

The analysis of destructive water infiltration into the Wieliczka Salt Mine – a unique UNESCO site

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The Wieliczka Salt Mine has been inscribed in 1978 on the first UNESCO list of World Cultural and Natural Heritage as a unique monument in the world scale. During more than 700 years of its operation, the inflow of outside water into the underground excavations constituted the biggest threat to the mine. Infiltration of water into the salt deposits can cause flooding of the mine and have a destructive influence on the state of the bedrock and the excavations through uncontrolled leaching of NaCl. The analysis of the geological structure and natural hydrogeological conditions in the area is one of many concerns in attempting to determine the water infiltration routes. Cluster analysis conducted for the different ions, and the correlations calculated, indicate that it is difficult to identify significant associations between the various ions other than the obvious and expected associations between, e.g., mineralisation of, Na and Cl, and Ca, Sr and SO₄. Similarly, the spatial distribution of the different ions in the analysed effluents does not allow to determine groupings of several effluents with characteristic changes in the content of one or more ions. Furthermore, no regularities are revealed by sample graphs of ion associations. Such considerations motivated focussing the work on the interpretation of ion concentrations which depart from the average, based on the analysis of the origin and location of the effluents, the geological structure, the operation time span for each region, the presence and accessibility of old chambers and galleries, and also the occurrence of chamber subsidence which reach the surface. It is possible to identify water migration routes and interpret the chemical composition of mine effluents only through a comprehensive analysis of the causes of water phenomena encountered in the mine which has operated since the thirteenth century.

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Key words: salt mine, underground water, ion concentration in the effluents, origin of effluents.

INTRODUCTION

Exploitation of salt deposits in the Wieliczka Salt Mine, ceased in 1996, led over the previous centuries to approximately 9.4 million m³ of underground excavations. Currently, as a result of closing down excavations and the contraction of the rock mass, approximately 4.4 million m³ of voids remain, consisting of 2.391 chambers and 245 km of galleries. Mining operations at the Wieliczka Mine have always been accompanied by problems with groundwater inflow into the excavations. Already in the first half of the fourteenth century, the Wodna Góra (“Water Mountain”) shaft was created in order to remove such water from the mine. The oldest preserved devices used for drainage, such as brine conducts, wooden pipes and water tanks, date back to the second half of the sixteenth century.

At the mine, 172 effluents with an overall volume of approximately 135 thousand m³/year are recorded. The most important of those, as far as the safety of the mine is concerned,

are grouped on the northern boundary of the deposit. Since, the effluents at the Level I have a destructive influence on the stability of the rock mass and the preservation of historic chambers the present study focuses on this level issues. The analysis of both effluents origin and evolution of their chemical composition allows better diagnoses to combat water hazards at all the levels of the mine.

GEOLOGICAL BACKGROUND

The rock salt deposits of the Wieliczka Salt Mine were formed in the Neogene period (Middle Miocene, Badenian Stage) within the Carpathian Foredeep Basin (see Oszczytko *et al.*, 2006 for recent summary and comprehensive reference list). Presently, Badenian evaporites of the Wieliczka area are entrained by the thrust structures of the frontal Carpathian fold-and-thrust belt (Fig. 1).

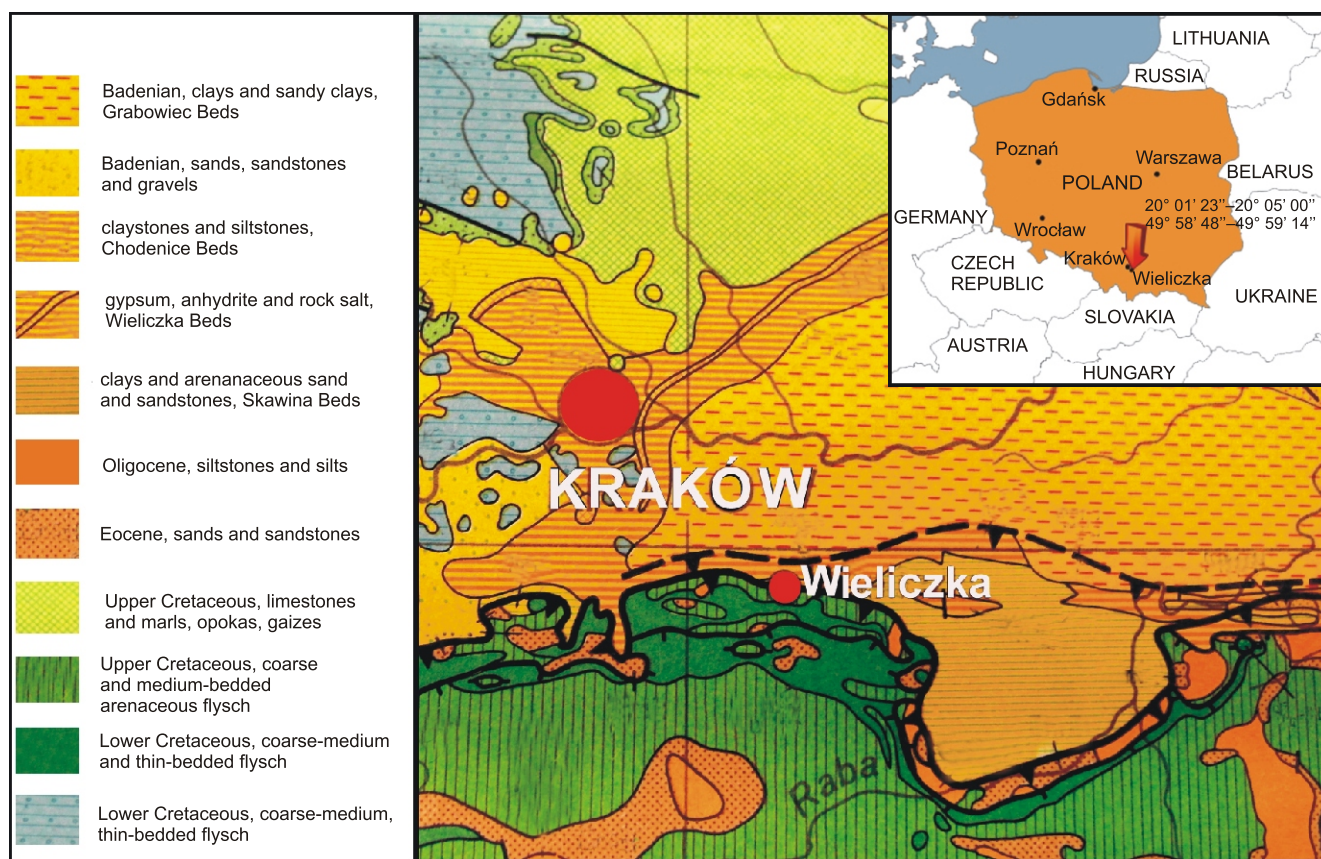


Fig. 1. Location of the study area at the background of geological map of Poland without Quaternary cover (based on Rühle, 1977)

Wieliczka salt deposits are characterized by rather unique structure due to complex geological evolution of this area, including development of soft-sediment deformations during early phase of the Carpathian thrusting, and formation of complex thrust-and-fold structure during final phase of the Carpathian orogenic movements (Gaweł, 1962; Czapowski and Bukowski, 2010). They consist of two different parts: boulder (blocky) deposit and stratiform (bedded) deposit. The blocky deposit has the form of a mass of unstructured gangue in which boulders (sometimes of very large size) of rock salt are entrained. The bedded deposit is composed of layers of different types of rock salt interbedded by siliciclastics, mostly claystone. The whole rock-bearing complex was subjected to intense folding and tectonic deformation. The salt deposits are separated from the aquifers by a later formed buffer zone composed of silty claystones and gypsum (Gaweł, 1962; Wiewiórka, 1985; d'Obyrn and Przybyło, 2010).

Upper levels of the Wieliczka Salt Mine are dominated by blocky deposits. Western part of these deposits consists of smaller blocks of salt, up to tens of thousands of cubic metres in volume, that are located within the mostly unstructured mass of marly claystones with dispersed halite crystals. Top parts of tectonic flakes of stratiform deposits can be found only in the central part of the Level I. Level I, the highest level of the mine, consists of chambers and galleries located from about 180 to about 200 metres a.s.l. These structures are available today or known from the archival materials (Figs. 2 and 3).

Quaternary deposits in the Wieliczka region consist of Pleistocene and Holocene (Wiewiórka, 1985). The Pleistocene deposits are composed mostly of loess with the thickness from about 3 to 20 m, developed as silty clays, dusts, silty loams, clays or loamy sands. The loess sheet overly directly the Neogene in the majority of the area. Within its layers the most important one for the mine is the quicksand, which consists of fine loose sediment mixed with water, with property to liquefaction. The Holocene deposits are represented by anthropogenic soils and fluvial deposits. Anthropogenic soils vary with thickness, ranging from on average about 2 m, up to 5.2 m, in the center of Wieliczka. These deposits are classified as water accumulation deposits (alluvium), developed primarily as loams, clays, sands and peats.

The northern border is delineated by the area of contact of blocky deposits with the Chodenice beds. The only place where the uncovering of the silty claystones of the Chodenice beds was recorded at the northern ends of the upper and lower Taras Wodny Gór Wschodnich galleries (location of effluents: WI-36, WI-37). The roof limit of deposits is very irregular. The bed is surrounded by a gypsum-clay buffer zone. In the buffer zone areas of fractures and fissures are locally found, together with karst formations developed along them. These systems of fractures and fissures are the routes of groundwater inflow as confirmed by effluents at Level I. On these formations, gypsum and mirabilite dripstones crystallise.

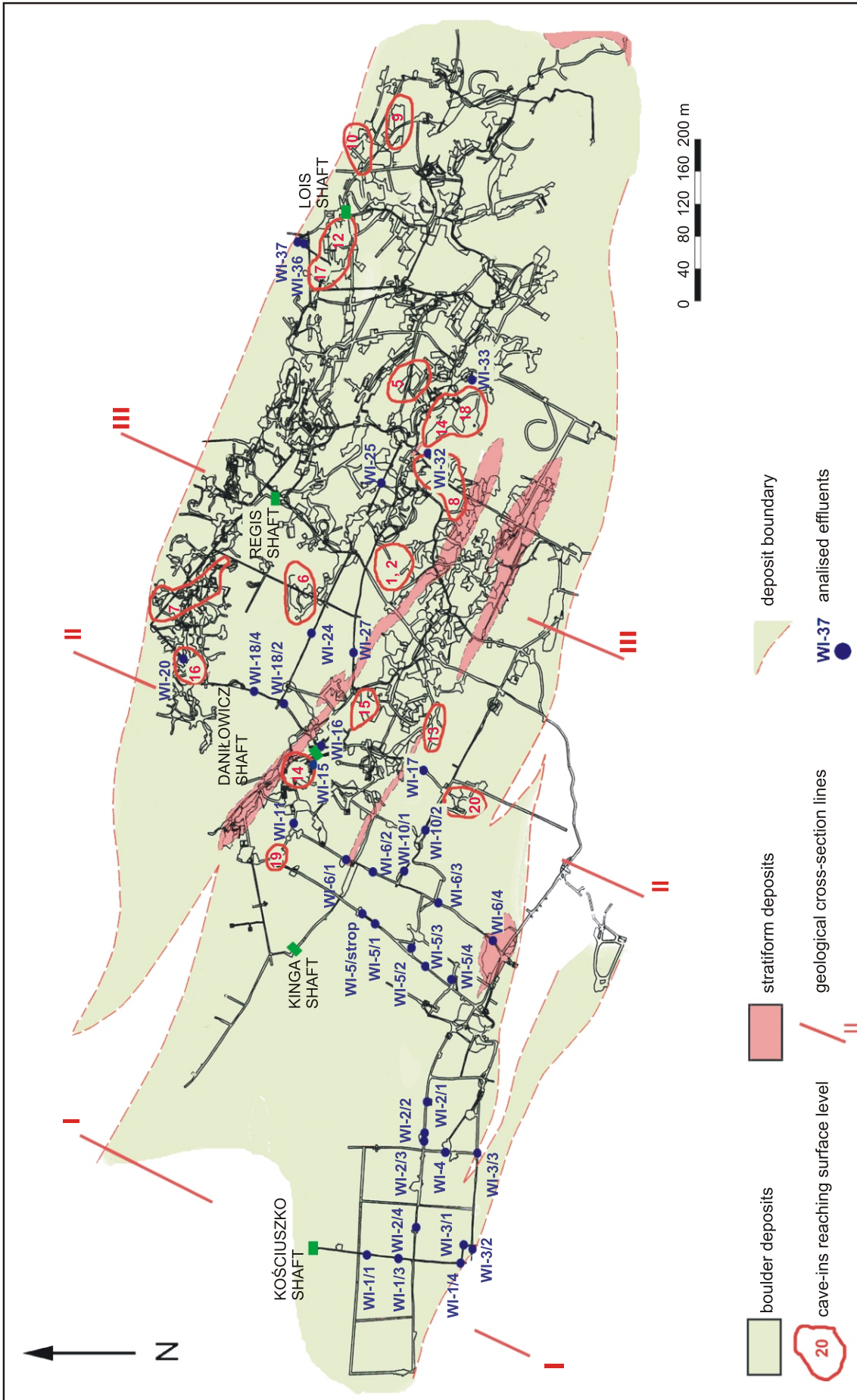


Fig. 2. Simplified geological map of Level I (after Przybyło and Winid, 1998)

HYDROGEOLOGICAL CONDITIONS OF LEVEL I IN THE WIELICZKA SALT MINE

Quaternary formations do not form a single aquifer and therefore do not pose a serious hazard for the mine. They were formed into local pockets of dust, sand and gravel embedded in impermeable clay. These deposits are the source of approximately 2% of water inflow into the mine. Layers situated under the salt deposit, the Skawina formation are poorly permeated with water and provide approximately 5% of the water flowing into the mine. The subsidence flysch adjacent to the deposit on the south is not water-bearing. The greatest water hazard is represented by the Chodenice beds which constitute the northern outskirts and a part of the overburden of the salt deposit. At present, water inflowing from these layers represents about 85% of the inflow into the mine (Wilk and Kulma, 2004; Brudnik *et al.*, 2010).

As of January 1, 2011, 163 effluents in the mine and 9 shaft inflows have been recorded within the Wieliczka Salt Mine. The effluents recorded in Level I are characterized by their considerable number (30 effluents) and minor output. In 2010, the average inflow to the excavation at Level I amounted to 3.36 dm³/min, which represents approximately 1% of the total inflow into the mine. More than half of which is provided by the output of WI-36 and WI-37 effluents (1.8 dm³/min). Effluents at the Level I mostly take on the form of drippings scattered throughout the excavation roof. The inflow conditions of Level I are affected not only by the form of its northern border but also the roof limit. Water always migrates into the mine through excavations leading from the surface, i.e., shafts, approximately twenty five of which existed at the Wieliczka Mine, and by boreholes. The northern deposit bor-

der was broken at least in one location (Taras Wodny Gór Wschodnich). One of the greatest water hazards were historically recorded in chamber subsidence reaching the surface (Fig. 2 and Table 1).

The surface-affecting subsidence in 1579 of the Gmińskie Chamber led to the inflow of surface watercourses, as did the subsidences of the Oszust Chamber in 1605, the Stary Lipowiec in 1648, and the Bąkle, Gołębie and Gawrony chambers in 1762. Another example of the occurrence of water hazards was the creation of the Międzykaszty Chamber subsidence in 1834. As a result, liquefied loamy Quaternary sands entered the excavations. In each case, subsidence caused breaking of the clay-gypsum coating and opened zones of water migration in to the mine. Probably some of these routes are still active (Kolasa and Kubik, 1983).

The distribution of effluents at Level I of the mine (Fig. 2) suggests that these are located south of the Kościuszko shaft and in the vicinity of the Daniłowicz and Kinga shafts, while a significantly smaller number of the effluents are recorded them in the eastern part. This diversity is caused by lack of or very limited access to many excavations in the eastern part of the level. Inflows into the old unavailable chambers and galleries in this region are recorded at the lower levels of the mine.

METHODOLOGY OF SAMPLING AND CHEMICAL ANALYSIS

The goal of chemical analyses was to determine the common characteristic of effluents at the Level I, their infiltration origin and impact of mining activities on the formation of groundwater chemistry in the surface part of the deposit. The effluents selection was performed on the basis of geological structure of surrounding deposits, and also results of long-term exploitation. Both, geological structure of the Wieliczka Mine and its exploitation are crucial to water migration paths in the deposit, and formation of their chemical composition.

The analysis was conducted on effluents described below and presented in Table 2. Effluents with symbols WI-1, WI-2 WI-3 WI-4, WI-5, and WI-6 are probably associated with the inflow of water from the Quaternary formations. The WI-10 effluent, located at the Karas longitudinal, is most probably associated with the lack of tightness of the TP-24 backfilling borehole or the Międzykaszty Chamber subsidence. The WI-11 effluent in the Kuchnia gallery is associated with the Paderewski shaft or the Rex Chamber subsidence. Effluents WI-15 (in the Letow Chamber) and WI-16 (in St. Anthony's Chapel) are associated with the Włodkowice Chamber subsidence or the Daniłowicz shaft. The origin of the WI-16 effluents could also be related to the old hollows, which probably overhang the chapel. The WI-17 effluent in the Koton transverse is associated with the old excavated material which overhangs the Słaboszów Chamber. The origin of the WI-18 effluent (Bąkle gallery) is associated to the Gołębie-Gawrony Chamber subsidence, and the WI-24 effluent (Klemens longitudinal) with the Opatkowice Chamber subsidence. In the WI-20, WI-25 and WI-27 effluents, water inflow may also be caused by the migration of surface water through old subsidence zones. The WI-32 effluent in the Powroznik transversal is also linked to the mi-

Table 1

Summary of known cave-ins extending to the ground surface above the excavations of the Level I of the Wieliczka Salt Mine

No.	Name of the cave-in (chamber)	Year
1	Gmińskie	1579
2	Małdrzyk	1582
3	around the Bonnier shaft	1591
4	over the Skalka Chamber	–
5	Oszust	1605
6	Opatkowice	1608
7	region of the Świętosławskie shaft and Za Sołtysim Kołem Chamber	1620
8	Konieczne	1642
9	Zapiłacie, Szreniawa, Śmieszek	1645
10	Piłat	1646
11	Stary Lipowiec	1648
12	Tragarskie	1658
13	Słaboszów	1698
14	Włodkowice	1703
15	Kręciny	1744
16	Gołębie, Gawrony, Bąkle	1762
17	Kuczków	1772
18	Lubna	1786
19	Rex	1832
20	Międzykaszty	1834

Table 2

Summary of basic information on the sampled effluents at Level I

No.	Name of excavation	Place of inflow	Manner and number of intake points	Date of phenomenon recording*	The average volume of inflow in 2010 [dm ³ /min]
WI-1	transversal Kwaterna	floor	sump – 3 units	08.04.1969	0.09
WI-2	longitudinal Słupów	floor	sump – 4 units	12.1961	0.05
WI-3	longitudinal Taras	floor	sump – 4 units	08.04.1969	0.13
WI-4	transversal Bronisława	floor	sump – 1 unit	10.04.1961	0.04
WI-5	transversal Izabela with the treadmill chamber	floor	sump – 4 units and roof inflow	14.04.1969	0.05
WI-6	transversal Blum	floor	sump – 4 units	11.04.1969	0.61
WI-10	longitudinal Karaś	floor	sump – 2 units	12.1961	0.06
WI-11	gallery Kuchnia	floor	sump – 1 unit	15.12.1943	0.03
WI-15	Chamber Łętów	floor	sump – 1 unit	12.1961	0.19
WI-16	St .Anthony's Chapel	roof	sump – 1 unit	16.04.1969	0.007
WI-17	transversal Kotoń	floor	sump – 1 unit	12.04.1969	0.04
WI-18	gallery Bąkle	floor	sump – 3 units	12.11.1943	0.02
WI-20	gallery Bąkle	floor	no intake	12.1961	0.03
WI-24	longitudinal Klemens	floor	sump – 1 unit	16.04.1969	0.01
WI-25	longitudinal Tanecznicza	roof	sump	18.11.1981	0.03
WI-27	gallery Długi	roof and floor	sump – 1 unit	27.11.1943	0.02
WI-32	transversal Powroźnik	roof	no intake	22.05.1969	0.01
WI-33	Chamber Zamtus and gallery to Chamber Pocięcha	floor	sump – 1 unit	22.05.1969	0.02
WI-36	gallery Taras Wodny Gór Wschodnich – lower	dam in the end of the gallery	gravitational flow from the threshold to the sump in the gallery	1895	1.20
WI-37	gallery Taras Wodny Gór Wschodnich – upper	dam in the end of the gallery	inflow from the wall dam to the sump in the gallery	1895	0.64

* – the date of recording a phenomenon marks the beginning of controlling it, not by the date of its occurrence, which is usually unknown

gration of water from the surface through the zone of old subsidence which reach the surface. The WI-33 effluent is probably linked with to the Lubna Chamber subsidence. In WI-36 and WI-37 effluents, water inflow originates in the Chodenice formations.

Samples of brine were collected into polyethylene containers supplied by the company conducting the analysis. The method of collection was dependent on the nature of the effluent. A part of brines was collected directly from the intake (e.g., water from WI-36 and WI-37 effluents). Other effluents in the form of brine drippings scattered on excavation roofs, were collected from roofing which gathers on the inflows supplied to the mine drainage system (e.g., WI-5/roof). The remaining effluents were collected from the pits. The pH of the water was determined by potentiometer according to PB-02 test procedures (Issue 1 dated 12.03.2009). NO₂ and NO₃ ions were marked using a *Slandi LF205* spectrophotometer. In order to determine chloride concentrations and alkalinity, the traditional volumetric method was used. Iodides and bromides were marked using *Perkin Elmer Elan 6100 Inductively Coupled Plasma Mass Spectrometer*. Metals and sulphates were marked using *Perkin Elmer OPTIMA 7300DV6100 Inductively Coupled Plasma Optical Spectrometer* (standard PB-03, Issue 2, dated 05/04/2010). All chemical analyses were conducted in the certified laboratory facilities.

RESULTS

The results of chemical analyses for the particular effluents are presented in Table 3. In order to group effluents (ions) and determine homogeneous groups, cluster analysis was employed. The agglomeration procedure (nearest-neighbour method) was performed for the result matrix previously having undergone logarithmic transformation. Results indicated as situated below the detection limit were replaced in the matrix by values amounting to 1/2 of the detection limit for a given effluent (ion). The analysis was conducted using *STAGRAPHICS Centurion XV* software. The results of clustering are presented in the dendrograms (Figs. 4 and 5), in which the horizontal axis represents the effluent or ions, and the vertical axis, similarity between the different groups. Euclidean distance was adopted as the measure of similarity for the conducted analysis. Correlation between particular ions was assessed using *Excel v. 2007* and correlation factors are presented in Table 4. Selected relations between ions are presented in Figure 6.

INTERPRETATION OF RESULTS

Both dendrograms and calculated correlations indicate that it is difficult to identify significant associations between the

Table 3

List of physical and chemical parameters of 36 sampled effluents at Level I

Parameter		Scope		Average \bar{x}	Standard deviation σ	\bar{x}/σ
		min	max			
pH		6.1	8.4	7.31	0.38	19.12
Eh	[mV]	228	328	290	24.8	11.7
Mineralisation	mg/dm ³	1423.0	348645.8	284335.32	84603.52	3.36
Na ⁺	mg/dm ³	334.5	141000.0	110571.82	33676.77	3.28
K ⁺	mg/dm ³	7.98	993.70	299.27	207.42	1.44
Ca ²⁺	mg/dm ³	7.26	1644.00	929.53	284.01	3.27
Mg ²⁺	mg/dm ³	6.43	1586.00	576.25	401.92	1.43
Sr ²⁺	mg/dm ³	0.20	33.56	17.54	5.52	3.18
Fe ²⁺	mg/dm ³	0.01	241.80	10.59	39.32	0.27
Mn ²⁺	mg/dm ³	0.02	5.01	0.87	0.94	0.93
Cl ⁻	mg/dm ³	265.5	213620.0	170123.96	50854.87	3.35
Br ⁻	mg/dm ³	1.50	79.00	20.92	17.04	1.23
I ⁻	mg/dm ³	0.50	36.70	4.59	8.65	0.53
SO ₄ ²⁻	mg/dm ³	201.70	8242.00	4213.78	1449.03	2.91
HCO ₃ ⁻	mg/dm ³	34.50	810.51	187.45	161.81	1.16
NO ₂ ⁻	mg/dm ³	<0.003	0.24	0.09	0.07	1.29
NO ₃ ⁻	mg/dm ³	<0.4	73.00	7.34	15.26	0.48

various ions other than the obvious and expected associations between, e.g., mineralisations, Na and Cl, and Ca, Sr and SO₄. Similarly, the spatial distribution of the different ions in the analysed effluents does not allow to determine groupings of several effluents with characteristic changes in the content of one or more ions. The lack of regularity is also indicated by sample graphs (Fig. 6). It seems the most appropriate to attempt an interpretation of values deviating from the average value on the basis of the analysis of the origin of the effluent, its location, the geology of the area, exploitation duration of the region, the actual and potential level of water flow through the old hollows, and the occurrence of chamber subsidence which reach the ground surface.

The WI-25, WI-27, WI-36 and WI-37 effluents are the least mineralised. The WI-36 (3.8 g/dm³) and WI-37

(1.4 g/dm³) are located at the limit of the Chodenice beds and probably conduct Quaternary deposits. Lower mineralisation of the WI-25 effluent (73.5 g/dm³) may be associated with the inflow of the Quaternary waters along the northern border of the layered deposit flake. Mineralisation of the WI-27 effluent (155.3 g/dm³) can be linked with the old hollows and possibly the surface sink-holes associated with the mining operation of the area before the creation of the first maps of the mine and the records of chamber subsidences affecting the surface. Concentrations of Na⁺ and Cl⁻ are closely related with each other and the mineralisation level, and the reasons for which the four effluents indicate lower concentrations are the same as for mineralisation. The content of Na⁺ in these effluents is as follows: 25.6 g/dm³ (WI-25), 55.9 g/dm³ (WI-27), 1.3 g/dm³ (WI-36),

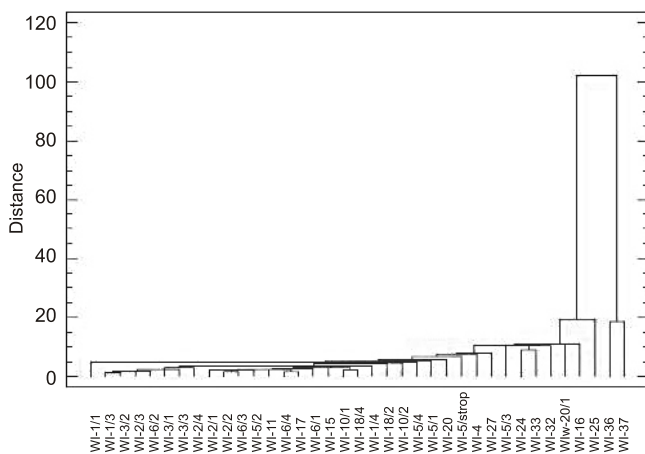


Fig. 4. Dendrogram for analysed leakage

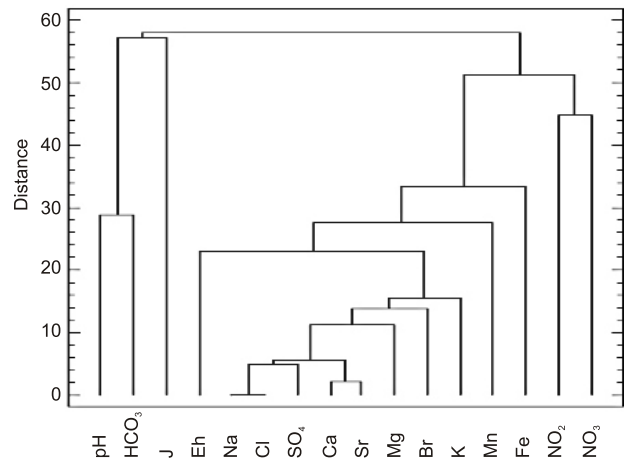


Fig. 5. Dendrogram for the analysed ions

Table 4

Correlations (R) between the tested water components from Level I effluents

	Eh	Mineralisation	N ⁺	K ⁺	Ca ²⁺	Mg ²⁺	Sr ²⁺	Fe ²⁺	Mn ²⁺	Cl ⁻	Br ⁻	I ⁻	SO ₄ ²⁻	HCO ₃ ²⁻
pH	-0.31	-0.49	-0.51	-0.37	-0.23	0.57	-0.16	-0.53	-0.61	-0.53	-0.22	0.04	-0.41	0.57
Eh		0.76	0.71	0.33	0.49	-0.05	0.41	0.04	0.17	0.70	0.12	-0.45	0.11	-0.47
Mineralisation			0.98	0.41	0.53	0.28	0.44	0.13	0.26	0.98	0.37	-0.19	0.52	-0.69
Na ⁺				0.39	0.52	0.27	0.42	0.11	0.33	0.99	0.36	-0.09	0.50	-0.68
K ⁺					0.29	0.57	0.24	0.19	0.47	0.43	0.55	-0.09	0.14	-0.01
Ca ²⁺						0.15	0.89	0.13	0.31	0.54	0.33	0.09	0.19	-0.46
Mg ²⁺							0.14	0.08	0.29	0.33	0.73	0.26	0.47	-0.27
Sr ²⁺								0.06	0.22	0.43	0.22	0.02	0.26	-0.49
Fe ²⁺									0.75	0.13	0.13	-0.10	-0.02	-0.16
Mn ²⁺										0.35	0.35	0.09	-0.08	-0.15
Cl ⁻											0.42	-0.06	0.52	-0.66
Br ⁻												0.34	0.11	-0.18
I ⁻													0.07	0.12
SO ₄ ²⁻														-0.59

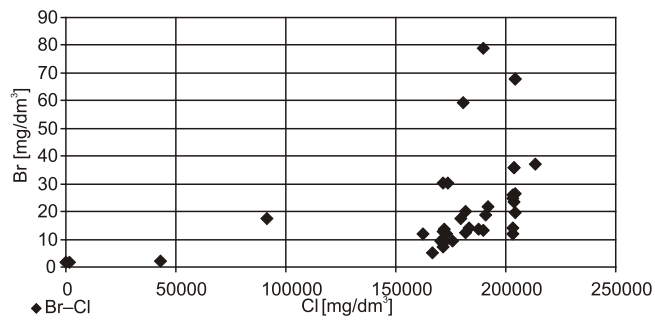
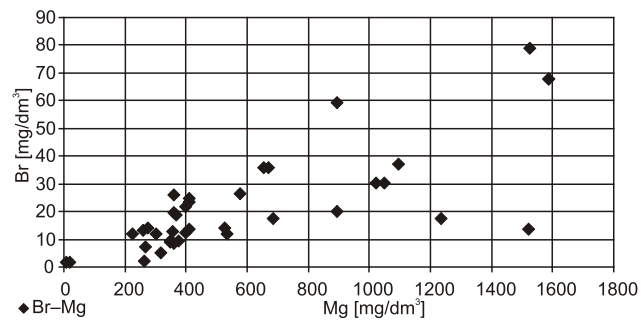
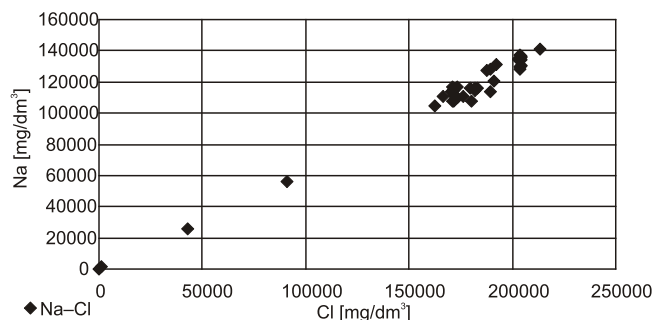
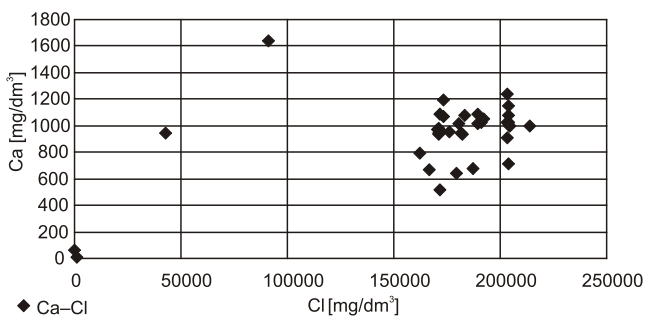
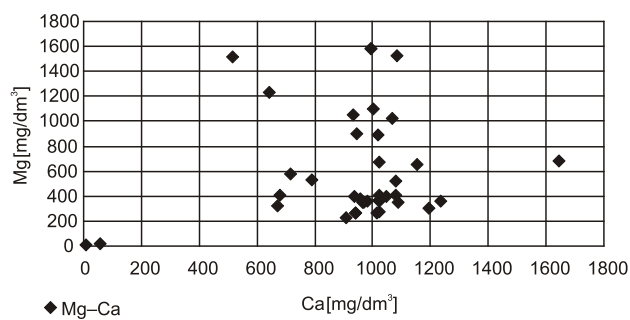
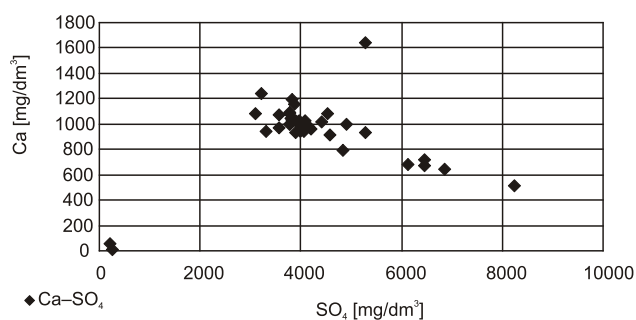


Fig. 6. Sample figures for ion associations in the analysed effluents

0.3 g/dm³ (WI-37), and Cl 42.9 g/dm³ (WI-25), 91.21 g/dm³ (WI-27), 1.36 g/dm³ (WI-36), 0.27 g/dm³ (WI-37).

The pH of the vast majority of effluents is mildly alkaline and ranges from 7 to 8. The highest pH (8.44) was found in the WI-36 effluent. The WI-5/3 (pH = 6.26) and WI-16 (pH = 6.10) effluents with slightly acidic pH are the exception to the rule. The results of pH measurements in effluents are typical of the Wieliczka deposit and shallow circulation waters, and the differences result from the local hydrogeochemical conditions along the routes of water migration.

The values of K⁺ display broad variations. The lowest concentrations are found in WI-5/1 (0.032 g/dm³), WI-20/1 (19.5 g/dm³), WI-36 (0.009 g/dm³), WI-37 (0.008 g/dm³), and the highest in WI-1/1 (0.739 g/dm³), WI-4 (0.994 g/dm³), and WI-5/4 (0.672 g/dm³) effluents. Both the variation and the minimum values found in the analysed effluents are difficult to explain. Possibly, these are determined by yet unanalysed processes along the routes which water effluents flow. The high values of K⁺ seem easier to explain; these are often the result of anthropogenic pollution such as fertilisers (potassium nitrate), the anthropogenic layer beneath the surface of the area and the seepage of leachate from landfills. Given the history of the mine and its location beneath a town whose history is as long as that of the mine, it seems that anthropogenic factors are of decisive importance here. The K⁺ values can be associated with historical development of the surface area, depending on the history of the surface architecture and the existence of stables, manure storage facilities, disordered waste management and lack of sewerage, as well as the presence of subsidence reaching the surface in past centuries.

The values of Mg²⁺ display a large variation. High values can also be associated with sources of pollution or the presence of rocks containing magnesium. The results of the analysis demonstrate a weak correlation between Mg and Br. The lowest Mg concentrations were found in the WI-36 (0.006 g/dm³), and WI-37 (0.021 g/dm³) effluents, and the highest in the WI-1/1, WI-16 and WI-32 effluents, where they range between 1.5 to 1.6 g/dm³. The concentrations of calcium do not display a large variation in the different effluents other than the increased value in WI-27 (1.644 g/dm³) and low values in the WI-36 (0.007 g/dm³) and WI-37 (0.058 g/dm³) effluents. The occurrence of calcium can be explained by the inflow of Quaternary waters from under-surface formations through the clay-gypsum cover, which causes the dissolution or precipitation of CaSO₄ (Winid and Witczak, 2007). Since, Sr analysis results show a very good correlation with Ca, the causes of the occurrence of minimum value of WI-36 (<0.2 mg/dm³), WI-37 (0.37 mg/dm³) and maximum for WI-27 (33.56 mg/dm³) will be identical as those described for Ca.

The highest values of Mn are present in the most acidic effluents. The presence of manganese in the effluents can be explained by it originating in the shallow groundwater in the Quaternary deposits, which in the Wieliczka region are rich in complex compounds of iron and manganese with organic matter. The highest concentrations of Mn and Fe occur in the WI-5/3 effluent (Mn = 5.01 mg/dm³, Fe = 241.8 mg/dm³). The increased Fe content in some effluents may be related to medieval mining activities. Waters inflowing into the effluent may pass through old hollows in which the miners left formerly

used equipment. Examples of this are provided by chambers once used as stables, in which piles of damaged and rusty horseshoes remain. On the other hand, very low values may be associated with a slightly basic environment. Fe values of <0.1 mg/dm³ are recorded for WIw-20/1, WI-24, WI-25, WI-32 and WI-33 effluents.

Variable values of NO₂ and NO₃ should be associated primarily with the centuries-old mining activity. Increased ion content may result from the functioning of stables and the lack of toilet facilities in the past centuries, when the mining operations also took place above the present-day Level I, and the locations where they were conducted are unavailable today. The presence of nitrates and nitrites can also be explained by the lack of sanitary sewage and leakages, leaking septic tanks and chamber subsidence, creating depression into which houses, farm buildings and animals fell, as well dung heaps. The concentration of NO₂ is characterized by high variability, with elevated NO₃ values recorded in the WI-15 (24.5 mg/dm³), WI-25 (19.97 mg/dm³), and WI-27 (73.0 mg/dm³) effluents.

The content of SO₄, which is weakly correlated with that of Ca, Mg and Sr, is associated with the occurrence of gypsum in the overburden. Elevated SO₄ may also indicate a lower water flow velocity. The lowest values occur in the WI-36 (0.25 g/dm³), WI-37 (0.20 g/dm³) and WI-16 (8.24 g/dm³) effluents.

Elevated HCO₃ values may be the result of carbonate rock dissolution, CO₂ or the reduction of sulphates. The values measured in the effluents do not depart from the known historical values specified for the shallow Quaternary waters surrounding Wieliczka.

Both the origin of the effluents and the up to date experience in interpreting the results of chemical analysis of mine waters (Winid and Witczak, 2004) does not permit an unambiguous interpretation of the elevated I and Br content. In three effluents it was found that increased content of I is accompanied by increased content of Br, but in some effluents this relationship is reversed. Bromine shows no correlation with other ions, and a very weak possible correlation only in the case of Mg. It seems that in order to explain the elevated content of Br and I, additional analysis would be necessary, including both surface water testing and mineralogical tests in order to determine the concentration of these elements in the clay-gypsum cover or the blocky deposit formations.

Such a large number of co-factors affecting the chemistry of water inflowing into the Level I, particularly time and flow paths cause lack of significant correlation between the ions. Lack of this correlation and variability of ionic composition point at impact of the effluents genesis as a reason of those. This factor was taken into account during effluent selection in the primary stage of the study.

CONCLUSIONS

Centuries of exploitation of the deposits has resulted in the creation of many groundwater flow routes between the surface and the bed. Breaks of the of clay-gypsum cover in the galleries and places of entering aquifers as well as chamber subsidence

reaching the surface, are the most dangerous for the preservation of the mine pits

The time and route of the flow of infiltration water through the deposit overburden (the clay-gypsum cover, Chodenice beds or blocky deposit formations) shape the natural chemical composition of the water. However, in the case when waters flow through old mining hollows, or the use of privileged routes in areas of old subsidence, their chemical composition can also be shaped by anthropogenic factors, including those related to historical and current developments of the surface area above the mine pits.

No presence of fossil connate waters was recorded on Level I of exploitation, based on chemical analysis. Mine effluents are fed by water of infiltration origin.

The process which determined the chemical composition of water is the dissolution of halite. The lower salinity of effluent, observed only in a few cases, results from the intake of the effluent near the border of the deposit, which results in lack of the possibility of leaching of NaCl by water circulation.

The results of chemical analysis confirm the need for controlling effluent as close as possible to the deposit boundaries in order to reduce the destructive impact of freshwater inflow to the historic salt mine.

The lack of spatial dependence and significant associations between coexisting ions indicates the need to perform individual interpretation of the chemical composition of various effluents, taking into account the history of the area of the mine operation and the management of the land surface.

The assessment of hydrogeological and hydrogeochemical conditions in historic mines, and in particular salt mines, should always take into account the effects of mining activities.

The tests carried out allow for better identification of water hazards to the Wieliczka Mine and planning securing work protecting from the destructive influence of poorly mineralised waters on the historic chambers and galleries. This study also provides an example of analysing water conditions in other historic mines.

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