Catastrophic and dangerous inflows to salt mines in Poland as related to the origin of water determined by isotope methods

A. Zuber · J. Grabczak · A. Garlicki

Abstract Tritium, ^{14}C, $\delta^{13}C$, $\delta^{18}O$ and δD measurements indicated as early as 1973 the existence of inflows of modern meteoric water to the Wapno salt mine in a Zechstein diapir. In spite of these early warnings, the continuation of improper exploitation led, in 1977, to sudden flooding of the mine followed by catastrophic land subsidence. The lesson learned from that catastrophe, as well as the results of isotope investigations performed in the Inowrocław salt mine, led to the decision to flood the mine artificially in order to avoid a similar land subsidence. The Kłodawa mine was not regarded to be in danger of flooding due to a thick clay cap. In fact, a large number of usually short-lasting water occurrences had the isotopic composition characteristic for evaporated ocean water. However, since 1956 an inflow has existed with $\delta^{18}O$ and δD values close to that of pre-Quaternary saline waters and brines in the Mesozoic formations adjacent to the diapir. Two other inflows have recently occurred with the initial $\delta^{18}O$ and δD values of modern waters. As a consequence, the mine is regarded to be in danger, and the exploitation of salt in the areas of inflows has been stopped. The Wieliczka mine, southern Poland, exploits Miocene salts overthrusted together with the Carpathian flysch from the south. The most dangerous and catastrophic inflows were caused by human errors. Isotope data show the water to be of glacial or Holocene age stored in Tertiary, slightly cemented rocks of low permeability, which neighbor the mine from the north. Owing to specific geology, the mine has survived for a long time, in spite of relatively large and long-lasting inflows. However, its existence is in permanent danger.

Key words Mine catastrophes · Salt mines · Mine inflows · Water origin · Mining errors · Environmental isotopes · Zechstein diapirs · Miocene salt deposits

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Introduction

Catastrophic inflows to salt mines, though quite frequent, are seldom described in literature and consequently students of mining and mine managers remain, to a high degree, ignorant in this respect. Contrary to common opinion, inflows are seldom caused by unavoidable forces of nature. Though some errors were unavoidable in the past, modern geophysical methods are, most probably, quite sufficient to solve the majority of problems (e.g., to determine a close presence of the salt boundary). Detailed study of the recent catastrophic floods, which happened in Polish salt mines, shows that they usually occur or have strong negative impacts due to human errors. Most probably similar human errors caused catastrophic inflows to salt mines in other countries. It seems that a knowledge of the real history of catastrophes, better education of mine engineers and the application of modern geophysical methods could lead to the reduction of floods in salt mines. Environmental isotope method belong to one of the modern tools, and, therefore, their applications in four Polish salt mines are briefly presented in relation to the known reasons of some catastrophic inflows. The areas of investigation are shown in Fig. 1. Measurements of tritium, ^{14}C, $\delta^{13}C$, $\delta^{18}O$ and δD are now regarded as standard methods for determining the origin and age of groundwaters (e.g., Fritz and Fontes 1980, 1986; Gat and Gonfiantini 1981). In Poland, particularly good conditions exist for the identification of the origin of brines in salt mines from $\delta^{18}O$ and δD data because both modern and paleo-waters distinctly differ from residual brines. Modern waters are characterized by $\delta^{18}O \cong -10‰$ and $\delta D \cong = -70‰$ with somewhat heavier values in north-western regions of Poland whereas glacial waters, which are quite common, have distinctly more negative delta values. In Mesozoic formations of central and northern Poland, which surround Zechstein diapirs, brines and saline waters dominate, which scatter moder-

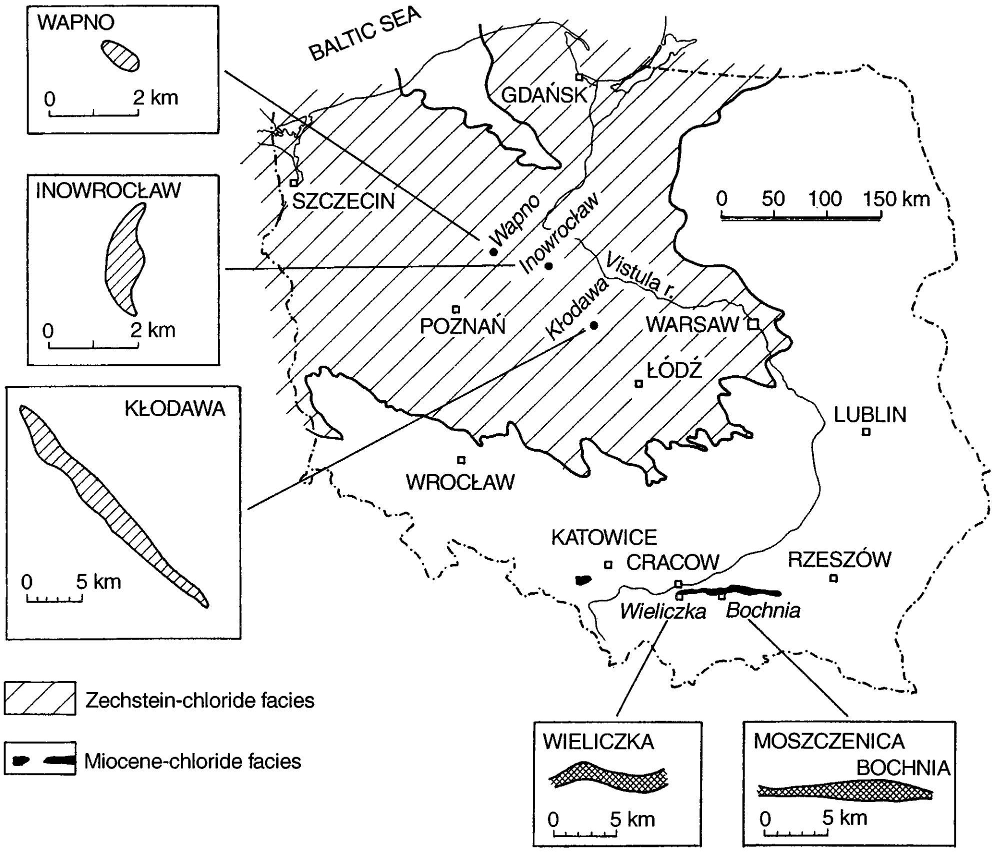

Fig. 1
Salinary provinces in Poland, and the areas investigated

ately along a line slightly shifted from the World Meteoric Water Line ($\delta D = 8\delta^{18}O + 10$), as shown further. Their isotope and chemical data indicate the origin related to meteoric waters of warm pre-Quaternary climates, with salinity gained mainly by leaching of Zechstein diapirs (Zuber and Grabczak 1991). Connate brines in Zechstein formations differ from all other waters and are characterized by a typical evaporation hook of the marine water (Sofer and Gat 1975). Tritium is helpful in identification of modern waters, i.e., those recharged after 1954 whereas ^{14}C dates older Holocene and late glacial waters. Due to problems related to the contamination prior to sampling, tritium was only reliably measured for inflows with high volumetric flow rates. For saturated brines, the extraction of carbonates was usually not possible, though chemical analyses showed their presence. Therefore, a better identification of ages by the tritium and ^{14}C methods was only possible for large inflows or unsaturated brines.
The number of measured samples were: about 600 for $\delta^{18}O$ and δD, about 380 for tritium, 32 for ^{14}C and $\delta^{13}C$ in DIC, and 2 for ^{14}C and $\delta^{13}C$ in DOC (Dissolved Organic Carbon) whereas more than 10000 chemical analyzes are available. Only a few examples have been published so far (Zuber and others 1979; Bąkowski and others 1984a, b; Grabczak and Zuber 1986; Geyer and others 1993). The discussion within this work is also limited to the most typical results.

The Wapno mine

The Wapno salt mine was built between 1912–1917 in one of the smallest Zechstein salt domes in Poland. That dome is of ellipsoidal shape in horizontal cross-section, with the main axes of about 900 m and 300 m at a depth of 350 m. Simplified geological cross-sections of the north-western and south-eastern parts of the dome are shown in Figs. 2 and 3, respectively. The first two levels were remnants of an abandoned gypsum mine, which undoubtedly contributed to an easier penetration of water to the salt dome and the weakening of the gypsum cap structure. The salt was initially exploited from the fourth (406 m) to the ninth (543 m) levels creating a volume of empty chambers and galleries exceeding 6.6×10^6 m^3. Dangerous inflows appeared when the exploitation began at the third level.
The isotope investigations started in 1973, ten years after the appearance of inflow Nr. 5 (Fig. 4) and soon after a sudden appearance of the largest inflow Nr. 18 (Fig. 5). Another large inflow (Nr. 19), with chemical and isotope compositions close to those of Nr. 18, appeared in October 1974, and was investigated from the very beginning. The isotope data of waters having meteoric origin are given in Table 1. Modern waters were found in the N_1 well and in inflows at the third level. Their modern origin was indicated by the presence of tritium, relatively easy extraction of carbonates with high ^{14}C contents (Ta-

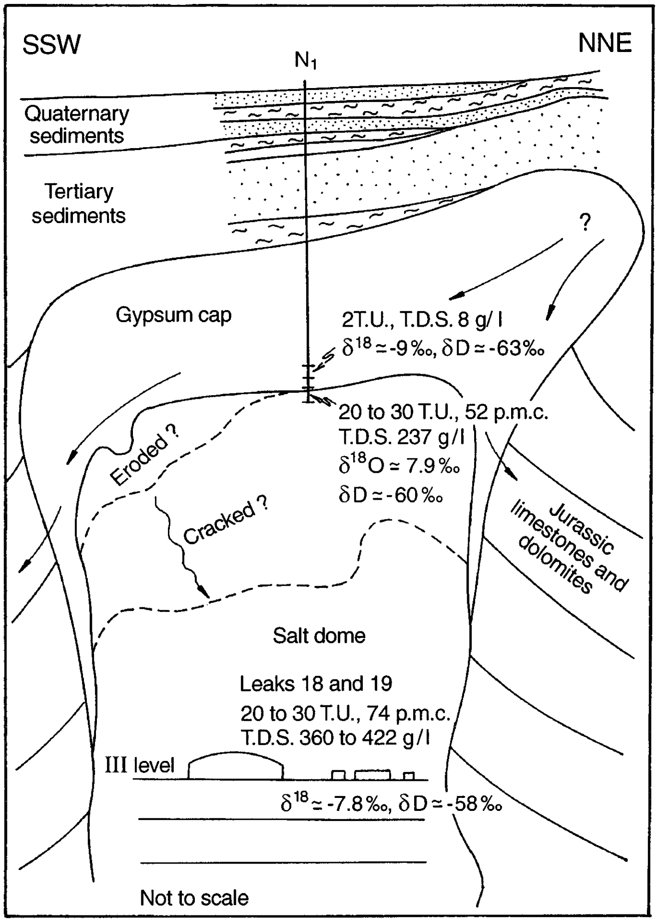

Fig. 2
Simplified geological cross-section through the north-western part of the Wapno salt dome with the isotope data observed at some sites near the cross-section plane (adapted from Zuber and others 1979)

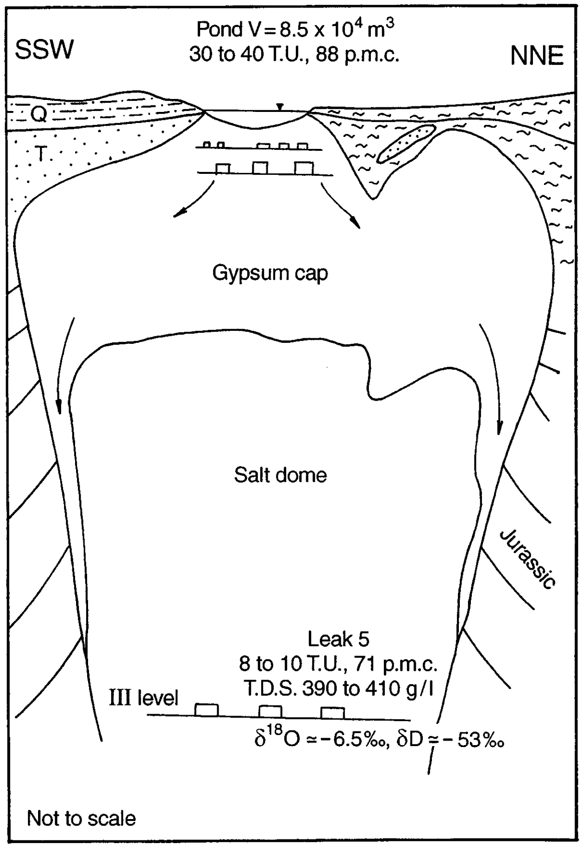

Fig. 3
Simplified geological cross-section through the south-eastern part of the Wapno salt dome with the isotope data observed at some site near the cross-section plane (adapted from Zuber and others 1979)

ble 1; Figs. 1 and 2). However, the δ^{18}O and δD values of inflows and waters in the N_1 well were shifted from the values typical for local meteoric water as shown in Fig. 6. The isotope composition of the local meteoric water was initially supposed to be represented by water exploited from a Quaternary aquifer in Damasławek, near Wapno. However, that water probably evaporated prior to infiltration because the maps of isotopic composition of modern groundwaters in Poland recently presented by d'Obyrn and others (1997) indicate $\delta^{18}O = -9.2‰$ and $\delta D = -65‰$ as more representative values for that area. Isotopic shifts of meteoric waters in salt mines in the direction of heavier values can be caused by evaporation, mixing with residual brines, dissolution of hydrated salts, and the isotope exchange with water of crystallization in the hydrated salt minerals. For the inflows discussed, characterized by large flow rates, the evaporation effect can be neglected, except for the inflow in the Shaft 1 (Table 1; Fig. 6). Simple mass-balance considerations show that mixing with residual brines and the dissolution of hydrated salts cannot dominate, which leaves the isotope exchange with water of crystallization in the hydrated salt minerals as the main reason.

In spite of the early warnings given by the environmental isotope methods, the deeper three levels (9–11) were prepared for exploitation, a third shaft was sunk, and a number of wells drilled from some of the chambers to inject sealing materials. These costly activities were continued though slow changes in chemical composition and density in the inflow 18 were seen in 1974 (Fig. 5), and in the inflow 19 in 1975, and were followed by sharp changes in 1976. No changes in chemistry and density were observed for the inflow 5, though its flow rate increased considerably in 1975 (Fig. 4). Catastrophic increases in flow rates occurred in the inflows 18 and 19 on the night of 4 August 1977. That was a direct result of leaching out of cavernous potash salts and coarse crystalline salts, which was followed by the break down of the safety pillar, and a large land subsidence above the mine. The appearance of bomb tritium and ^{14}C in the mine, in spite of a large water volume stored in the gypsum cap, and Tertiary and Quaternary sediments, is worth considering. The amount of water present above the diapir was estimated to be about 2.5×10^6 m^3, which was partly confirmed by the amount of water which entered the mine

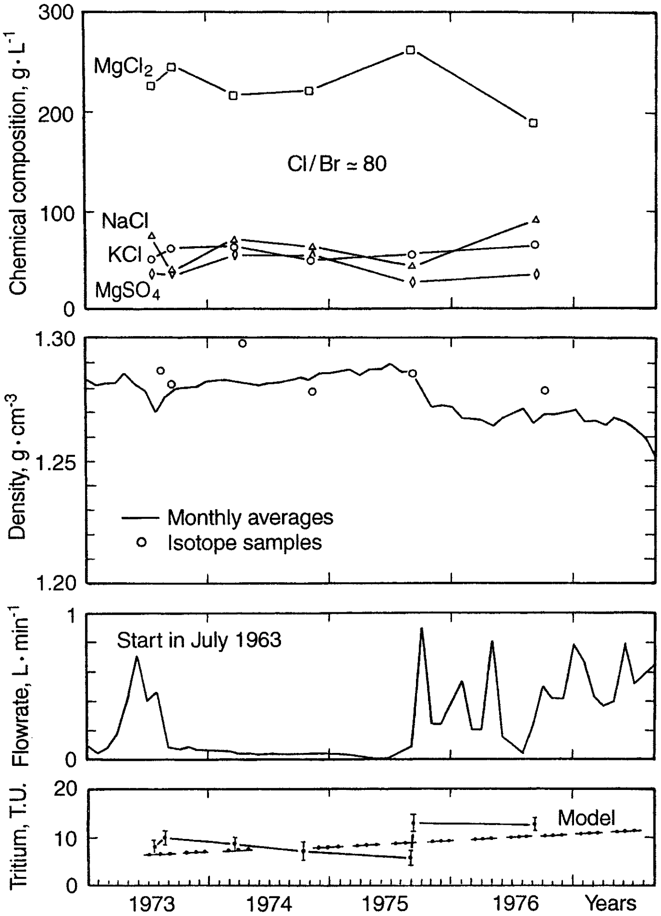

Fig. 4
Time records of chemical data, brine density, flow rate and tritium concentrations for inflow 5/III together with fitted model for the estimation of age (adapted from Zuber and others 1979)

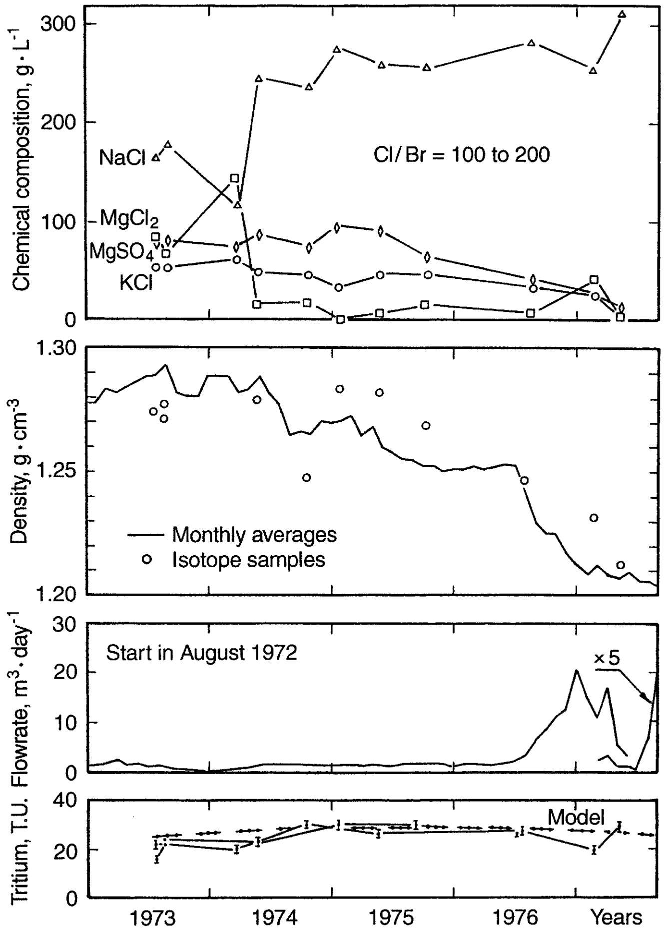

Fig. 5
Same as Fig. 4 but for inflow 18/III

during the catastrophe (about 1.5×10^{6} m^3). The mine specialist initially thought that the meteoric water was reaching the mine through an improperly sealed well N_1. However, when that well was redrilled, it appeared that older water was found above the younger one (Fig. 2). Therefore, most probably, other privileged paths existed in the gypsum cap as suggested in Figs. 2 and 3. A relatively fast, downward movement of water was caused by an increase in its density in the gypsum cap and at the salt interface. On its downward movement around the diapir, the density of that water further increased. Therefore, young waters were present around the diapir independently of the presence of the mine. When cracks appeared in the salt, due to improper exploitation at the third level, that modern water was able to reach the mine immediately because the volume of the cracks was negligibly low.

The tritium ages can be estimated by applying the lumped-parameter models described in detail by Małoszewski and Zuber (1982, 1996) and Zuber (1986). Several dispersion and exponential-piston flow models yielded equally good fits, which means that a unique solution is not available. The most reliable seems to be the dispersion model with the dispersion parameter (reciprocal of the Peclet number) equal to 1.0, and the fraction of non-modern water of 0.1 for inflows 18 and 19, and 0.3 for inflow 5. The fractions of non-modern water were estimated from the shifts of the $\delta^{18}O$ and δD values caused by contribution of water of crystallization as discussed above. The results of fits shown in the lowest parts of Figs. 4 and 5 suggest the mean ages of about 140 years for the inflows 18 and 19, and about 180 years for the inflow 5. The extremely high value of the dispersion parameter yields the shortest flow time of about 7–9 years, the maximum of flow lines at 22–29 years, and the longest flow times above one thousand years. In general, methods of age modelling are based on a number of simplifying assumptions; and, therefore, they can be questioned. However, in any case, high tritium contents were characteristic for the bomb-era, whereas their nearly constant concentrations can be explained only by great values of the mean age (residence time). Similarly, the ^{14}C content of about 70 pmc with the $\delta^{13}C$ values of about −11‰ indicates the dominance of water recharged after 1952. A wide distribution of the flow times with dominance of low values is difficult to explain for sampling

Table 1
Isotope data of meteoric waters in the Wapno salt mine; a–$\delta^{13}C = -11.4$‰; n.d. not determined

Sampling site	Date	$\delta^{18}O$ [‰]$_{SMOW}$	δD [‰]$_{SMOW}$	Tritium [TU]	^{14}C [p.m.c]	T.D.S. [g/l]
Tap water	05.1975	−8.1	n.d.	10±1	61.7±1.0[a]	Fresh
	03.1978	−8.2	−62	13±1	n.d.	water
Pond	08.73	−6.0	n.d.	39±2	n.d.	19
	11.75	−6.8	n.d.	32±2	88.1±1.0	n.d.
Shaft 1, 215−225 m	08.73	−6.2	−51	69.5±5	n.d.	318
N_1 well, 143−150 m	01.75	−8.8	−65	3.0±1.5	n.d.	8.2
N_1 well, 155−159 m	02.75	n.d.	n.d.	32±1.5	n.d.	237
	03.75	−7.6	−58	27±1.5	136±14	237
Inflow 5/III	1973−75	abt. −6.5	abt. −53	6−10	71.0±1.0	383−411
Inflow 18/III	1973−75	abt. −7.8	abt. −58	24−30	74.0±1.0	381−412
Inflow 19/III	1974−75	abt. −8.0	abt. −60	26−30	n.d.	381−412

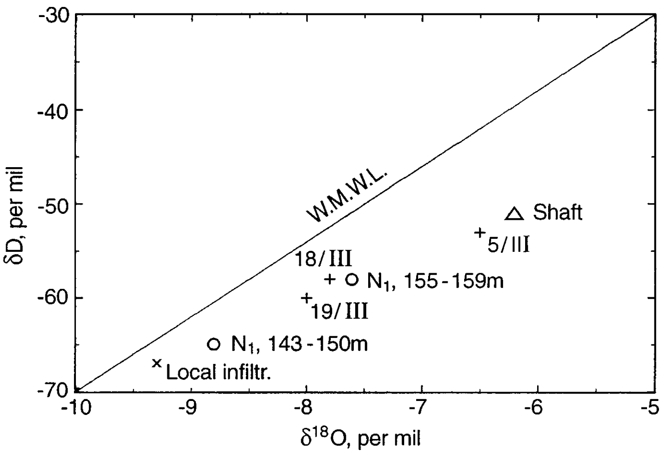

Fig. 6
Simplified isotopic data of the inflows to the Wapno mine

sites at the third level (384 m). Most probably, fast flow lines through shortcuts in a fractured gypsum cap joined slow flow lines close to the salt interface.

Summarizing, the environmental isotope data showed that since 1973 the mine was in serious danger due to the inflows of modern waters. The catastrophe was perhaps unavoidable, but its large-scale, early and sudden occurrence, and a high cost were caused by the following reasons:

1. Exploitation at the third level.
2. Exploitation in too large chambers (15 m wide, 180 m long, and up to 12 m high), which led to safety pillars being too thin, especially in the presence of cavernous salts at the third level.
3. Exploitation by applying too strong explosions.
4. Continuation of improper exploitation methods in spite of an evident danger caused by occurrences of modern waters.
5. Construction of a new shaft and deeper mine levels.
6. Attempts to stop the inflows by injections of sealing materials through bore-holes drilled from the mine, which caused further destruction of salt rock.
7. Too late a decision on the construction of a pipeline to flood the mine artificially with water from a nearby lake.

Reasons 3–7 were easy to avoid completely or partly by taking into account the warning given by the isotope data. Unfortunately, at that time, the isotope methods were not trusted by mine specialists who regarded the inflows to be of residual origin. The ignorance and blindness which lead to the catastrophe is well demonstrated by the following citations from an unpublished report of a team of mine specialists written in November of 1976: "The main potential danger to the mine is from waters surrounding the diapir ... dimensions and situation of the exploitation chambers do not cause any direct danger ... a proper method has been used to stop the inflow at the third level ...." In a report written in April 1977, just before the catastrophe, the following conclusions appeared: "Obtained results of investigations allow us to state that the exploitation by explosions has had no influence, and will not have, on the occurrence of inflows at the third level. At present there is no danger for the loss of stability by the safety pillars due to too high pressures".

The Inowrocław mine

The Inowrocław salt diapir is about 2.5 km long and 1 km wide. The gypsum cap is at a depth of 6–221 m, and the salt mirror at a depth of 122–272 m. The first shaft was sunk between 1873–1878, later two more shafts were sunk. Salt was exploited in two underground mines and solution chambers operated through wells. In 1907 both mines were catastrophically flooded whereas the solution chambers were exploited until 1924 to depths of up to 180 m. The flood and further exploitation by solution chambers caused a number of land subsidences. Between 1924–1933 a deeper mine was built with the first level below the older ones at the 470 m. Its exploitation began in 1933, finally at ten levels separated by 18-m distances.

Table 2
Selected isotope data of water occurrences in the Inowrocław mine

Sampling site	Date	$\delta^{18}O$ [‰]$_{SMOW}$	δD [‰]$_{SMOW}$	Tritium [TU]	$NaCl+KCl$ [Moles/kg H_2O]	$CaCl_2+MgCl_2$
Tertiary aquifer, Trzaski 2	06.1982	−10.0	−74	n.d.	Fresh water	
Quaternary aquifer, Trzaski 13	06.1982	− 9.5	−69	n.d.	Fresh water	
Lake Pakoskie	02.1983	− 6.7	−54	30.0±1.5	Fresh water	
Lake Siedzisław	02.1983	− 9.7	−69	44.5±2.3	Fresh water	
River Noteć	02.1983	− 6.4	−54	35.0±1.5	Fresh water	
Shower in chamber 7/IX	07.1982	− 5.8	−57	n.d.	Fresh water	
Shower in chamber 5/IX	02.1983	− 7.0	−58	29.6±1.6	Fresh water	
Solno 1 shaft, Quaternary w.	05.1982	− 9.6	−70	n.d.	0.27	0.01
I level (470 m)	05.1982	− 7.1	−54	41.6±2.1	5.87	0.11
Solno 3 shaft, 124 m	01.1983	− 8.3	−68	14.4±1.5	3.00	0.07
400 m.	01.1983	− 3.2	−45	51.5±2.0	5.30	0.57
Solution chambers, Ch. 60794	07.1982	− 7.3	−59	n.d.	5.97	0.15
Ch. 70757	06.1982	+ 0.9	−36	n.d.	5.61	0.46
Occurrence 40/I	09.1979	− 3.9	−49	n.d.	0.96	3.58
	04.1980	− 3.1	−51	n.d.	1.51	2.91
	03.1983	− 1.7	−52	31.1±1.6	1.6	3.60
Occurrence 87/I	09.1979	− 6.6	−61	n.d.	2.19	2.72
	04.1980	− 1.5	−35	n.d.	1.08	3.44
Occurrence 94/I	01.1979	+ 5.6	−11	0.3±1.1	1.04	4.47
Occurrence 1/I	01.1980	+ 7.1	− 8	0.0±1.0	3.73	1.52
Occurrence123/I	04.1980	+ 6.3	−12	18.0±1.3	0.86	4.35
Occurrence 145/I	04.1980	+ 7.1	−10	3.7±1.5	4.09	1.52
Occurrence 149/IV	01.1979	− 2.6	−45	n.d.	3.55	2.42
	03.1983	− 6.6	−60	n.d.	5.81	0.26
Occurrence 127/VI	09.1982	− 5.2	−47	n.d.	5.84	0.41

Selected isotope and chemical data are given in Table 2 after Grabczak and Zuber (1986). Tap water obtained from Quaternary and Tertiary aquifers as well as river and lake water was used for exploitation by solution method. The identification of the origin of water occurrences was difficult due to two reasons. First, the presence of tap water which was used for the exploitation in solution chambers and showers; and, second, the presence of strongly evaporated water in some chambers, with the isotope composition close to that of residual brines. Further difficulties resulted from secondary changes in isotopic composition of waters caused by evaporation, mixing, dissolution of hydrated salts, and isotopic exchange during the migration through the cracked salt rock to deeper levels. The presence of tritium in some waters of evidently residual origin (e.g. 123/I and 145/I) was most probably due to contamination caused by molecular exchange of water with atmospheric vapor prior to sampling. The water occurred usually at the ceilings of chambers with volumetric flow rates from several to 300 ml/h. It is interesting that at the first level, only the occurrences Nrs. 40/I and 87/I were probably of meteoric origin, perhaps via the old mines. All the other occurrences at the first level were of residual origin as demonstrated by the most typical examples given in Table 2.
However, a large number of unidentified water occurrences, large volumes of water above the mine present in the older flooded mines, and the lesson learned in Wapno, led to a decision on the artificial flooding of the mine lasting from 1986 to 1995. The total volume of chambers and galleries filled with brine is 16.4×10^6 m^3, and 0.26×10^6 m^3 with dry material. That flooding removed the immediate danger to the town of Inowrocław, but possible hydraulic connections, especially between the old mines and adjacent groundwater systems, enhance a slow destruction of the salt dome, and may lead to subsidence events in future.

The Kłodawa mine

The Kłodawa deposit is situated at the central part of a 63-km-long salt structure. That central part completely pierces through the Mesozoic strata and forms a diapir, which is 26 km long and 0.5–2 km wide. The gypsum-clayey cap is at a depth of 40–500 m, up to 250-m thick, and is surrounded by Quaternary and Tertiary water-bearing sediments. Below the Tertiary sediments, the diapir is surrounded by Mesozoic formations. Salt is exploited at the four main levels (450, 525, 600, and 750 m), and several mid-levels, through three shafts. The exploitation began in 1956 and is planned to last up to 2020 with over 0.6×10^6 tons/year. The volume of free chambers is 15×10^6 m^3, with typical dimensions of $120\times12\times12$ m^3.

Table 3
Selected isotope data of water occurrences in the Kłodawa salt mine

Sampling site	Date	$\delta^{18}O$ [‰]$_{SMOW}$	δD [‰]$_{SMOW}$	NaCl + KCl [Moles/kg H_2O]	$MgCl_2 + CaCl_2$ [Moles/kg H_2O]
Inflow 17/680	12.1987	− 9.5	−80	3.32	0.79
Inflow 106/600	04.1991	−11.1	−80	6.06	0.12
	12.1991	− 8.1	−72	5.91	0.23
	07.1996	− 2.3	−53	5.92	0.24
Inflow 93/525	05.1985	− 9.2	−71	5.79	0.95
	09.1992	− 8.4	−66	5.44	1.09
	02.1998	− 6.4	−60	5.11	1.16
Inflow 7/450	02.1981	− 2.6	−29	0.37	4.94
	02.1998	− 2.4	−33	0.58	4.82
Inflow 14/550	09.1978	− 3.2	−40	3.30	1.79
	07.1981	− 1.8	−38	3.12	1.98
Occurrence 12/450	02.1979	+ 9.7	− 3	3.52	1.62
	09.1983	+ 6.8	−17	3.36	1.93
Occurrence 4/630	04.1981	+ 4.7	+ 8	5.96	0.17
Occurrence 73/525	09.1978	+ 9.1	+ 2	n.d.	n.d.
Occurrence 88/600	06.1977	+ 3.9	−13	0.74	4.29
	06.1981	+ 2.2	−19	0.74	4.37
Occurrence 29/572	09.1980	+ 1.5	−21	0.73	4.23
	05.1987	+ 3.0	−25	0.49	4.76
Occurrence 10/750	10.1986	+ 7.6	− 4	5.18	0.87
Occurrence 12/750	10.1986	+ 6.8	−18	1.06	4.32
Occurrence 30/750	02.1997	− 7.4	−69	6.12	0.10
Occurrence 27/600	09.1992	+ 2.4	−39	2.84	2.32

The inflow to the Kłodawa mine is about 18 l h^{-1} from the shafts and about 3 l h^{-1} from the mine workings. In 1995, about 450 water occurrences were observed, with 90% as moist walls and drops of water. Only 25% of occurrences are continuous, in that only 6 act as inflows. The inflows and other water occurrences have been monitored since 1974 for their isotopic and chemical compositions, and the isotope and simplified chemical data of the most interesting water occurrences in the mine are summarized in Table 3. The tap water in Kłodawa is isotopically heavier ($\delta^{18}O = -9.2‰$ and $\delta D = -64.5‰$) than the expected mean value of the modern infiltration in the area, i.e., $\delta^{18}O \cong -9.8‰$ and $\delta D \cong -69‰$ (d'Obyrn and others 1997). Though the exact isotope composition of local modern meteoric water is unknown, it has no influence on the interpretation given below.

In 1987, a horizontal borehole at the mid-level of 680 m reached the boundary of the diapir and an inflow of glacial water occurred (Nr. 17/680). That borehole was tightly sealed and the inflow stopped. However, the isotopic content of that inflow confirmed that relatively young waters migrate around the diapir to great depths.

In May 1985, during exploitation by explosions in one of the chambers, a cavern was opened with a sudden inflow of 7 m^3 of brine (Nr. 93/525). The flow rate was variable, with a tendency to decrease from the initial value of about 30 l h^{-1}, dropping to about 0.6 l h^{-1} at the end of 1985. The present, nearly constant flow-rate is in the range of 0.009–0.014 l h^{-1}. Controversial opinions exist on the origin of that inflow. Initially a number of specialists claimed the inflow to be unrelated to meteoric waters. These opinions were mainly based on high TDS (about 380–405 g l^{-1}) and Br^- (about 10 g l^{-1}) contents, as well as on a long-lasting decreasing flow rate. However, the initial isotopic composition of that inflow was typical for the Quaternary water of meteoric origin. A better identification of age was not possible, because of the lack of tritium (0.0 ± 0.5 TU), and expected non-measurable ^{14}C content. It is very interesting that after the initial phase the isotopic composition was shifted to heavier values represented in approximation by those of 1992 in Table 3. Recently, even heavier values are observed as shown in Table 3 and Fig. 7. That shift is supposed to be caused by evaporation in caverns from which the water flows to the mine, and probably also by an increasing influence of the isotopic exchange with hydrated salt minerals. The inflow is in the central part of the mine and it is surprising how the Quaternary water can reach that site. The only possibility is through folded and fractured anhydrite layers. Though opinions on the origin of water were initially controversial, the isotope warning led to the decision to stop any exploitation in the region of the inflow.

In 1991, another inflow appeared (Nr. 106/600), with the initial flow rate of 3 l h^{-1}, which dropped to the present value of about 2 ml h^{-1}. Its initial isotopic composition was characteristic for glacial meteoric waters in central Poland. With the decreasing flow rate, a continuous change in isotopic contents due to isotopic exchange and evaporation was observed (Table 1; Fig. 7). That inflow occured near a horizontal borehole which crossed the boundary of the deposit. Most probably, the Quaternary water which flows around the dome, as described above

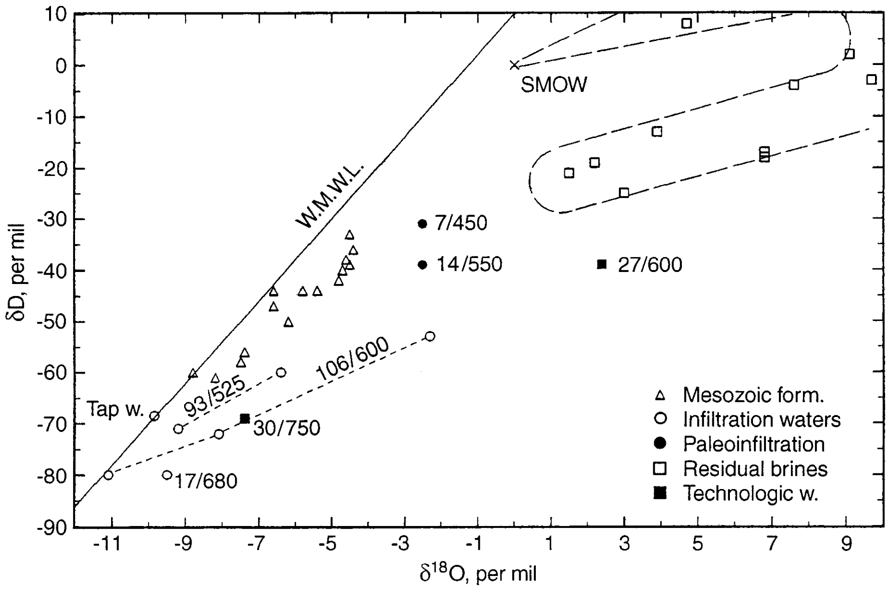

Fig. 7
Selected isotope data of water occurrences in the Klodawa mine

for the Wapno mine, enters the mine through that, perhaps improperly, sealed borehole, and next it flows through folded anhydrite layer to the site of its occurrence.

The oldest inflow (Nr. 7/450) exists since 1956, with the initial flow rate of about 900 l/h from a large crack in anhydrite. The flow rate soon dropped to about $2\ l\ h^{-1}$ and next started to increase to about $17\ l\ h^{-1}$ in 1964. At the end of 1964, a dam was built, which reduced the flow rate to a nearly constant value of about $3\ l\ h^{-1}$. The isotopic composition of that inflow scatters around the mean values of -2.5‰ for $\delta^{18}O$ and –31‰ for δD (Fig. 7). That brine most probably originates from the adjacent Mesozoic formations, with further saturation and isotopic shifts caused by exchange with hydrated salt minerals within the diapir. According to the data presented by Dowgiałło and Tongiorgi (1972), and Zuber and Grabczak (1991), in the Mesozoic formations in central and northern Poland dominate paleowaters of pre-Quaternary warm climates. They are characterized by isotope compositions distinctly heavier than those of Quaternary waters, and slightly shifted from the World Meteoric Water Line (WMWL) to more heavy values, as shown in Fig. 7. A similar isotopic composition was observed for the inflow 14/550 (Grabczak and Zuber 1986) which disappeared. Therefore, most probably, its origin can also be related to pre-Quaternary water, but perhaps entrapped from the Mesozoic formations during one of the uplifting phases.

The majority of water occurrences most often had the isotopic composition characteristic for evaporated ocean water. For instance, occurrences Nrs. 4/630 and 73/525 were related to the initial stages of the ocean evaporation (both ^{18}O and δD had positive values). Occurrences Nrs. 88/600, 29/572, 10/750 and 12/750 can be related to the end stages of the evaporation of marine water (Zechstein ocean) as indicated by a typical hook on the $\delta^{18}O$-δD diagram, in agreement with the results of Sofer and Gat (1975). Occurrences of residual brines usually disappear quickly, though examples represented by Nrs. 88/600 and 29/572 show that sometimes they exist for several years. A very interesting example is given by occurrences Nrs. 10/750 and 12/750, which appeared nearly at the same time. As indicted in Table 3, Nr. 10 was dominated by monovalent whereas Nr. 12 by bivalent salts. The isotopic composition showed that both were of residual origin as confirmed by their quick disappearance.

Some appearances of water are difficult to identify, because they are strongly shifted from the modern waters to heavier $\delta^{18}O$ and δD values, which are between modern meteoric and evaporated marine waters, as indicated by examples given at the end of Table 3. Close inspection of such occurrences showed that, contrary to other occurrences, they appear at the floors of mine workings and can be related either to condensed air moisture or to outflows of technologic water.

Summarizing, only three water inflows are regarded as potentially dangerous (Nrs. 93/525, 106/600 and 7/450). However, the staff of the Kłodawa mine regards the isotope method as very useful. Whenever a new water occurrence is found to be potentially dangerous (e.g., saturated with NaCl), the exploitation in its region is stopped till the origin by the isotope analyses have been completed and the residual character confirmed.

The Wieliczka mine

The Wieliczka mine exploits the Miocene salts which are characterized by two structures: the lower one consists of layered salt strongly tectonically displaced with fallen flexures, and the upper one consists of salty clays with large salt blocks. The salt deposit, and the flysch sediments overthrust from the south, are quite well known. Relatively little is known about the Tertiary water-bearing rocks, the Chodenice beds, which are at the northern boundary of the deposit. They consist mainly of clays, slightly cemented sandstones and sandstone conglomerates, probably strongly fractured during the tectonic events, which folded the Miocene sediments. A simplified map of the western part of the mine area with the position of main inflows is shown in Fig. 8. These main inflows occur at the southern boundary of the Chodenice beds.

Over seven centuries of exploitation has created about 2040 chambers with the total volume of about 7.5×10^6 m^3 and over 190 km of galleries in nine levels and several local mid-levels. There were many catastrophic intrusions of water and loose sands, which were caused by the lack of knowledge on the boundary of the deposit and the character of adjacent rocks. A simplified historical record of inflow rates in m^3 day^{-1} is as follows: 6 in 1381–1819, 31 in 1820–1919, 50 in 1925–1960, 135 in 1960–1971, 500 to 418 in 1972–1991, and about 900 in 1992. In 1991, there were about 260 inflows with very low flow rates and several larger inflows at the fourth, fifth, sixth and seventh levels. These large inflows considerably increased the total inflow to the mine in the last several decades.

Some inflows have been monitored since 1973 for determining the origin and age of water by analyses of δ^{18}O, δD and tritium content. The most important inflows were also occasionally analyzed for ^{14}C content and δ^{13}C values (Table 4). All the inflows appeared to be of meteoric origin with water ages ranging from the end stages of the last glacial to the modern. The glacial waters were recognized by the lack of tritium, the ^{14}C content of zero or several per cent of modern carbon (pmc), and the isotopic composition more negative than the mean values of the modern meteoric water in the area. That glacial water has NaCl content up to about 100 g l^{-1} and is stored in the Chodenice beds, near the salt deposit.

In the Chamber Z-32, at the fifth level, an inflow occurred in 1960 with a flow rate of 85 m^3 day^{-1} as a result of a ceiling fall in a chamber at the second level. Initially, the isotopic composition and the lack of ^{14}C suggested the glacial age of water. The presence of some tritium (0–2 TU in 1974–1977 and about 8–20 TU in 1979–81) was initially supposed to result from an unknown contamination. However, a number of samples taken in the period of 1980–1990 showed tritium concentrations from 20 TU to about 30 TU with a following slow decline to about 25 TU in 1996. Some increase in the concentration of ^{14}C was also observed, from zero in earlier years to 3.8 ± 1.0 pmc in dissolved inorganic carbon (DIC), and 3.2 ± 0.4 pmc in dissolved organic carbon (DOC) in 1991 (Table 4). Concentrations of such anthropogenic pollutants as C_2HCl_3 and C_2Cl_4 in concentrations close to those in equilibrium with the atmosphere were also found as well as HPO_4^{3-}. High tritium contents (20–25 TU) without measurable ^{14}C concentrations at the

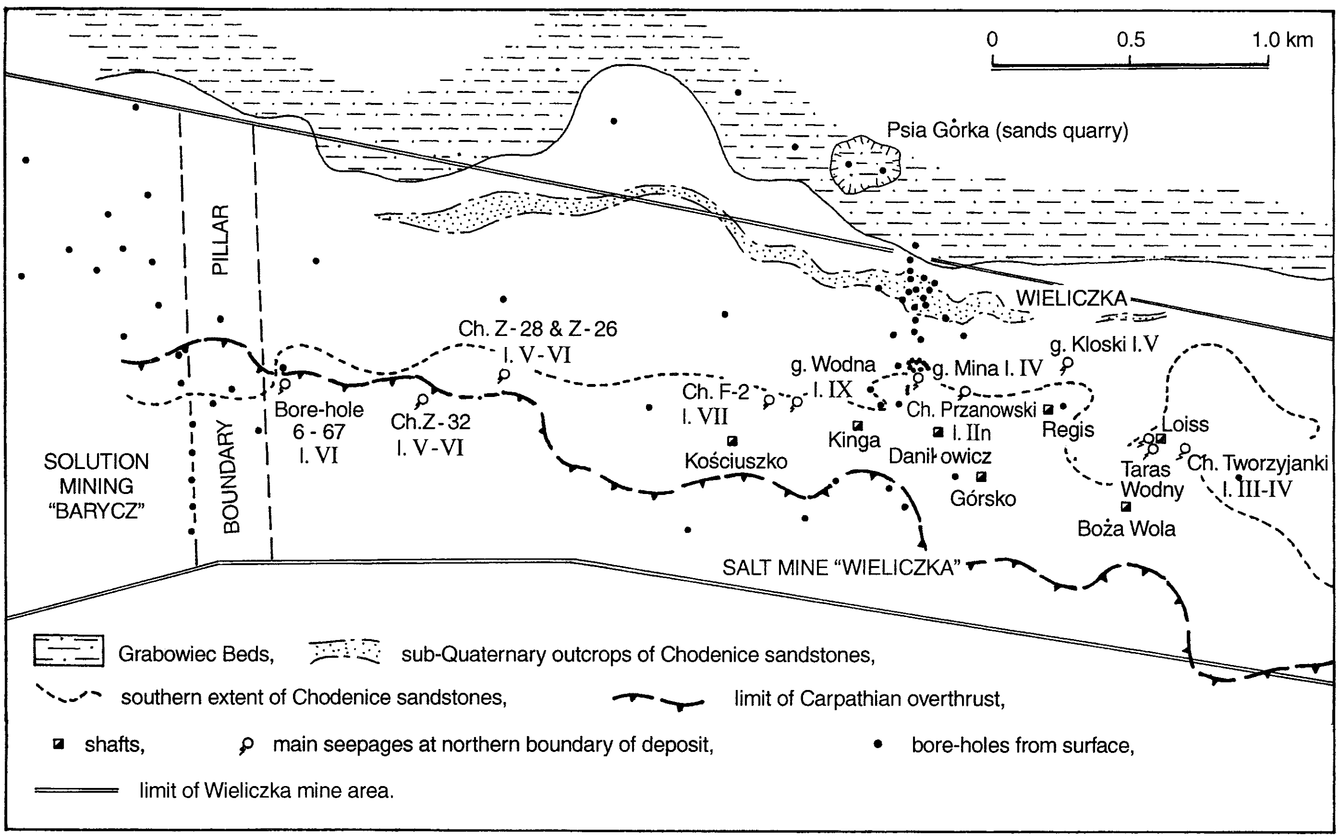

Fig. 8
Simplified geological map of the western part of the Wieliczka deposit with the position of main inflows

Table 4
Selected isotope data of inflows in the Wieliczka salt mine

Sampling site	Date	$\delta^{18}O$ [‰]$_{SMOW}$	δD [‰]$_{SMOW}$	Tritium [TU]	^{14}C [p.m.c.]	$\delta^{13}C$ [‰]$_{PDB}$
Taras, I-36	23.10.1980	− 9.5	−68	5.2±1.5	28.5±1.0	−16.0
	20.09.1987	− 9.6	−68	4.8±0.5	n.d.	n.d.
Taras, I-37	18.05.1987	− 9.9	−68	20.7±1.1	n.d.	n.d.
		− 9.9	−71	23.1±1.1	n.d.	n.d.
Chamber F-II	15.09.1977	−10.5	−73	1±2	2.6±1.0	-15.2
	25.06.1979	−10.7	−76	0.6±1.5	0.9±1.0	−14.1
	10.07.1987	−10.8	−76	0.0±1.1	n.d.	n.d.
	10.09.1991	−10.8	−78	0.4±1.0	1.4±1.0	−14.4
	10.09.1991				3.4±2.9[a]	−25.0[a]
Chamber Z-32	15.09.1977	−10.5	−73	1±2	1.3±1.0	-12.5
	25.06.1979	−10.7	−76	7.4±1.5	0.7±1.0	−10.3
	10.03.1983	−10.6	−74	22.3±1.5	1.3±1.0	−12.0
	15.10.1986	−10.2	−74	29.4±1.4	0.9±1.0	−12.4
	11.09.1991	−10.4	−75	29.6±1.4	3.5±1.0	−13.0
	11.09.1991				11.8±2.9[a]	−24.7[a]
Chamber Z-26	10.10.1995	−10.1	−73	4.5±0.5	n.d.	n.d.
	22.09.1997	−10.4	−76	2.9±0.5	n.d.	n.d.
Chamber Z-28	22.10.1988	−10.6	−75	1.1±1.0	n.d.	n.d.
	12.10.1990	−10.9	−77	0.6±1.0	n.d.	n.d.
	10.12.1992	−11.0	−77	0.4±1.0	n.d.	n.d.
	22.09.1997	−10.8	−78	0.6±0.5	n.d.	n.d.

[a] in DOC after Geyer and others (1993)

initial stages of the tritium breakthrough curve cannot be explained by any mixing hypothesis. However, all these effects can perhaps be explained by the hypothesis of Małoszewski and Zuber (1991). According to that hypothesis, intrusion of modern water (transient state) through fissured marly sediments may result in a strong delay of the tritium migration due to matrix diffusion effects (the retardation factor of about 100). A much stronger delay of the inorganic carbonates (DI^{14}C) results from matrix diffusion and exchange reactions in micropores with the solid carbonates. The low ^{14}C content in DOC was unexpected, but it can probably be explained by isotopic exchange with dead organic matter (2–3%) in the Miocene sediments as suggested by Geyer and others (1993). The NaCl content in that inflow is linearly increasing from about 120 g l^{-1} at the beginning to the present value of about 200 g l^{-1}. In conclusion, due the modern age of water, that inflow should be considered as potentially very dangerous.

A large inflow of unsaturated brine (about 100 g l^{-1}) occurred in Chamber F-2 at the seventh level in 1972 due to the crossing of the salt boundary. It started with a nearly constant flow rate of 480 m^3 day^{-1}, which decreased presently to 290 m^3 day^{-1}. The inflow was caused by accidental destruction of thin gypsum layer at the northern boundary of the deposit, which is strongly inclined to the south with increasing depth. Early isotope data showed the same glacial age of inflowing brine and brine observed in the H-8 well in the Chodenice beds in the vicinity of the Chamber F-2 (Zuber and others 1979). Therefore, it was concluded that a strong concrete dam constructed to prevent further destruction of the chamber walls by inflowing brine should be sufficient as a safety measure. Consequently, that inflow, though impossible to be stopped, is regarded as relatively safe.

One of the most catastrophic inflows started in 1992 in the Mina gallery at the fourth level (Figs. 8 and 9). That gallery, before the First World War, crossed the salt boundary and was stopped 20 m beyond the salt deposit in the gypsum and clay cover. In 1935, the first information on the inflow of water appeared ($Q=1$–2 l min^{-1}, TDS = 240 g l^{-1}). In 1994, the NaCl content was about 110–120 g l^{-1}. After the Second World War, the gallery was not accessible due to rock falls, and slag used to fill in the Dunajewski chamber, crossed by the gallery. However, water migrated downward through the deposit and was observed at the fifth level (Badeni gallery) with the flow-rate of 4–5 l min^{-1} and TDS ≅ 300 g l^{-1}.

Serious troubles started during the reconstruction of the Mina gallery aimed at closing the inflow behind a dam. As the decisions on the sampling sites and sampling frequency for isotope analyses were always of the mine staff, that inflow was regarded to be safe. A sample taken when the reconstruction reached the water flow in the gallery in 1991 indicated glacial water from the Chodenice beds (Table 5). In general, mine works aimed at the reconstruction of the Mina gallery and its “safe taming” were started without any investigations in that region of the mine and adjacent area. A catastrophe began on the night of 13 April 1992 when the flow rate increased to 200–300 l min^{-1} (290–430 m^3 day^{-1}), i.e., nearly equal to the sum of other inflow rates to the mine at that time. The concentration of suspended matter was about 500 kg/m^3, and the pumps then in use were not able to pump it

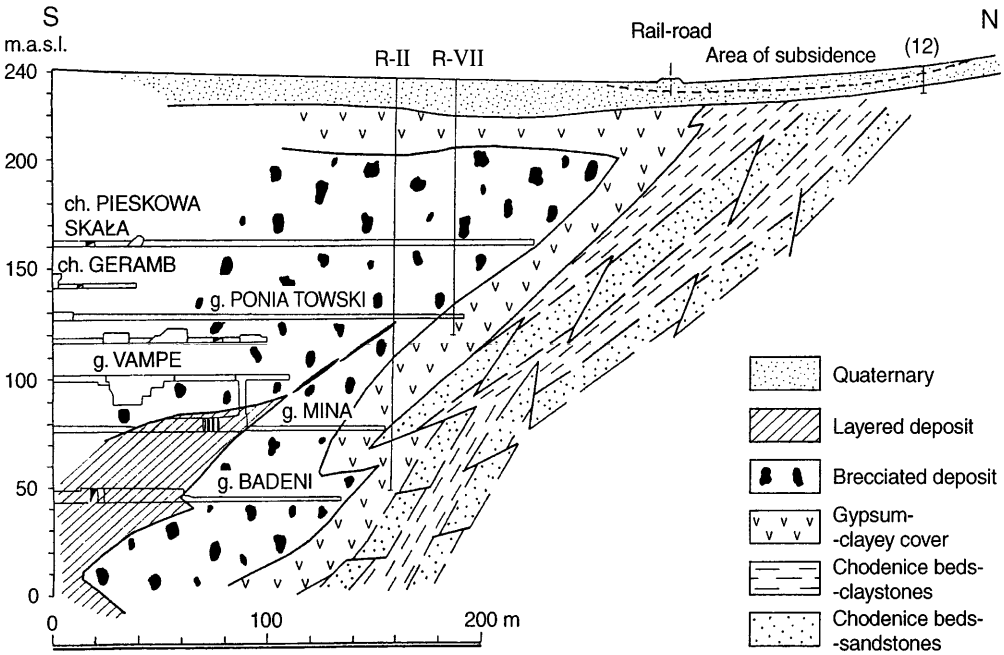

Fig. 9
Geological cross-section through the northern boundary of the deposit in the region of Mina gallery (Garlicki and Wilk 1993)

Table 5
Selected isotope data of the inflow in the Mina gallery

Date	$\delta^{18}O$ [‰]$_{SMOW}$	δD [‰]$_{SMOW}$	Tritium [TU]	^{14}C [p.m.c.]	$\delta^{13}C$ [‰]$_{PDB}$	NaCl [g/l]
21.10.1991	−10.5	−78	0.0±1.0	n.d.	n.d.	37.4
14.04.1992	−10.4	−76.5	0.0±0.5	n.d.	n.d.	27.5
28.04.1992	−10.2	−72	0.0±0.5	n.d.	n.d.	36.2
22.05.1992	−9.3	−66	0.5±0.5	9.5±1.0	−15.0	59.4
11.08.1992	−10.65	−74	0.1±0.5	n.d.	n.d.	51.5
13.09.1992	−10.3	−72	0.4±1.0	n.d.	n.d.	27.8
23.10.1992	−9.85	−68.5	1.1±1.0	n.d.	n.d.	6.1, 2.9[a]
25.10.1992	−9.4	−67.5	0.7±1.0	n.d.	n.d.	75.8
23.04.1993	−9.4	−65.5	2.1±0.5	n.d.	n.d.	12.9, 1.8[a]
04.08.1993	−10.0	−71	0.5±0.5	18.0±1.0	−15.3	19.2
15.12.1993	−9.9	−71	0.5±0.5	n.d.	n.d.	18.9
17.05.1994	−9.4	−69	1.0±0.5	n.d.	n.d.	14.2
06.08.1994	−9.45	−68	7.1±0.5	n.d.	n.d.	3.0, 0.7[a]
30.12.1994	−9.85	−70	1.1±0.5	n.d.	n.d.	14.6
20.04.1995	−9.9	−71.5	1.2±0.5	n.d.	n.d.	13.2[b]
11.03.1996	−9.75	−68	2.6±0.5	n.d.	n.d.	10.6[b]
15.10.1996	−9.9	−69	3.2±0.5	n.d.	n.d.	10.6[b]
28.08.1997	−10.05	−70.5	3.8±0.5	n.d.	n.d.	8.4[b]

[a] short-time values during increased inflow and collection of isotope sample, other data represent mean daily values
[b] mean yearly values

out. In consequence, the gallery was filled nearly to the ceiling with mud.
Variable isotope and NaCl data given in Table 5 show waters of different ages, i.e., glacial water, Holecene water, and mixed waters, even with a modern component. The flow rates were also extremely variable (Fig. 10). It can be supposed that the glacial water stored in the Chodenice beds in the vicinity of the gallery initially was drained. However, at later stages either water stored in the Chodenice beds west and east of the gallery was drained, or there is a hydraulic contact with the sands of the Tertiary Grabowiec beds (Fig. 8). The Grabowiec beds are mostly confined, and in confined parts contain water of the Holocene age. Unfortunately, wells in the area adjacent to the gallery were not sampled for isotope analyses. Therefore, it is impossible to say if the observed continuous freshening is caused by a contribution of fresh water from the Grabowiec beds, or from water stored near the outcrops of the Chodenice beds. In any case, the catastrophe has not influenced the flow rates of

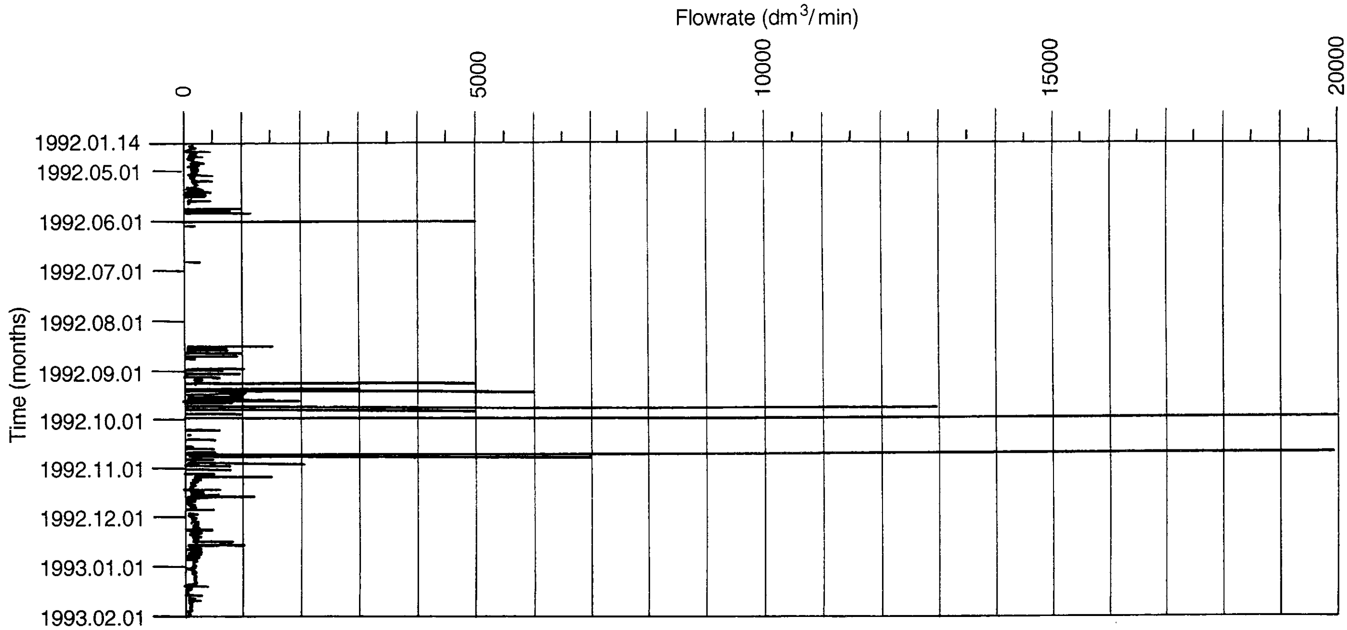

Fig. 10
Irregular flow rate of the inflow in Mina gallery (adapted from Garlicki and Wilk 1993)

other inflows, and the local recharge, especially within the subsidence cone, is negligible.

The pulse character of the inflow is caused by natural instability of adjacent rocks, and by unsuccessful attempts to stop the inflow. In consequence, washing out (suffosion) periods are during high inflow rates, and are followed by land subsidences, which lead to clogging (colmatation) when the flow rates and pressure drop. A temporary colmatation leads to an increase of the water table in the Chodenice beds, and the whole cycle is repeated. That process is quite complicated as shown by differences in water levels observed in a number of boreholes in the northern fore-field of the mine adjacent to the Mina gallery (Garlicki and others 1996). In general, when the water pressure builds-up sufficiently, dams, or any other sealing forms, are easily destroyed or moved from their positions because they cannot be anchored in stable rocks, especially as the Chodenice beds are naturally unstable and additionally deformed by a long action of the inflow. If the inflowing water is recharged indirectly through the Grabowiec sands, the inflow rate can perhaps be reduced only if their bottom parts are sealed in the region of the contact with the Chodenice beds. If the water comes from the distant parts of the Chodenice beds, the inflow rate can be reduced by pumping in wells installed at distances sufficient to avoid further rock destabilization in the vicinity of the gallery. Undoubtedly, any such operation would be very expensive.

It is worth mentioning that when the inflow to the Mina gallery developed to catastrophic dimensions, the mine specialists tried to use dowsing and witch methods. For instance, dowsers were claiming that through the mine a river flows at the rate of 1.5 m^3 s^{-1} (sic!). A 100-m-long trail was buried 1 m below the ground surface, and was believed to stop the inflow at the depth of 170 m, and to change the flow direction upwards (sic!). Considering the importance of the Wieliczka salt mine and its underground museum, the Polish government and international institutions supplied special funds to save it from a flood caused by the Mina inflow. Therefore, it is not surprising that a number of "specialists" recognized an easy way to reap undeserved profits. What is surprising, however is the trust of mine specialists shown in non-scientific methods.

Summarizing, the main errors committed in the Mine area were as follows:

1. The construction of the gallery through the salt boundary and ending it far from that boundary.
2. Attempts to reconstruct that gallery without any investigations.
3. Attempts to stop the inflow by the construction of a dam in weak rocks, which was followed by closing the through-flow pipes, against hydrogeologists' advice, and against the experience obtained in the Wapno salt mine.
4. Drilling of wells in the area of the inflow, and attempts to solidify the rock by injections of sealing materials.
5. Little correlated investigations which were not fully taken into account in planning actions aimed at decreasing the catastrophic impacts.
6. Waste of funds on the application of dowsing and witch methods.

The inflowing waters are being used for the exploitation by the solution method (partly in a nearby Barycz mine, see Fig. 7), which, of course, leads to a further destabilization of the whole structure of the deposit, and endangers the famous historical part of the mine and the underground museum. However, if the exploitation is stopped, there is no possibility to discharge the saline water. Therefore, the Wieliczka salt mine is greatly endangered, unless the flow rates of the main inflows are considerably reduced. Unfortunately, it is not clear how it can be achieved.

Conclusion

The environmental isotope methods have appeared to be very useful in identifying the origin of mine waters, and in many cases they can be helpful in taking proper measures aimed at decreasing the potential dangers caused by the presence of inflows. It has been shown that some catastrophic inflows to Polish salt mines, could have been avoided, or their environmental and economic consequences could have been lower, if the isotope data had been taken into account. A particular usefulness of the isotope methods in Polish salt mines results from a large difference in isotopic composition between Quaternary meteoric waters and pre–Quaternary waters of warm and hot climates, which occur in the Mesozoic formations in central and northern Poland adjacent to Zechstein salt domes. In some cases, secondary effects in the mines (mainly evaporation prior to sampling and isotope exchange with the water of crystallization in hydrated salts) hinder the interpretation. It is particularly difficult to avoid isotopic changes prior to sampling for inflows with low flow rates, which occur in large cavities, and at the roofs of large chambers. The presence of technologic water also hinders the interpretation, especially if its amount is sufficient for migration to deeper levels.

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