughout the following years, technological improvements were introduced into the mine, exchanging simple linear shafts for ladder wheels and later horse treadmills. With technological improvements, salt could be exploited from deeper and deeper levels, successively deepening the mine. In the 16th century, the salt mine in Wieliczka was one of the biggest enterprises in Europe. Groups of specialised workers gathered around the mine, including miners, clerks, and also craftsman, who supplied the mine with various tools and products. Collections of the oldest maps of the Wieliczka Salt Mine, made by Marcin German in 1638, are presented in the Museum of Cracow Salt Mines. The first confirmed cases of visiting the salt mine in Wieliczka come from the end of the 18th century when they were sporadic and reserved for the elite only.

Fig. 1. Crystals cover fragment of the Lower Crystal Cave. Photo by J. Przybyło

The next phase of the history of the salt mine industry is the period of Polish partitions, when at the end of the 18th century the southern part of Poland (called Galicia) was included in the Austrian Empire. During that time, intensive development of the mine and the town of Wieliczka took place, including building a power station and a railway line that linked the town with Cracow. New mining techniques were introduced to the mine. Mechanical mining methods using pneumatic drills, salt mills and steam lifts became more and more popular. In 1911, the lye method for salt extraction was implemented in the mine. Subsequently, in the following year, the mechanical salt works were opened.

The partition period was a breakthrough point for salt mine tourism, during which organised tours around the mine were introduced. There was no special route created in the mine, but tourists were given a tour throughout the production area and places in which mining works were finished. From numerous reports regarding those visits, the main interest of tourists was focused on underground chapels, cut in the salt rock, where there were many sculptures and paintings of saints. The first official tourist route was established at the turn of the 18th and 19th centuries and the majority of it is still in operation at the present time (Kurowski, 1990).

Over the period of 1918–1939 the salt mine in Wieliczka was developing very rapidly, not only with regard to its mining business but it also expanded on its tourist and therapeutic functions. The enlarged extraction of salt that started in the Wieliczka mine during the Second World War continued after the war in the 1940s and 1950s. Increased intensity of work in the vicinity of historical chambers led to the progressive destruction of tourist pits. At the end of the 1950s, the first measures were taken to secure some parts of the tour and a special funding instrument was created, called the Preservation Fund for the Historic Mine in Wieliczka, whose function was to secure the natural heritage of the mine. In 1965, production of salt using dry mining methods was ceased in the mine, and after 1978, the central and western parts of the mine were closed down. At present, due to depletion of the salt bed available for safe extraction, the mine carries out only the enrichment of saline groundwater coming from seepages. Brines that are created in this process are directed to a modern salt making facility, which produces some 2650 kg/h of rock salt (Ślizowski & Saługa, 1996b).

The salt mine in Wieliczka, as the only mine in the world that has been operating since the Middle Ages, has been included on the UNESCO World Heritage Site list. It was one of the first 12 sites from all over the world included on the list.

Geological setting

The salt mine deposits in the vicinity of Wieliczka comprise a part of the Miocene salt formation that occurs within the Carpathian Foredeep, in the shape of a narrow strip, which runs from Upper Silesia, throughout Cracow and Tarnów, towards the eastern border of Poland.

The Wieliczka bed runs in the direction from West to East and extends for some 10 km, and its width in the vicinity of Wieliczka town is some 1.2 km. The bed lies in an area of a complicated geological structure. The most important in this regard are the Carpathian flysch deposits that are densely folded and shifted towards the north (Fig. 2).

In response to strong tectonic movements in the vicinity of Wieliczka, associated with the Carpathian orogeny, the salt bed is divided into two distinct parts: blocky deposits (breccias), where salt beds are highly dislocated and mixed with respect to one another; and layered deposits, where despite frequent tectonic movements the general layering and sequencing of layers remained undisturbed.

Due to the fact that blocky salt deposits lie at generally shallower depths, these deposits were subjected to early mining exploitation. The specific lumps of salt, often with large sizes and volumes reaching 100 000 m^3 were dug out from the inside and at present their remnants form chambers located at upper levels of the mine. Parts of them are included in the tourist route throughout the Wieliczka Salt Mine (Fig. 3).

The thickness of the salt formation within the Wieliczka salt bed is some 350 m and comprises three subsequent lithostratigraphic layers:

- ❏ Skawina beds,
- ❏ Wieliczka beds (salt formation),
- ❏ Chodenice beds.

Skawina beds lie at strongly dislocated formations of the older basis, mainly on the Upper Jurassic limestone formation. The thickness of these deposits ranges from some 50 m in the western part of the bed to some 350 m in the eastern edge. These deposits comprise grey-green marls, rich in organics (Foraminifera) marls, sandstones and claystones.

Wieliczka beds comprise rock salt, gypsum and anhydrite. In its lower parts, despite frequent deformations and folds, the bed preserved its continuity and layering. Numerous different types of rock salt occur in the Wieliczka beds profile with variable thicknesses and NaCl content. The most significant types of salt rocks are as follows: the oldest salt bed; a complex of layered green deposits; shaft salt deposits; and a complex of red bronze salts with characteristic striped deposits. Salt beds are separated from each other with layers of siltstones, claystones and sandstones that represent sulphate facies of gypsum and anhydrite. In the upper part of Wieliczka beds, above the layered part of the bed, blocky deposits occur. These mostly consist of

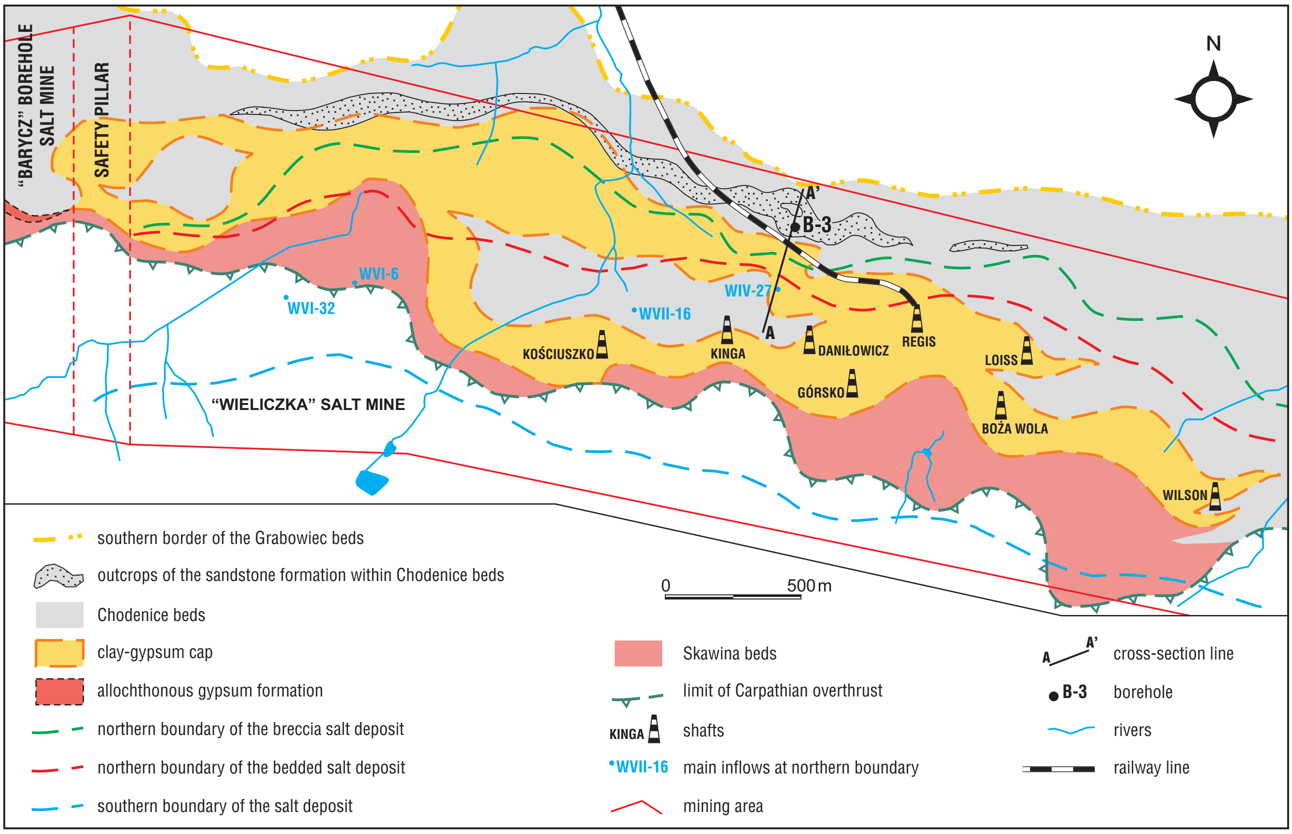

Fig. 2. Geological map of the Wieliczka salt mine

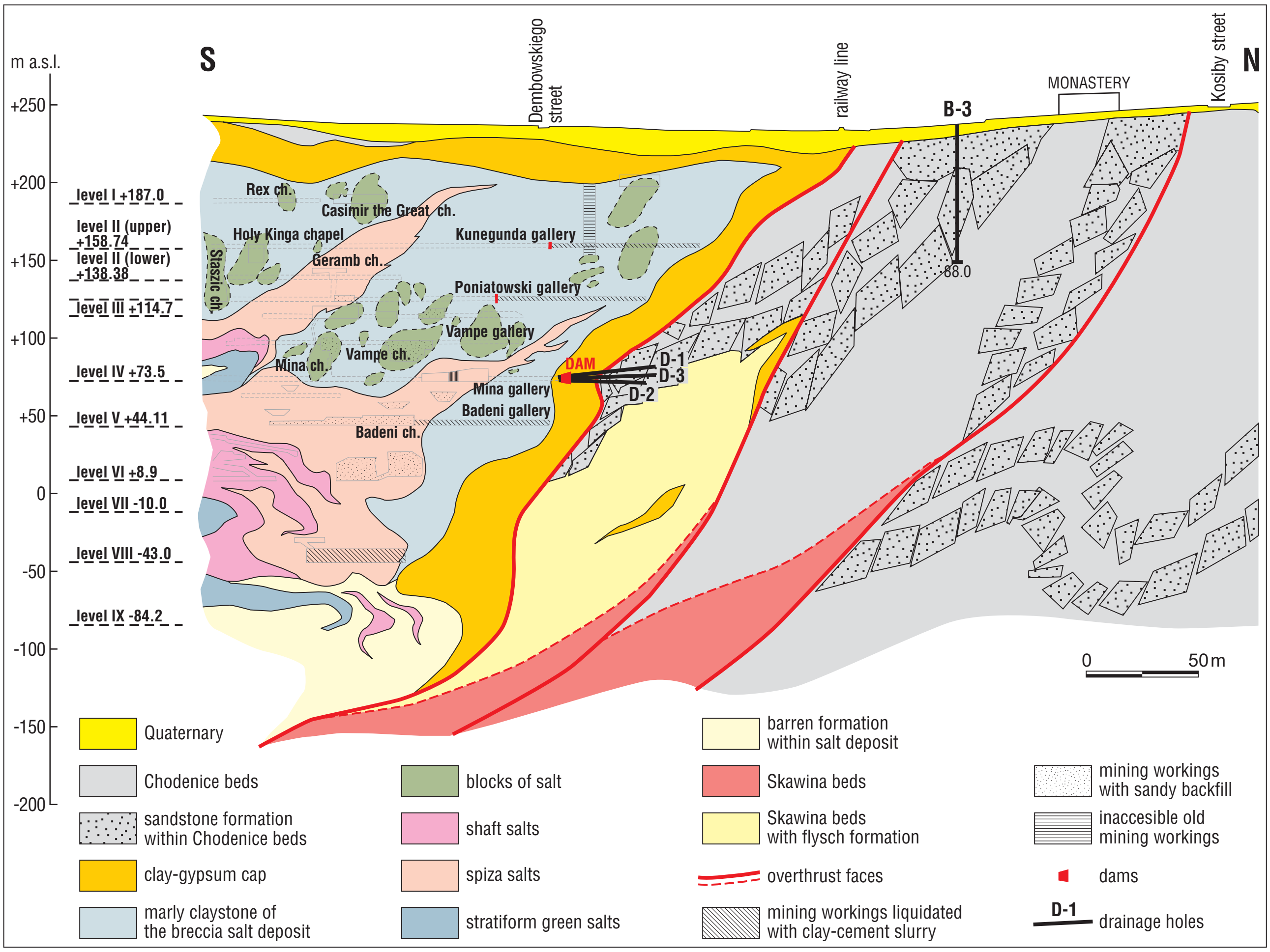

Fig. 3. Geological cross-section at the northern edge of the Wieliczka salt mine

blocks of marly claystones, among which salt cubes of different sizes are located irregularly. The majority of these salt deposits are laminated green salts and large grained salts, called stained salts (Ślizowski & Saługa, 1996a).

Chodenice beds are represented by dark grey siltstones, clayey shale deposits and siltstones containing lenses of gypsum and anhydrite, limestone and dolomites. There are also some formations of sands, conglomerates and clastic sediments within the complex of Chodenice layers.

At the top of the evaporite, there is the youngest Quaternary layer with highly variable thickness and lithology. Within the quaternary profile, the most common are clays and silt sediments with lenses of sands and gravels.

Hydrogeological settings

Rock masses in the vicinity of the salt mine in Wieliczka usually have low permeability and low water storage. There are four water levels within the Tertiary deposits (Tab. 1) and one in the Quaternary one.

The oldest water level occurs within the Tertiary stage and is associated with the sandstones and mudstones of Skawina beds and, occurring within the same system, fissured marly claystones. The Skawina bed formation comprises fissured groundwater bedrock aquifers, where water is confined and occurs under relatively high water pressure of 3.8–4.0 MPa. Conductivity of the Skawina bed formation ranges between 10^{-7}–10^{-9} m/s.

Small amounts of water can be associated with sulphate bearing layers at the fringes of the salt bearing evaporite formation. Water occurs here mainly in sandstone lenses in the main rock mass of marly claystones and the gypsum-mudstone cap. Gypsum rocks contain water mainly in fissures and cracks and within karst features that have developed within the rock. Water within evaporite rocks is confined with hydrostatic pressure of up to 3.0 MPa. Conductivity within these rocks is usually between 10^{-8} – 10^{-7} m/s.

The next water level, in the Tertiary rocks, occurs within Chodenice beds. In general, these rocks are hardly or slightly permeable – mudstones and clayey shales.

There is, however, a layer of poorly consolidated and crumbly, coarse-grained sandstones and a lens of fine sands and mudstones. Water in sandstones or sands within the Chodenice bed complex is confined with water pressure of 1.6 MPa. Hydrogeological studies were undertaken for sandstones mainly and proved conductivity ranging from 5.8×10^{-9} m/s to 6.4×10^{-6} m/s.

The youngest water level within the Tertiary formation occurs within Grabowiec beds, which consist mainly of

Table 1. General characteristics of the Tertiary water-bearing horizons

Stratigraphy	Aquifer rocks	Aquifer type		Groundwater pressure [MPa]	Conductivity [m/s] / [m/d]	Permeability rank	Specific capacity [l/min/m]	Average salinity of water [g NaCl/dm3]	Number of boreholes	Number of measurements
Grabowiec beds (Bogucice sands)	sand, weak sandstone	porous	unconfined, locally confined	0.015–1.5	$2.4\times10^{-5} - 8.5\times10^{-5}$ / $2.073 - 7.36$	medium	55.0	0.3	13	14
Chodenice beds	mudstone, silt, sand and coarse-grained sandstone with claystone interbeddings	porous-fissured	confined, locally unconfined	0.0–2.5	$5.8\times10^{-9} - 6.4\times10^{-6}$ / $0.0005 - 0.55$	semi-permeable ÷ practically impermeable	0.04–8.58	5.0–58.5	24	52
Evaporite formation	marly claystone with anhydrite and gypsum	karst- fissured	confined	0.20–3.2	$2.5\times10^{-9} - 7.2\times10^{-6}$ / $0.00022 - 0.619$	low-permeable ÷ semi-permeable	0.03–0.167	140–254	11	11
	sandstone and mudstone with gypsum and anhydrite interbeddings	porous-fissured								
Skawina beds	marly claystones, sandy marls, mudstone and sandstone	porous-fissured	confined	0.12–1.2	$1.0\times10^{-7} - 8.2\times10^{-7}$ / $0.0086 - 0.071$	semi-permeable ÷ practically impermeable	0.21–1.70	68.1–295.2	5	7

Bogucice sands. This layer lies directly above Chodenice beds and is in direct contact with Quaternary deposits, recharged by precipitation, overlying the Grabowiec bed formation. Conductivity of Bogucice sands is very high and ranges between 2.4×10^{-5} m/s and 8.5×10^{-5} m/s.

The Quaternary water level in the vicinity of the salt mine in Wieliczka is associated with sands of variable particle sizes, gravels and rubble. The water table in these deposits is usually unconfined or sometimes slightly confined. The depth to the groundwater table in the Quaternary deposits reaches a maximum of a couple of metres.

History of water intrusions into the Wieliczka Salt Mine

The very good solubility of rock salt in water, reaching 360 g/dm^3, allows for using the leaching method for its exploitation. At the same time, this characteristic feature of salt, as the mass building rock, is a very unfavourable attribute in the vicinity of a pit. In the event of groundwater intrusion, where groundwater is not fully saturated, NaCl leaches from the rock making the rock mass very unstable. This mechanism is regrettably well known from several major accidents that happened in the history of salt mining.

The most famous Polish catastrophe of that kind was an accident that happened in the Wapno salt mine, which exploits a small salt dome of the Permian salt bed (Zechsteine). Over a night from 4th to 5th August 1977, a sudden increase in water inflow occurred in a place where a few years earlier, young meteoric waters were found using the isotopic tracer analysis. Due to intense dissolution of the salt rock mass, large parts of the ground surface started to subside, causing damage to more than 40 buildings and structures. The scale of the catastrophe and its fast progress forced more than 1500 people living in Wapno, central Poland, to be evacuated quickly (Zuber et al., 2000).

In the history of the salt mine in Wieliczka there were a few events when, due to increased groundwater inflow to the salt bed, the subsidence of the ground surface caused extensive damage to buildings and structures. It is likely that such events had been occurring in the salt mine in Wieliczka, with variable intensity, from the beginning of the mine's foundation. No written documentation regarding such events exists; however, there are some printouts presenting damaged buildings that were destroyed by subsiding ground. Such events could have been caused either by the presence of post-exploitation chambers at shallow depths or by the process in which salt minerals in rocks are dissolved by groundwater.

The oldest documented case of a catastrophe associated with groundwater leakage into the salt mine in Wieliczka regards the year of 1868. Fresh groundwater leaked into Kloski crosscut at the 5th level and into Colloredo crosscut at the 4th level at a rate of 360 m^3/h (6000 l/min). The rate of seepage became reduced to some 0.3–3 l/min in 1879 due to collapsing rock masses in the vicinity of the seepage area. At the present time, there is no possibility to get near the seepage at Kloski crosscut. Water seeping in there flows to the lower (6th) level, to

Regis crosscut, where groundwater also leaks into the mine at a rate of 2–3 l/min.

The next event of a sudden groundwater inflow into the mine occurred in 1959, in the Kosocice crosscut, which is located at the 5th and the 6th levels. Inflow of fresh, unsaturated groundwater at a rate of 60 m^3/h (1000 l/min) appeared from an old borehole that was left open. The leak was plugged and head pressures were recorded at the plug with a maximum value reaching 20–25 atm. In the following year, inflow of unsaturated brines with mineralisation of 190 g/dm^3 was recorded at Schmidt crosscut. Discharge of groundwater inflow that was created due to a subsidence of Schmidt adit ranged from 0.04 to 3.5 m^3/h (0.7–60 l/min). As in the case of Kosocice crosscut, groundwater inflow at Schmidt crosscut was plugged and hydrostatic pressure recorded at the dam reached 7 atm over the past few years. Large groundwater inflow into the Wieliczka salt mine occurred in 1966. As a result of the uncontrolled development of Z-32 chamber, located at V/VI level, inflow of unsaturated groundwater from outside the salt formation occurred. The leak of an initial salt content of 140 g/dm^3 NaCl and groundwater flow rate at some 3.6 m^3/h (60 l/min) was captured outside the salt bed, underneath the Z-32 chamber. This groundwater seepage still exists and is monitored by an internal groundwater monitoring network of the mine (point no. WVI-32; Fig. 4).

The next episode of large groundwater inflow into the mine happened in 1972. Groundwater inflow occurred in a chamber known as Fornalska II and had relatively low salt content of ca. 70 g/dm^3 NaCl and a flow rate of 9–20 m^3/h (150–330 l/min). The seepage area was secured by destroying adjacent chambers and creating a dam that closed the Fornalska II chamber. The leak was later enclosed using a tubing casing which still exists as a monitoring point WVII-16 (Fig. 4).

In 1981 another leak was found at the 6th level of the mine, in Kosocice 3 crosscut, in the vicinity of post exploitation chambers Z-28 and Z-25 that were exploited in the 1960s at a border of the salt bed. The inflow was primarily coming from a discharge pipe located in the Z-28 chamber. Initial groundwater inflow rate was some 10 m^3/h (167 l/min) and, with time, it decreased to 1.5 m^3/h (25 l/min) and later to 0.6–0 m^3/h (10–13 l/min). While the flow rate was decreasing, the salt content in groundwater was rising to a point of fully saturated brine. Since the beginning of the leak, the flow rate has been sustained at a constant level of 0.75 m^3/h (12.5 l/min); but the salt content decreased to ca. 55–65 g/dm^3. In the mine's groundwater monitoring network, the leak was given the number of WVI-6.

The most dangerous groundwater leak to the mine in its recent history happened on 13th April 1992. In Mina crosscut, at the 4th level, a groundwater inflow of unsaturated brine with a high content of silt and sands occurred with a rate of 12 m^3/h (200 l/min). A small leak with the flow rate of a few l/min was known in this location before and was created in 1911–1913 by puncturing an isolating layer between the salt bed and adjacent saturated sandstones while extracting the salt bed from Mina chamber. In the early 90s, as part of a project that aimed to liquidate a number of groundwater leaks into the Wieliczka Salt Mine, a decision was made to stop the groundwater inflow into the Mina crosscut. The groundwater inflow into that pit, which happened in April 1992, was associated with reconstruction works at the end of the crosscut before the final closure of the inflow (Garlicki & Wilk, 1993). Many attempts to cease the leak resulted in increasing flow rates, and each time, the groundwater leakage was rich in sediments and had the consistency of a pulp. The mass loss that was being created within the mine as a result of soil transfer into the mine resulted in deformations of ground surface. North of Mina crosscut, a large subsidence trough was created, which covered an area between the mine and the Monastery of Franciscan Fathers. The centre of the basin occurred at a railway line linking Wieliczka with Cracow causing damage to its trackways. Specifically large land deformations occurred at the monastery grounds, where walls surrounding the monastery were damaged and cracks with a depth of 2–3 metres occurred in the hill on which the monastery stands (Fig. 5). The failure of Mina crosscut caused numerous cracks and crevices in the monastery's walls, whose stability was greatly endangered in light of the further development of the subsidence trough. To remedy the situation, two-component polyurethane resin was injected into the trough

Fig. 4. Two main water inflows in the Wieliczka Salt Mine (from the left) WVII-16 and WVI-32. Photo by J. Motyka

Fig. 5. Beginning of the subsiding trough formation on the outskirts of Mina crosscut. Photo by J. Przybyło

using boreholes drilled in the vicinity of the scouring basin. A waterproof dam was also built in Mina crosscut, within the gypsum-clay layer surrounding the salt bed. To do so, groundwater inflow into Mina crosscut had to be taken away and this was achieved by pumping water out via boreholes drilled from the ground surface (drainage line R). Three horizontal drainage boreholes were drilled (drainage line D), which drained water seeping from outside the salt bed, directly from Chodenice sandstones. After finishing building the dam, the total groundwater discharge from drainage boreholes accounted for some 7.2 m^3/h (120 l/min). Within the groundwater monitoring network of the Wieliczka mine, this inflow was named as WIV-27. For the subsequent 15 years after the Mina crosscut accident, a programme of measures was carried out in the mine that aimed at tightening and reinforcing the pit in the vicinity of the dam by injecting a mortar of cement and silt. Between May and October 2007, drainage pipes in Mina crosscut were either liquidated or plugged and groundwater inflow into the pit was successfully stopped.

Analysis of all accidents of groundwater leaks that occurred in the Wieliczka Salt Mine proved that the majority of them resulted from human errors while undertaking mining operations. They were usually associated with either accidental puncturing the natural gypsum-clay barrier that surrounds the salt bed and encroachment into Chodenice sandstones or with uncontrolled enlargement of post-exploitation chambers. In the case of the oldest documented water catastrophes of the 19th century, the reason for which they happened was a collapse of a post-exploitation chamber that created an opportunity for groundwater to inflow into the mine's pit.

All water catastrophes that happened in the Wieliczka Salt Mine, despite the expensive losses that they created, led to very good recognition of the hydrogeological conditions of that unique mine. This is due to numerous expensive studies that were undertaken in order to protect the threatened existence of the mine, and which would probably never have been undertaken if there were no failures in the mine.

Groundwater inflow into the mine

Groundwater inflow into the Wieliczka Mine had increased with time in parallel to subsequent water accidents described above. Escalation of these cases occurred after the 1960s and carried on until the catastrophe in Mina crosscut in 1992. It was at the beginning of the 1990s, when groundwater inflow volumes into the mine reached their maximum level, which in 1994 was estimated at 29.1 m^3/h (ca. 485 l/min). Over the subsequent years, the inflow stabilised at a little below 24 m^3/h (400 l/min) (Fig. 6).

Liquidation of the inflow at Mina crosscut, which just before its closure was some 7.2 m^3/h (120 l/min), led to sharp decline in the total groundwater inflow volume into the mine, to a volume equivalent to that from before the catastrophe.

The total groundwater inflow into the Wieliczka Salt Mine is a sum of all leaks at several pits. To prevent any unforeseen water hazards, the mine undertakes continuous monitoring of groundwater inflows including water condensation on the mine's walls (Fig. 7). At present, the total number of inflow zones that are under continuous observation is 170. However, there are three major leakages that dominate the total inflow volume and these are remnants of past catastrophes that happened in the following chambers: Fornalska II (WVII-16), Z-32 (WVI-32) and Z-28 (WVI-6). The total discharge volume from these three leaks is 13.32 m^3/h (222.02 l/min), which constitutes nearly 86% of the

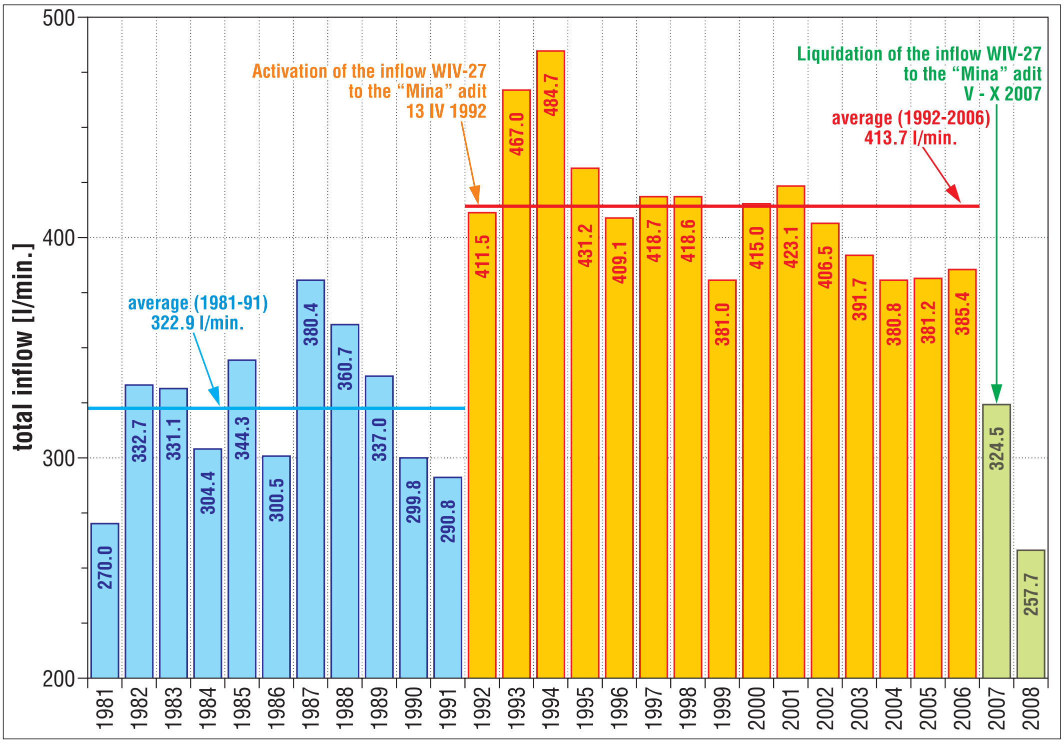

Fig. 6. Groundwater inflow to the Wieliczka salt mine during the period of 1981–2008

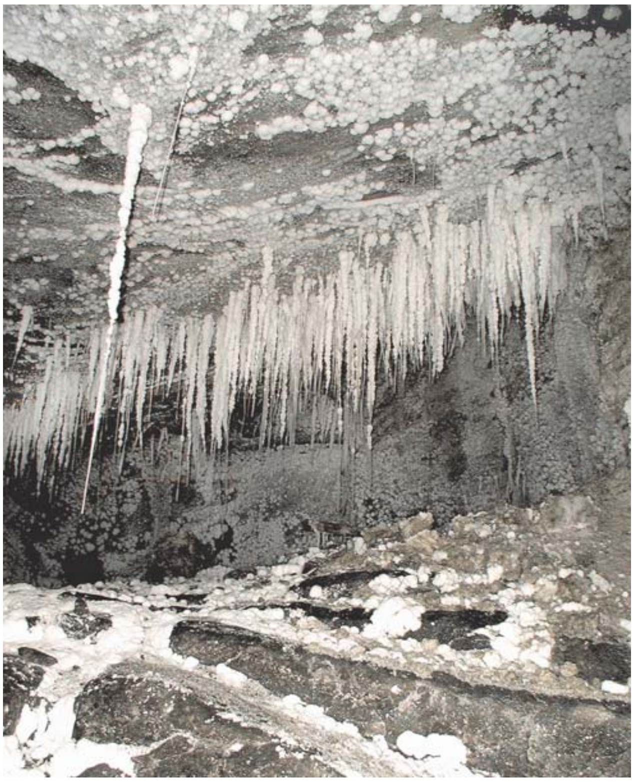

Fig. 7. Artificial dripstones in a Ferro chamber in the vicinity of the inflow WIIn-19. Photo by J. Przybylo

total groundwater inflow into the Wieliczka Salt Mine. The remaining over 160 leaks/condensation areas give only 2.14 m^3/h (35.71 l/min), which is barely 14% of the total groundwater inflow (Table 2).

Genesis and distribution of water inflows

Salt deposits of the Wieliczka Salt Mine are, obviously, totally dry. All leaks into the salt pits come from outside the boundary of the salt bed, mainly from Chodenice sandstones (85%) that borders the bed from the north. The remaining 15% of water discharge is associated with water movement of brines between horizontal layers (8%), from Skawina formations underneath the salt bed (5%) and from Quaternary deposits that lie above the bed (2%).

The contact zone of the Wieliczka bed with saturated sandstones of the Chodenice formation runs parallel to the northern edge of the salt bed. From the hydrogeological viewpoint, this area is the most troublesome zone. All of the most dangerous water leaks that have occurred in the mine happened within pits located in the northern border of the mine, where the naturally isolating barrier of the gypsum-clay casing was accidentally cut through on a few occasions.

All groundwater inflows from rocks that surround the salt bed are continuously monitored due to a serious flooding hazard in the event of their intensification. Key parameters that the groundwater monitoring system of the mine focuses on are the inflow rate, salinity and the amount of suspended solids in groundwater. In all current groundwater leaks to the mine, including the major three, all the above parameters have been relatively stable over the past decades.

Groundwater leaks and water condensation are also continuously being checked using isotopic methods. Results of this work indicate high variability in the age of these isotopic waters (from present times to pre Holocene) and their very irregular stratification. The reason for this lies in the very specific structure of the Tertiary water bearing layer – the Chodenice sandstones formation. This layer was strongly deformed by tectonic movements which made rock fragments become highly displaced in relation to one another. There is general hydraulic connectivity within the Chodenice sandstones; however, water bearing deposits within the specific tectonic rock masses are isolated from one another and constitute rather poor groundwater aquifers. Such a structure of the mine's surroundings increases the safety of the Wieliczka Salt Mine. There are no major groundwater aquifers in its direct vicinity, which, in the event of cutting through the gypsum-clay casing that surrounds the mine, could flood the mine.

Hydrogeological effects of liquidation of the groundwater inflow in the mina traverse

Hydrogeological data gathered during the accident in Mina crosscut and the liquidation of the groundwater inflow in this location allowed for an interesting interpretation of hydrogeological conditions within the water bearing layer of the Chodenice sandstones. The leak was named WIV-27, and during its existence it was the 2nd major groundwater inflow into the mine with a rate of 7.59 m^3/h (126.5 l/min). The leak originated from the Chodenice sandstone formation that was controlled with three horizontal drainage pipes (D-1, D-2 and D-3). These were drilled in the face of the water dam that was constructed in the end of the crosscut.

In May 2007, the groundwater discharge from the D-1 borehole, in which water had flowed at 7.2 m^3/h (120 l/min), was plugged. As a result of this, the groundwater discharge at the D-2 pipe increased from 6 l/min. to 20 l/min. In the case of the D-3 pipe, after a short period of variable discharge ranging between 0.5 and 1 l/min, the flow stabilised at 0.7 l/min. The total discharge volume stabilised at 20.7 l/min after some 105 hours from plugging the D-1 pipe. There was practically no effect of the liquidation of the D-1 pipe on the discharge from two other draining pipes (D-2 and D-3) which allowed the decision to be taken (October 2007) on the total closure of the inflow into the Mina crosscut.

During the successive closure of leaks from the remaining drainage pipes, changes in the hydraulic head within the bed were observed. In the case of the D-2 borehole, some effects of liquidation of the D-1 hole were observed, which resulted in building up pressure by some 0.6 MPa. After the final closure of the D-2 hole, a sudden increase of pressure from 0.7 MPa to 1.3 MPa was ob- served. In the following phase, rebuilding the pressure in the D-2 borehole was slow and from the middle of October 2007 until the end of 2009 it increased by only 0.2 MPa (Fig. 8).

Table 2. Water inflow balance for the Wieliczka salt mine dewatering system

Inflow	Location	Activation time	Actual situation (2008)				
			Discharge [m3/h]	Discharge [l/min.]	Discharge [% of total inflow]	NaCl [g/l]	Solids [g/l]
WVII-16	level VII chamber Fornalska II	december 1972	9.50	158.26	61.4	64.69	0.009
WVI-32	level VI chamber Z-32	nineteen sixties	3.10	51.73	20.1	236.18	0.001
WVI-6	level VI chamber Z-28	mid nineteen eighties	0.72	12.03	4.7	61.60	1.164
Sum of the three major inflows			13.32	222.02	86.2	104.48	–
Remaining inflows			2.14	35.71	13.8	218.66	–
TOTAL INFLOW			15.46	257.73	100.0	120.30	–

With regard to pressures observed in the D-3 hole, after the initial phase of changeable conditions in June 2007, no major effect of the liquidation of the D-1 drainage hole was observed over the subsequent few months. Even plug- ging the D-2 hole caused rather a small increase in water pressure in the D-3 hole (only by some 0.07 MPa). It was only after closing the D-3 drainage hole that a sudden increase in hydraulic pressure, over 5 hours only, from 0.23 MPa to 1.42 MPa was observed (Fig. 9). At the same time, hydraulic pressure measured in the D-2 hole was at 1.39 MPa. Similarly to the D-2 hole, starting from the middle of 2007 until the end of 2009, a continuous increase in pressure was observed in the D-3 hole, when it changed from ca. 1.4– 1.42 MPa to 1.54 MPa (Fig. 8).

Changes in hydraulic pressure after closing the drainage pipes followed the same pattern in the case of both drainage holes. A large increase in pressure, by 0.6-1.2 MPa, was observed in the first stage. This phenomenon can be associated with flooding the volume of drainage pipes and free spaces in the vicinity of discharge zones. The next stage on the pressure curve (Fig. 8) is associated with the slow recovery of the water table in Chodenice sandstones.

Analysis of changes in the hydraulic head after closing the D-2 and D-3 holes was undertaken using specialist software – *Aquifer Test ver. 3.0* by *Schlumberger Water Services*. To define hydrogeological parameters of the water bearing layer drained by the D-2 and D-3 holes, the *Theis Recovery Method* was used.

Conductivity of the Chodenice sandstones, estimated from the pressure curve for the D-2 and D-3 holes was small and reached 5.68×10^{-8} m/s and 3.41×10^{-9} m/s, respectively.

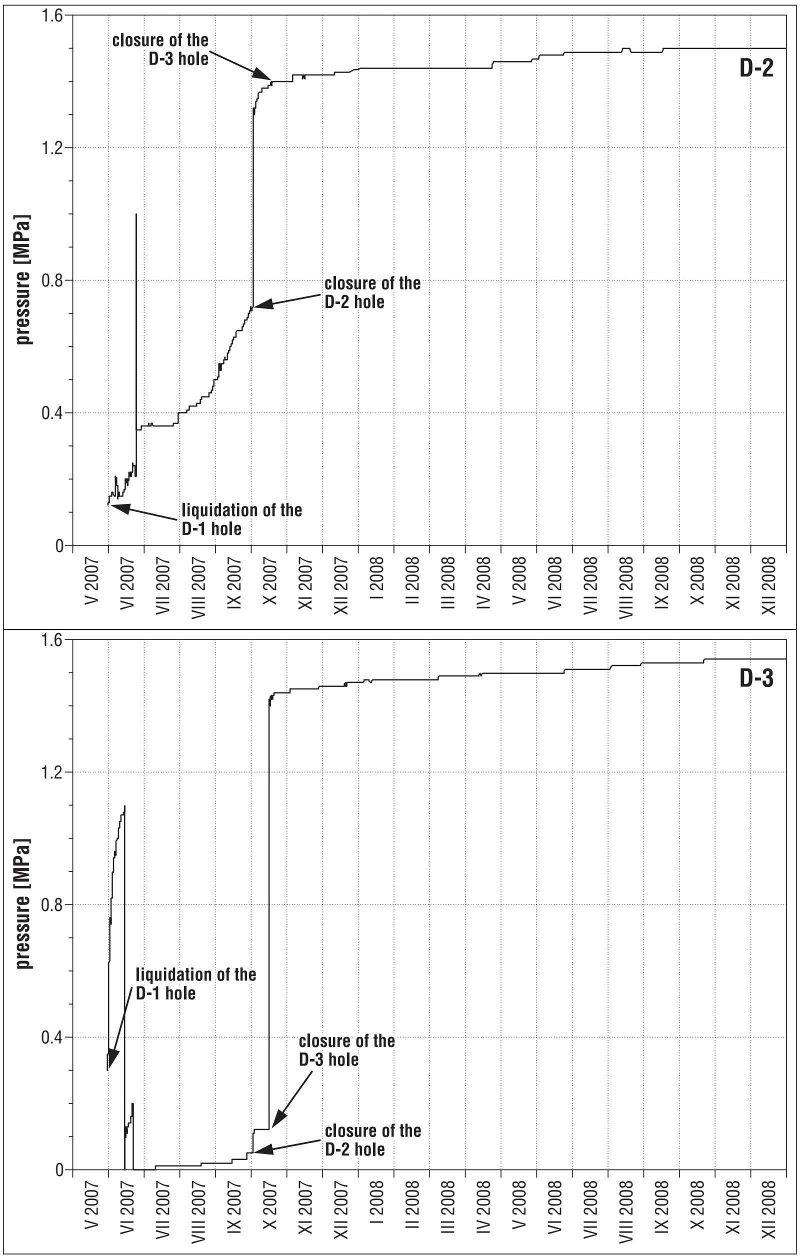

Fig. 8. Water pressure changes in the drainage holes D-2 and D-3 connected with liquidation of the inflow WIV-27 in the Mina crosscut

Results of changes in the hydraulic pressure observed in the D-2 and D-3 holes and the B3 well, which was located in the Monas- tery, were also analysed using the Horner test. This method allows the approximate hydraulic head in tested holes and the conductivity within Chodenice sandstones to be established.

Recovery of the pressure observed in all the above holes showed that rebuilding the natural conditions occurred in a stable manner, which is in line with theoretical principles. Groundwater from the depth of the Mina crosscut will reach a pressure higher than that in subsurface groundwater layers and will flow towards the nearest depression located in the vicinity of the railway line and the Sefara River valley, i.e. to the natural drainage zone of Chodenice sandstones.

The linear pattern that was shown from the Horner test allowed the assessment of permeability conditions of Chodenice sandstones and the definition of approximate conductivity for the formation. Conductivity of the Chodenice layer at the Mina crosscut's depth (except for the tighten zone of drainage holes D-2 and D-3) was established at 4.4×10^{-7} m/s, and in the subsurface area (B-3 well) it was 7.6×10^{-7}m/s.

Interpretation of data gathered while preparing for closure of the groundwater leakage at the Mina crosscut (leak no. WIV-27), gave another proof of low water storage within Chodenice sandstones. In addition, lack of any reaction to subsequent closures of drainage holes that were located closely to one another proved the significant isolation of individual blocks of sandstone (rock masses).

Summary

The Wieliczka Salt Mine is a unique monument that is visited by over a million tourists every year. The mine is especially interesting for geologists and hydrogeologists, because it cuts through a highly complex rock stratum. Since not that long ago, there has been a possibility to take a geological tour through the mine that is less accessible for tourists due to its lower flow capacity than a regular tour.

Due to the few water leaks into chambers and workings located in the northern border of the salt bed, the Wieliczka salt mine has relatively large groundwater inflow of some 15.6 m^3/h (~ 260 l/min). The inflow should be considered large as the amount of water leaking into the mine over 1 hour is the same order of magnitude as the daily groundwater inflow into the adjacent salt mine in Bochnia.

Despite relatively large volumes of groundwater discharging into the Wieliczka mine, it is naturally sheltered from water catastrophes. The decisive factor for that is not the clay-gypsum casing that shields the bed, as this was punctured in the past by mining activities and uncontrolled development of post exploitation chambers. Of the biggest importance in this matter is the structuring of the Chodenice sandstone formation, which is the major water bearing layer discharging into the mine. Despite general hydraulic connectivity within the water bearing layer of Chodenice sandstones, the formation comprises numerous small water bearing zones of little water storage. In the event of cutting through such a zone, large groundwater discharge is observed only at the beginning of an accident, which is associated with draining static groundwater resources. This initial stage is very dangerous to the safe functioning of both the mine as well as structures at the ground surface, as leaking water quickly dissolves salt from the rock mass causing rocks to collapse and the ground surface to subside. With time, groundwater leaks significantly reduce their discharge rates and, when properly managed, they do not cause any threat to the safe functioning of the mine.

At present, the Wieliczka Salt Mine is safe from water hazards. However, one cannot exclude potential future groundwater leaks into the mine. Closing down the mining activities within the Wieliczka salt bed guarantees that the gypsum-clay casing surrounding the mine will not be cut through by workings or uncontrolled development of post-exploitation chambers. However, one cannot exclude a potential collapse of rock masses in the proximity of workings and chambers located along the northern, most dangerous border of the mine. Taking into account the above, it is necessary to continue further reconstruction works in this area and successive filling in the post exploitation chambers.

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