Hydrogeochemistry of the Mine Water from "Bochnia" Salt Mine (Kraków Region, South Poland)

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Abstract "Bochnia" salt mine, located about 40 km east from Kraków, is one of the world oldest mines with about 765 years old history. The amount of water inflow into the mine from the surrounding rocks range from 9.11 to 14.59 m^3/d, averaging 11.24 m^3/d. Total dissolved solids in the mine water from "Bochnia" mine range from 5.6 g/L to about 311 g/L. The lowest values of the TDS are observed for the inflows in the shallow mining levels and highest TDS in a deepest levels. As a consequence of salt dissolution mine water possessed Na-Cl type.

Keywords hydro-geochemistry, mine water, salt mine, Bochnia, Poland

Introduction

"Bochnia" salt mine is located in the south of Poland about 40 km east from Kraków (fig. 1). It is one of the world oldest mines, operating continuously since 1248. Rock salt mining was indeed finished in 1992, but the operations related to maintaining the mining infrastructure have been still carried on, since the mine is now a tourist facility with a big accommodation, didactic and spa center. "Bochnia" mine has three shafts Trinitais, Campi and Sutoris, and their openings are located at the depth from 76 m to 330 m below the surface.

"Bochnia" salt mine is located within the

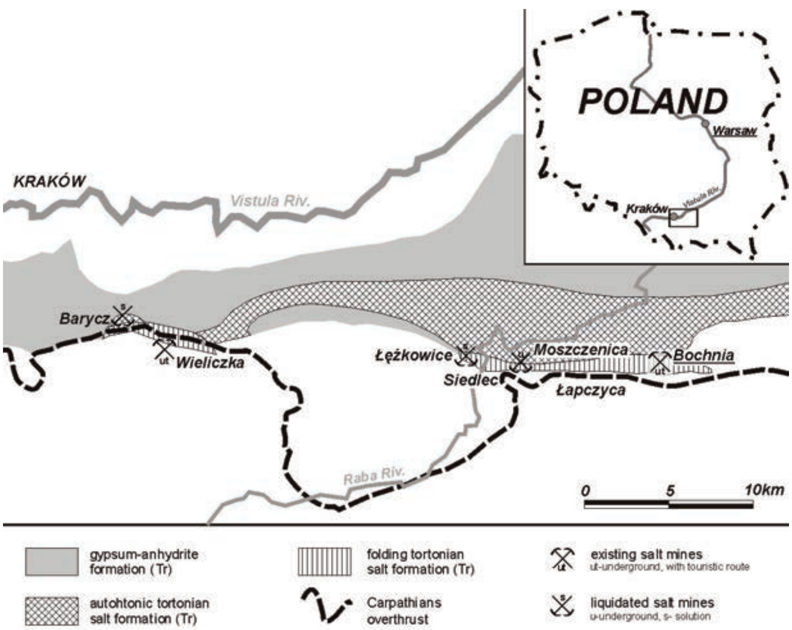

Fig. 1 *Map of the salt deposit occurrence near Cracow (Osika 1970).*

series of practically impermeable rocks. However, some water from the rocks surrounding the mine, mainly from the overburden, inflows into the mine. The water inflow to the salt mine is potentially dangerous for stability of the ground over underground workings. As a consequence of the intensive salt dissolution catastrophic events with mine and surface failures were observed in the past. In Poland in the 1970s the Wapno Salt Mine located in a salt dome was completely destroyed by the catastrophic inflow of low TDS groundwater from gypsum-clay cap formation. In the 1990s also the famous Wieliczka Salt Mine had the event with hazard inflow of groundwater originating from the outside surrounding rocks not related to the impermeable gypsum-clay cover formation. The methodology of detailed research on the groundwater inflows, hydrogeochemistry and isotopic composition was started in Polish salt mining industry after Wapno Salt Mine catastrophe. This research is especially important for the historical mines (Wieliczka and Bochnia) which are operating also as tourist centers.

Geology and Hydrogeology

“Bochnia” salt deposit occurs on the Carpathian Foredeep, in its south part within the so-called allochthonous Miocene folded on Carpathian foreland. The equally famous “Wieliczka” salt mine is located there as well, about 30 km west from Bochnia (fig. 1).

“Bochnia” salt mine is located in the north side of the steep fold (Bochnia fold) within allochthonous Miocene (fig. 2). The Miocene formation is represented by claystone with silty and sandy intercalations (over-salt series – Chodenice beds), gray claystones with salt and anhydrite (salt series) and claystones (Skawina beds) underlying the salt series. In the core of Bochnia anticline, additionally flysch (Cretaceous-Tertiary) rocks composed of the alternating beds of sandstones and claystones occur there (Garlicki 1968, Wagner *et al.* 2010).

“Bochnia” salt mine is located within the series of claystones, which are practically impermeable. However, some water from the rocks surrounding the mine, mainly from the Quaternary formations, Chodenice beds (Tr) and flysch rocks (Cr-Tr) being a part of Bochnia anticline core, inflows into the mine.

Mine Water

Inflow of water from the layers occurring above the deposit formation takes place through the old workings or abandoned shafts since lots of them have been excavated during 765 years of mining operations. Most of those excavations have been self-closed by collapse or compression, but those areas are the preferred ways of underground water flows, allow-

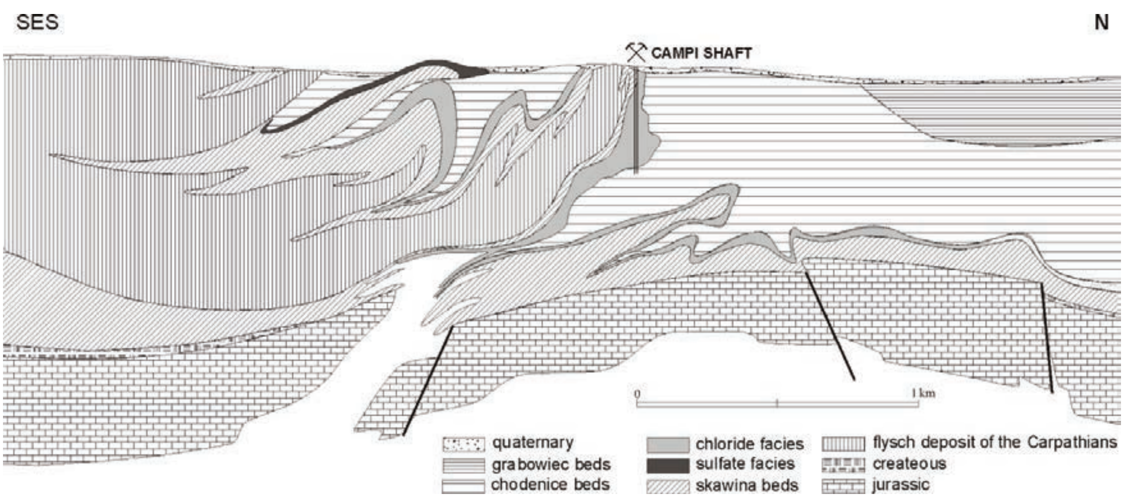

Fig. 2 *Geological cross-section of the “Bochnia” salt deposit (Garlicki 1968)*

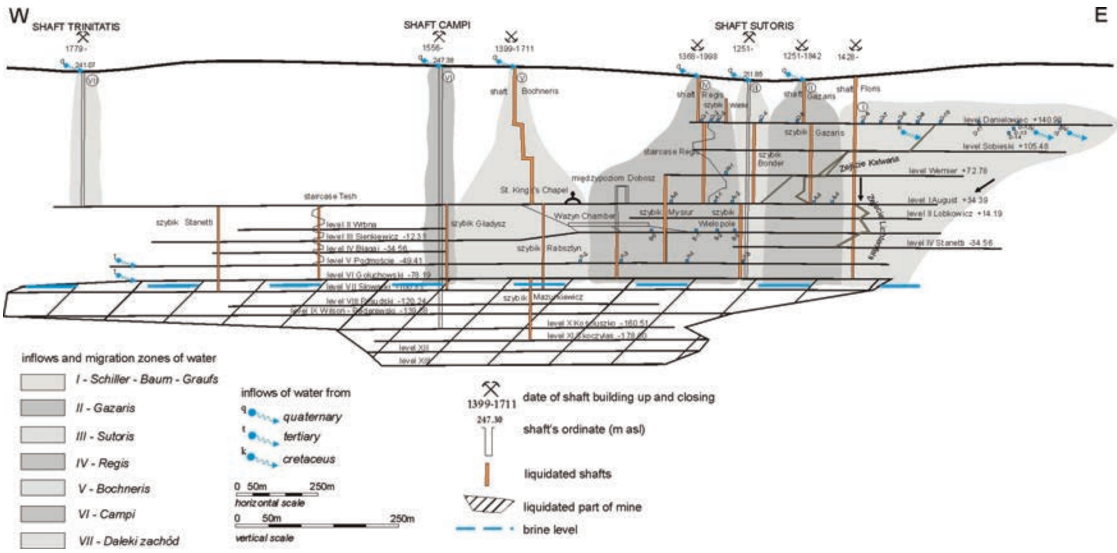

__Fig. 3__ Scheme of the groundwater inflow zones to the "Bochnia" salt mine

ing the inflow of infiltration waters directly from the surface (fig. 3).

The amount of water inflow into the mine from 2001 to 2011 ranged from 9.11 to 14.59 m^3/d, averaging 11.24 m^3/d. Main inflows into "Bochnia" salt mine are concentrated on the shallowest mining level *i.e.* Danielowiec level. Only part of this inflow is directly taken, while the rest of water penetrates down to the deeper parts of the mine.

Mine Water Chemistry

Chemical composition of the water inflowing into "Bochnia" salt mine is very varied. Total of dissolved solids in the mine water from "Bochnia" mine range from 5.6 g/L to about 311 g/L (Table 1). The chlorides and sodium are of the highest values among all other elements and impacts strongly the water TDS. Chlorides in mine water from "Bochnia" mine range from 1.4 g/L (D-1) to 190.1 g/L (A-5). In the same

SampleID	Wtype	TDS	Na	K	Li	Ca	Mg	Sr	SO_4	HCO_3	Cl	SiO_2
		[g/dm^3]	[mg/dm^3]									
A1	Na-Cl	287.4	109096.4	348.5	3.5	613.7	1089.5	15.4	5474.1	346.6	170408.3	2.64
A2"	Na-Cl	257.7	95310.1	143.8	1.3	643.8	435.1	13.3	2908.7	137.1	158045.2	1.38
A3	Na-Cl	267.6	98529.4	273.6	3.6	665.6	916.2	15.6	5612.6	266.4	161600.4	2.48
A4	Na-Cl	261.9	101360.4	262.8	3.9	456.6	1000.0	10.8	4397.1	256.1	154106.7	1.65
A5	Na-Cl	311.1	112280.8	577.4	9.0	1254.9	1972.6	34.7	4660.6	129.3	190121.9	1.46
A6	Na-Cl	260.1	93402.6	625.0	11.7	1045.0	1339.8	25.8	3078.0	294.8	160260.1	2.05
D1	Na-Cl	26.6	8681.4	147.9	0.8	607.9	177.4	11.3	3842.9	605.2	13063.75	13.71
D10	Na-Cl	234.3	86583.3	110.4	1.7	769.4	438.3	10.5	2965.6	256.1	143104.2	1.09
D11	Na-Cl	310.9	118200.7	248.2	4.0	855.0	603.5	22.6	6619.6	170.7	184321.6	1.14
D12	Na-Cl	281.2	104901.7	173.2	2.8	615.2	442.6	16.7	4729.0	178.5	170314.0	2.42
D13	Na-Cl	305.1	112830.3	319.9	4.1	920.3	473.7	25.8	5604.1	131.9	184894.4	1.32
D14	Na-Cl	161.9	58067.8	694.9	6.7	3171.7	645.4	100.4	2936.8	121.6	96170.9	7.53
D2	Na-Ca-Cl-SO_4	5.1	1139.1	19.0	0.1	601.4	66.2	8.2	1693.3	488.8	1491.9	24.56
D3	Na-Cl	34.5	11450.7	125.0	0.9	752.1	204.8	13.9	4882.8	615.6	17087.4	6.59
D5	Na-Cl	57.0	19081.4	145.4	1.2	1289.2	334.4	31.4	4176.0	1761.3	31722.8	11.63
K1	Na-Cl	288.5	106143.8	154.3	2.6	692.7	654.5	16.6	6772.2	239.2	174009.9	1.07
Kanalek	Na-Cl	305.5	109938.6	454.5	9.1	500.9	1553.0	16.6	9943.7	253.5	183035.1	0.86
OS1	Na-Cl	308.6	115279.0	300.2	3.0	1073.5	888.6	23.8	5229.5	175.9	185610.5	1.13
P2	Na-Cl	304.2	106995.8	774.8	10.3	630.7	2755.1	22.3	7812.3	162.9	185041.4	1.55
P3	Na-Cl	308.1	112593.0	769.4	9.6	879.0	2062.2	24.0	6127.6	186.2	185467.3	1.55
P4	Na-Cl	303.5	111553.6	770.8	7.9	876.0	2149.2	25.5	5983.3	385.4	181743.6	5.37
P5	Na-Cl	308.7	114689.0	783.2	9.7	913.2	1952.1	30.2	6077.6	240.5	183963.5	3.83
Pompownia	Na-Cl	266.5	99054.7	434.8	3.7	1100.8	1483.6	21.0	4025.7	232.8	160046.1	12.18
Regis	Na-Cl-SO_4	67.9	22554.6	389.3	3.7	671.4	485.8	13.4	12699.2	266.4	31080.8	3.69
SO2	Na-Cl	311.1	115200.4	606.7	11.0	1518.8	2039.5	44.2	4069.1	212.1	187329.1	68.68
W1	Na-Cl	292.4	106044.1	185.9	1.5	1008.9	519.9	19.8	4244.0	297.4	180169.8	0.10

__Table 1__ Mine water chemistry for the samples from "Bochnia" mine.

inflow (D-1), the minimum concentration of sodium, equal to 1.1 g/L (D-1) was also observed, but the maximum value of this constituent, about 118.2 g/L, was measured in the D-11 inflow.

A relatively high concentration of sulfate, observed in the concentration between 1.7 g/L (D-2) and 12.7 g/L (Regis) is an important feature of the mine water from “Bochnia” mine is. In case of this sample, sulfate ion is incorporated into the water type so D-2 sample is a Na-Ca-Cl-SO_4 type and Regis sample is of Na-Cl-SO_4 type. Calcium and magnesium concentrations in all samples vary with the wide range, from dozens to a few hundreds mg/L to about 1–2 g/L.

The chemical composition of the mine water from “Bochnia” mine results from dissolution process of halite (Na Cl). Water inflowing to the underground working from the surrounding rock formation in contact with Na Cl increased the concentrations of chloride and sodium, and also TDS. Longer residence time of water within the mine workings increases the amount of dissolved salt. So, all mine water samples form “Bochnia” mine are located on

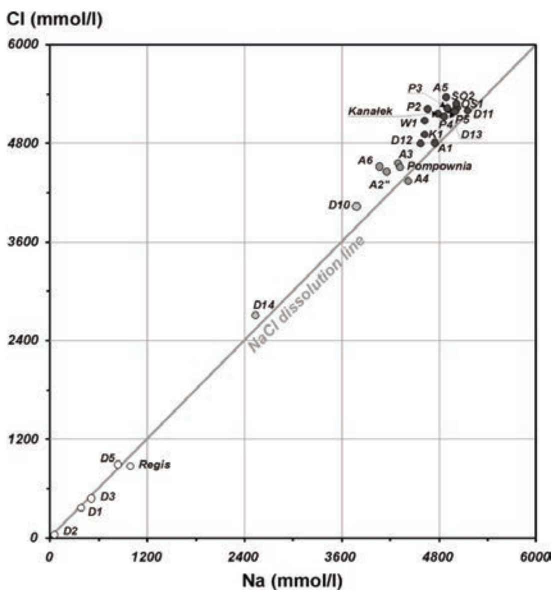

Fig. 4 *Chloride and sodium concentrations in mine water from “Bochnia” mine*

the theoretical line of the halite (Na Cl) dissolution (fig. 4).

Halite dissolution is the main process of mine water chemistry formation in case of “Bochnia” mine, but other processes, especially in the shallow part of the mine are also important. Inflow of the groundwater from the overlaying formations to the mine’s underground workings is connected with complete change of hydrogeochemistry. The sample D-2 from Danielowiec level has the lowest TDS, in the whole population of the samples, and this state is certainly connected with its origin from the Quaternary aquifer (sands and sandy loam). The water type in this point Na-Ca-Cl-SO_4 indicates that a process of dissolution both of halite and also gypsum is occurring.

Groundwater from the Quaternary deposits flow to the mine through fracture or discontinuity zones within gypsum-clay cover formation. Changes of the Quaternary water within “Bochnia” salt mine in the shallow Danielowiec level occur not only due to successive dissolution of halite (Na Cl) but also magnesium salts, mainly sulfate ($MgSO_4$). According to this process the increasing trend of the Mg/Ca ratio can be observed in the population of the Danielowiec level samples. Increasing trend in magnesium concentrations with relation to calcite is also connected with limitation of Ca level by gypsum solubility. In a spite of relative increase of Mg/Ca ratio the intensive dissolution of relatively pure halite results in decreasing of Mg/Na ratio(fig. 5).

Population of the mine water samples collected in the deeper levels of “Bochnia” mine originate from the Quaternary groundwater inflows to the main shafts (Sutoris, Regis, Gazaris and Bochneris). The water sample with lowest TDS for this group was collected in the Regis shaft and it shows chemical composition similar to the samples from the shallow Danielowiec level. In the deeper part of the mine the increasing admixture of magnesium salts in the halite is responsible for the increase of the relative concentrations of magnesium (or increase of Mg/Ca ratio; fig. 5). At

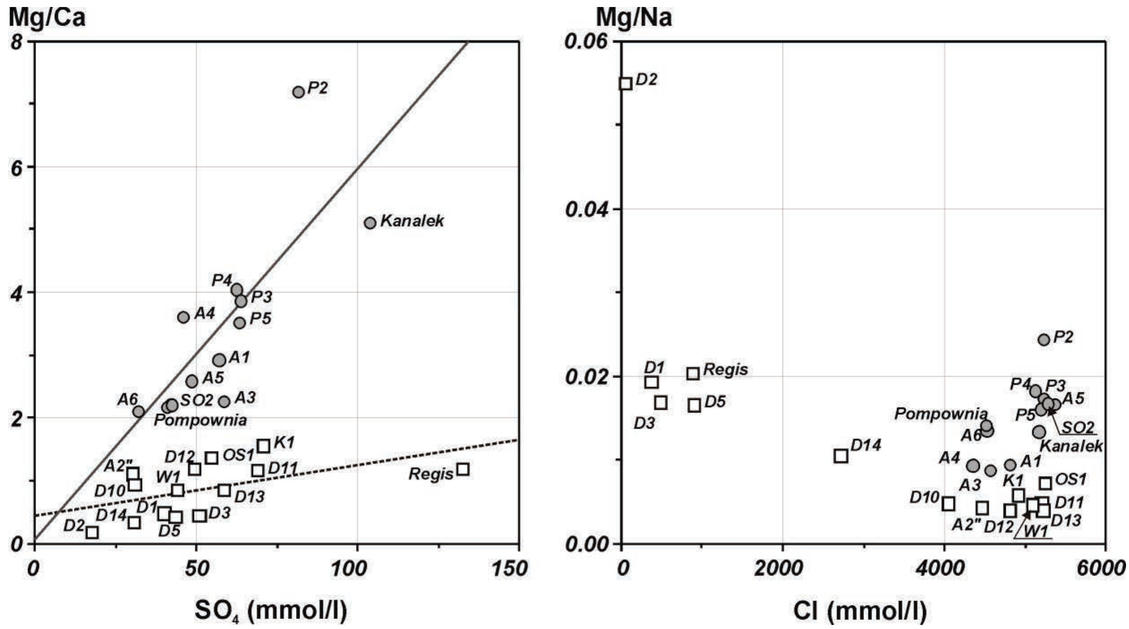

Fig. 5 *Relative concentrations of main ions in the mine water samples*

the highest concentration of magnesium and sulfate, the calcium level is limited by solubility of gypsum, and decreases to about a few hundreds of mg/L (Table 1). The trend of the Mg/Na ratio increase resulting from halite dissolution can be also observed but it is not so clear. It occurs due to large impurity of salt and increasing admixture of magnesium and potassium evaporate salts.

Conclusions

The lowest values of the TDS have been observed in the mine water inflows to the shallow mining level of "Bochnia" mine – Danielowiec, located at the depth of about 60–70 m. The group of the three inflows (D1, D2 and D3) with the lowest TDS between 5.6 g/L and 34.5 g/L is located close to the Regis shaft. This zone is known as possible hazard for mining galleries due to the inflow of slightly mineralized groundwater from the Quaternary aquifer, aggressive to the salt formation.

The next zone with low water TDS (inflow D5 – 57 g/L) is connected with the vicinity of the Gazaris shaft and also with the inflow of the Quaternary groundwater. Groundwater from the Quaternary aquifer inflowing into the zone of Sutoris and Gazaris shafts and migrating to the deeper parts of "Bochnia" mine is responsible for formation of the inflows with TDS of about 260–270 g/L at the August level located at the depth of 160–170 m.

Groundwater inflowing to the "Bochnia" mine from the Cretaceous flysch formation is observed also in the southern part of the mining area. The origin of the three inflows with the TDS between 160–260 g/L, located in the Danielowiec and August levels is strictly connected with Cretaceous groundwater. Total of dissolved solids in the other water inflows in the mining galleries of the "Bochnia" mine ranges from 280 g/L to 310 g/L. The origin of these inflows is connected with percolation of the natural and also artificial water (*e.g.* from drilling and mining operations) in the mining galleries. Low flow of water and also contact with salt formation is responsible for the origin of saturated brines.

Analysis of the water chemistry from inflows to the "Bochnia" salt mine is an important factor in safety of mining operation. Inflow of the groundwater, especially with low

TDS is potentially dangerous for stability of the ground in the vicinity of the mine (geotechnical problems). The main hazard for the "Bochnia" mine is connected with possible activation of the groundwater inflow from the Quaternary aquifer in the zone of shafts. Water chemistry analyses in the inflow are an important element of the failure preventing monitoring system.

Water chemistry of inflows in the shaft zones is relatively stable over the time. Groundwater from Quaternary aquifer dissolved some amount of evaporate minerals (halite and dolomite) in the border zone of "Bochnia" salt deposit. Small recharge of salt formation by the groundwater from Quaternary aquifer is a reason for minimizing the possible failure hazard in "Bochnia" mine.

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