TRACER INVESTIGATIONS IN FLOODED MINES – THE STRASSBERG/HARZ MULTITRACER TEST

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Abstract

After having constructed three new water adits, the water budget of the abandoned Straßberg mine increased substantially. To solve the questions arisen from this, a multi-tracer test was conducted. By the use of potassium chloride, coloured club moss spores, and microspheres, the hydrodynamic relation between the three mining districts could be shown. Generally, the flow direction is from north to south, the mean effective flow velocities ranging from 0.1–1.5 m min^{-1}. Furthermore, it is clear now, that a dam between two of the three pits is hydraulically inactive at the current flow situation. No reasons, up to now, were found for the increased water budget infiltrating from the Brachmannsberg mining district. It could be shown, that solid tracers in conjunction with a reliable injection and sampling technique are a good means to investigate the hydrodynamic conditions within this abandoned underground mine.

Introduction

In 1991, economic and environmental reasons caused the closure of the Straßberg fluorspar mine, owned by the GVV (Gesellschaft zur Verwahrung und Verwertung von stillgelegten Bergwerksbetrieben mbH; Company for remediation and utilisation of abandoned mines Ltd; Kuyumcu & Hartwig, 1998). Situated in the Mid Harz Fault Zone of the eastern Harz Mountains (Fig. 1), approximately 30 km south of Quedlinburg and 6 km west of Harzgerode, the Straßberg mine (TK 4332 Harzgerode) was the most important producer of fluorite in the former GDR (Mohr, 1978). Besides fluorite, the hydrothermal polymetallic mineralisation of the vein structures comprises several ore minerals of Permian to Cretaceous age (e.g pyrite, galena, sphalerite, chalcopyrite, arsenopyrite, wolframite, scheelite, siderite; Kuschka & Franzke, 1974).

At the beginning of the mining, which might go back more than 1000 years, silver, copper, and lead were the targets of the miners. From the 18th century until 1990, mining focused on fluorspar, which was mainly found in the deeper parts of the mine (Bartels & Lorenz, 1993). Sinking the Fluor dayshaft at the Straßberg pit in 1910 marked the start of the last production period and between 1950 and 1970, the VEB Harzer Spatgrube joined the three most important deposits of the Straßberg mining district by driving two deep adits on the 5th and 9th level (from north to south: Brachmannsberg pit: No 539 shaft, Straßberg pit: Fluor shaft and Glasebach pit: Glasebach shaft). Whilst the 3.5 km long Nordquerschlag (northern adit) connects the Brachmannsberg and Straßberg pit on the 5th level, the 1.5 km long Glasebachquerschlag (Glasebach adit) connects the Straßberg and Glasebach pits on the 9th level. Ultimately, when the ore reserves in the Brachmannsberg underground pit decreased in the 1980ies, a dam was constructed in the northern adit, to separate the water to be flooded Brachmannsberg pit from the Straßberg pit.

Tab. 1: Mean composition of the mine water in the Straßberg mine during the time of the tracer test (May 30th–July 27th 2000) in mg L^{-1}. Li: < 0.1 mg L^{-1}, NO_3: < 0.5 mg L^{-1}.

Shaft	n	Na	K	Ca	Mg	Fe	Mn	Cl	SO_4	HCO_3	F
No 539	15	22	2	56	21	21	12	28	198	64	5
Fluor	11	15	2	140	29	22	6	17	387	77	8
Glasebach	9	14	5	178	32	10	13	17	385	184	7

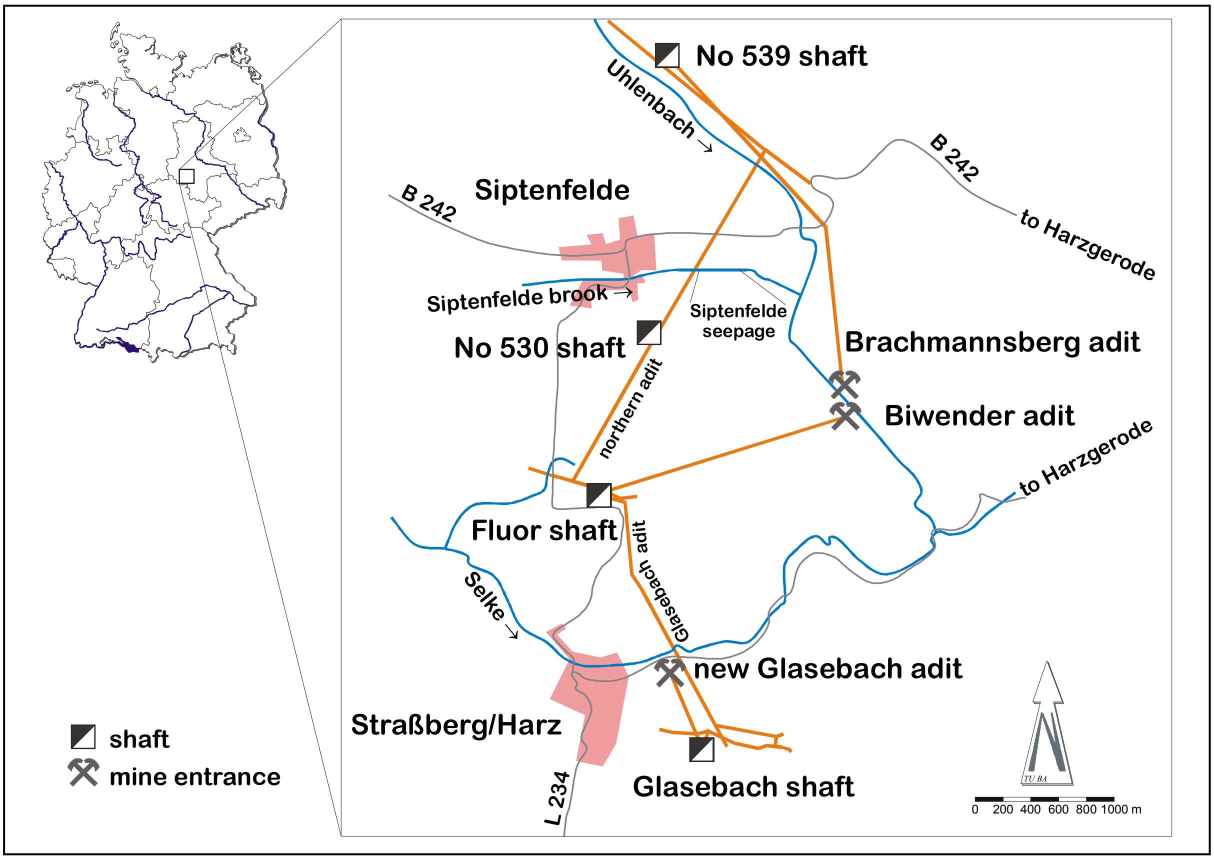

Fig. 1: Location of the Straßberg mine in the eastern Harz mountains and its main galleries and shafts

On May 31st 1991, by stopping the drainage water pumps, the Straßberg and Glasebach underground pits started to be flooded (Tab. 1). Between July 1992 and August 1998, accompanying in-situ temperature and conductivity measurements within the No 539 shaft and the Fluor shaft (310 and 147 m deep, respectively), clearly showed that a stratification within the water body was taking place (Kindermann, 1998, Rüterkamp & Messer, 2000). In the Fluor shaft, 3 water bodies, being separated from each other at the 2nd (328 mHN) and 5th (243 mHN) levels, established. Only 2 water bodies, separated by the 4th (357 mHN) level, could be recognised in the No 539 shaft. Evidence for the stratification were differences in temperature, conductivity, and metal-concentration between each of the water bodies (Tab. 2), the uppermost always low, the lowermost higher contaminated by iron, manganese, and sulphate.

Consequently, in 1993 the DMT – German Mining Technology, proposed to construct three new adits (Brachmannsberg adit, Biwender adit, new Glasebach adit; Fig. 1), to drain and treat the lower contaminated mine water within the uppermost water bodies at a water level of

357,7 mHN (Rüterkamp & Messer, 2000). These three adits were build between 1995 and 1998 and are draining the mine since then. Two provisional active water treatment plants near the Fluor shaft and in the Uhlenbach Valley (close to the entrances of the Brachmannsberg and Biwender adits) are cleaning the circum-neutral mine water (pH 6.2–8.0, n = 22, 95 % conf.) by the use of conventional liming technology.

After completion of the 3-adit-system in 1998, the stratification totally broke down in the No 539 shaft and partly in the Fluor shaft (Rüterkamp & Messer 2000, appendixes 1 and 5), resulting in a generally higher contaminant load than expected. Similar circumstances already had been found and investigated during the flooding of the Niederschlema-Alberoda mine (Erzgebirge/Germany, Wolkersdorfer, 1997a). There, as long as the water level was under a main level, stratification could be seen in the shafts above the last level that had been flooded. When the main level was flooded a new loop established and the stratification broke down immediately (Wolkersdorfer, 1996). Furthermore, the annual water budget of the Straßberg mine increased by almost $2 \cdot 10^6$ m³.

Due to the new circumstances after installing the 3-adit-system, the mine's owner suggested to conduct a tracer test within the flooded part of the mine. The aim of the tracer test was to investigate the hydrodynamic conditions within the mine and the pathways of the water between the three pits. Furthermore, it should be examined, if there was a connection between a small brook, the Siptenfelde brook, used as a sewer and the underground mine. Therefore a multi-tracer test with sodium chloride, microspheres, and club moss (*Lycopodium clavatum*) spores was carried out (Wolkersdorfer, 2000).

This paper describes the implementation and the results of the tracer test at the abandoned Straßberg mine conducted in June 2000.

Tab. 2: Selected constituents of the mine waters in the Fluor and No 539 shaft in mg L^{-1} before and after the 3-adit-system taken in use (after Rüterkamp & Messer, 2000). mHN: meters above Sea Level (Kronstadt elevation).

	Fluor shaft						No 539 shaft						
Depth, mHN	25.8.1997			24.2.2000			Depth, mHN	26.8.1997			24.2.2000		
	Fe	Mn	SO_4	Fe	Mn	SO_4		Fe	Mn	SO_4	Fe	Mn	SO_4
~ 340	40	8	466	31	6	359	367	22	1	143	23	1	204
284	42	9	478	27	11	417	272	79	2	389	22	1	196
204	52	19	600	50	18	525							

Methods

Previous Tracertests in Underground Mines

Published results of tracer tests in abandoned underground mines are rare. Until now, the results of only two tracer tests in flooded underground mines using colloidal tracers (microspheres with 15 µm diameter and club moss spores) are published (Wolkersdorfer 1996, Wolkersdorfer et al., 1997a, 1997b). Skowronek & Zmij (1977) traced the pathway of a water inrush into a shaft and Goldbrunner et al., (1982) investigated the water inflow into a producing alpine magnesite mine. Aldous & Smart (1987) conducted a tracer test in an abandoned and flooded coal mine field by injecting a fluorescent dye tracer into the surrounding overburden. Another tracer test with fluorescent dyes was performed in a flooded mine by Davis (1998; Rico, Dolores County, Colorado). A yet unpublished tracer test with discontinuous sampling of microspheres (0,4 µm diameter) was carried out in the Königstein mine (Elbtal-zone/Germany; Käss, pers. comm. 2000). However, microspheres had been used successfully in ground water tracing (McKay et al., 1997, Moline et al., 1997, Turin & Reimus, 1997, Petrich et al., 1998, Becker et al., 1999).

To guarantee reliable results, continuous sampling of the tracer used is necessary. Unfortunately, microspheres and club moss spores cannot be sampled continuously, but quasi continuously using filters, that have to be changed regularly (Käss, 1998). Niehren & Kinzelbach (1998) presented an on-line microsphere counter (flow cytometer) for microspheres with a diameter of 1 µm and a flow rate of up to 1 mL min^{-1} to be used in ground water studies. Due to the requirements on a tracer test in a flooded mine (rough underground conditions, high flow rates), and the conditions of the mine water itself (e.g. high suspension load), using a flow cytometer was unfeasible. Therefore, the methods, filter systems, and procedures described by Wolkersdorfer et al. (1997a) were used in a modified form.

Tracer Injection

As the area under investigation extends about 5 km in north-south and 2 km in east-west direction, several injection and sampling points were needed (Fig. 1, Tab. 3). Coloured fluorescent microspheres with a 15 µm diameter (Triton Technology Inc, San Diego CA, USA; Zhang et al., 1998) were injected at 4 localities, thereunder one were also coloured club moss spores (Sigma-Aldrich Chemie GmbH, Deisenhofen/Germany) were used. 350 m east of Siptenfelde, saturated sodium chloride brine (Kali + Salz GmbH, Bernburg/Germany) was introduced into the Siptenfelde brook. Details of the tracer quantity injected and the injections times can be found in the Table (Tab. 3).

Based on the assumption, that 277,000 m³ of water are in the mine and that 13,000 m³ of water per day will be exchanged, the tracer amount was calculated. This resulted in 40 mL of microspheres per injection point, 500 g of spores and 20,000 L of saturated brine to be used for a successful tracer test.

For injecting the microspheres (June 5th 2000), two different injection techniques were used. In the No 539 shaft, the Fluor shaft and the Glasebach shaft, 3 LydiAs (Lycopodium Apparatus: probe for injecting colloidal tracers) were lowered down to 266 mHN (92 m below water level), 110 mHN (247 m below water level) and 354 mHN (4 m below water level), respectively. At the partly plugged No 530 shaft, connecting the northern adit to the surface, a different injection technique was used. 40 mL of microspheres were mixed with 50 L of clear water, poured into a borehole through the plug and flushed into the mine with another 1000 L of water.

Tab. 3: Injection points, depth in shafts, and injection times of the 7 tracers used. Add 40 hours to the times marked with an asterisk, as LydiA (Lycopodium Apparatus) opened approximately 40 hours later.

Injection points (depth)	Tracers	Quantity	Injection time
Siptenfelde brook	NaCl brine	20 m³ (6.2 t)	June 2nd: 9:08–10:15
No 539 shaft (92 m)	microspheres "blue"	40 mL	June 5th: 14:44 *
No 530 shaft (20 m)	microspheres "orange"	40 mL	June 5th: 9:50–10:13
Fluor shaft (247 m)	microspheres "red"	40 mL	June 5th:12:18 *
Fluor shaft (247 m)	spores "malachite green"	264.9 g	June 5th: 12:18 *
Fluor shaft (247 m)	spores "saffron coloured"	279.5 g	June 5th: 12:18 *
Glasebach shaft (4 m)	microspheres "green"	40 mL	June 5th: 8:11 *

Tab. 4: Pump capacity of mini piston pumps and total amount of water pumped through the filter systems during the tracer test (June 5th–June 26th 2000).

Sampling point	Pump capacity	Water pumped through filters
No 539 shaft	0.08–0.13 L min^{-1}	2,421 L
Fluor shaft	0.08–0.09 L min^{-1}	2,419 L
Glasebach shaft	0.12–0.69 L min^{-1}	5,038 L

To test the reliability of the microspheres and for correlation reasons, 544.4 g of club moss spores (malachite green, saffron coloured) were injected into the Fluor shaft at the same depth as the microspheres.

At the time of the tracer injection (June 2nd 2000), 30 L min^{-1} of water were flowing in the Siptenfelde brook (measured at the pipe outlet Siptenfelde) and the water trickled away 410 m east of Siptenfelde ("Siptenfelde seepage"). Usually, the flow in the Siptenfelde brook ranges from 300–600 L min^{-1} and it flows into the Uhlenbach brook, the latter one flowing into the river Selke. During summer time, the flow decreases and as soon, as the flow is lower than 300 L min^{-1}, the Siptenfelde brook does not reach its mouth. 350 m east of Siptenfelde, near "tree one", 20,000 L of saturated sodium chloride brine were introduced into the Siptenfelde brook with a flow rate of 300 L min^{-1}. All of the brine was trickled away 150 m downstream "tree one"

During the tracer test, approximately 4.5 m³ min^{-1} of mine water flew out of No 539 shaft, 3 m³ min^{-1} left the Fluor shaft and 1 m³ min^{-1} the Glasebach shaft.

Tracer Sampling and Analyses

Due to the tracers' characteristics, two different sampling techniques were used. The sodium chloride was detected by continuos conductivity measurements with sampling points at the Uhlenbach brook (PIC GmbH, Munich/Germany), No 539 shaft (LogIn GmbH, Gommern/ Germany), Fluor shaft (LogIn GmbH, Gommern/Germany) and the Glasebach shaft (EcoTech GmbH, Bonn/Germany). Filter systems, each with 300 µm and 15 µm filters (NY 300 HC, NY 15 HC; Hydro-Bios, Kiel/Germany), for collecting the solid tracers (microspheres, spores) were installed at No 539 shaft, Fluor shaft, and Glasebach shaft. Sampling was done by the use of mini piston pumps (Pleuger Worthington GmbH, Hamburg/Germany) being installed 5–10 m under the water surface (Tab. 4). Every 12 hours the filter system was changed and the filters were stored in 500 mL brown glass bottles.

Most of the 147 filter samples contained noticeable amounts of Fe-oxides. Therefore, oxalic acid was added to remove both, Fe-oxides and carbonates. In the laboratory, after at least one day of reaction, the filters were carefully rinsed and the solids filtered through 8 µm cellulose nitrate filters (Sartorius, Göttingen/Germany) with 47 mm diameter, using Nalgene plastic filters for membrane filtering with a hand vacuum pump. After each filtration the Nalgene filters, the filter unit, and the working tables in the laboratory were cleaned to exclude any kind of contamination during sample preparation.

After drying and mounting the 147 cellulose nitrate filters to glass plates, the fluorescent microspheres and the spores were counted under a fluorescence microscope (Leica, Wetzlar). Depending on the number of solid tracers on the filters, an aliquot part of the whole filter was counted and the whole number of solid tracers collected was calculated on the basis of these data.

In addition to the tracer test, 21 water samples were collected on a regularly basis (Tab. 1). The detailed results of these samples will be described elsewhere.

Results

Sodium chloride

An increase in conductivity could only be detected at the Fluor shaft (Fig. 2). Neither of the other sampling points (Uhlenbach brook, No 539 shaft, Glasebach shaft) showed a significant change in conductivity that would be caused by the sodium chloride tracer. During the time of conductivity measurements in the Fluor shaft (May 30th to July 31st) a total of 39 % (2.4 t) of the tracer injected (6.2 t) could be recovered. Considering the geological and tectonic conditions, this recovery rate is unexpectedly high, proving a good hydraulic connection between the Siptenfelde brook and the mine.

Approximately 1 day after a rainfall, the conductivity in the Fluor shaft increases significantly for 1 minute (June 11th, 7:49 p.m.) to 247 minutes (June 11th, 10:28 p.m.), the highest peak occurring on July 3rd, 9:34 p.m. (185 minutes). Each peak starts quickly and tails out slowly within the time mentioned before (see inset in Fig. 2). Based on a distance of 2,250 m between the Siptenfelde seepage and the Fluor shaft, a mean effective velocity of 1.5 m min^{-1} can be calculated for the meteoric and mine water flowing between the brook and the shaft's outflow (Tab. 5).

Club moss spores (*Lycopodium clavatum*)

Club moss spores were only detected at the Fluor shaft and the Glasebach shaft (Fig. 4). A total of 323,220 spores in the Fluor shaft and 200,820 in the Glasebach shaft could be found after June 8th. Based on the ratio of the water pumped and the water flowing out of the three shafts, the recovery rate is as high as 6 %.

Within the Fluor shaft, 2.5 days after tracer injection, the club moss spores peak reached 199,200 in a relatively short time and decreased to nearly 4,000 after 1.5 days. A second peak with 6,500 spores can be seen 6 days after tracer injection. From the injection point to the water's surface, the spores have to travel 238 m, thus the mean effective velocity calculates to 0.1–0.2 m min^{-1}.

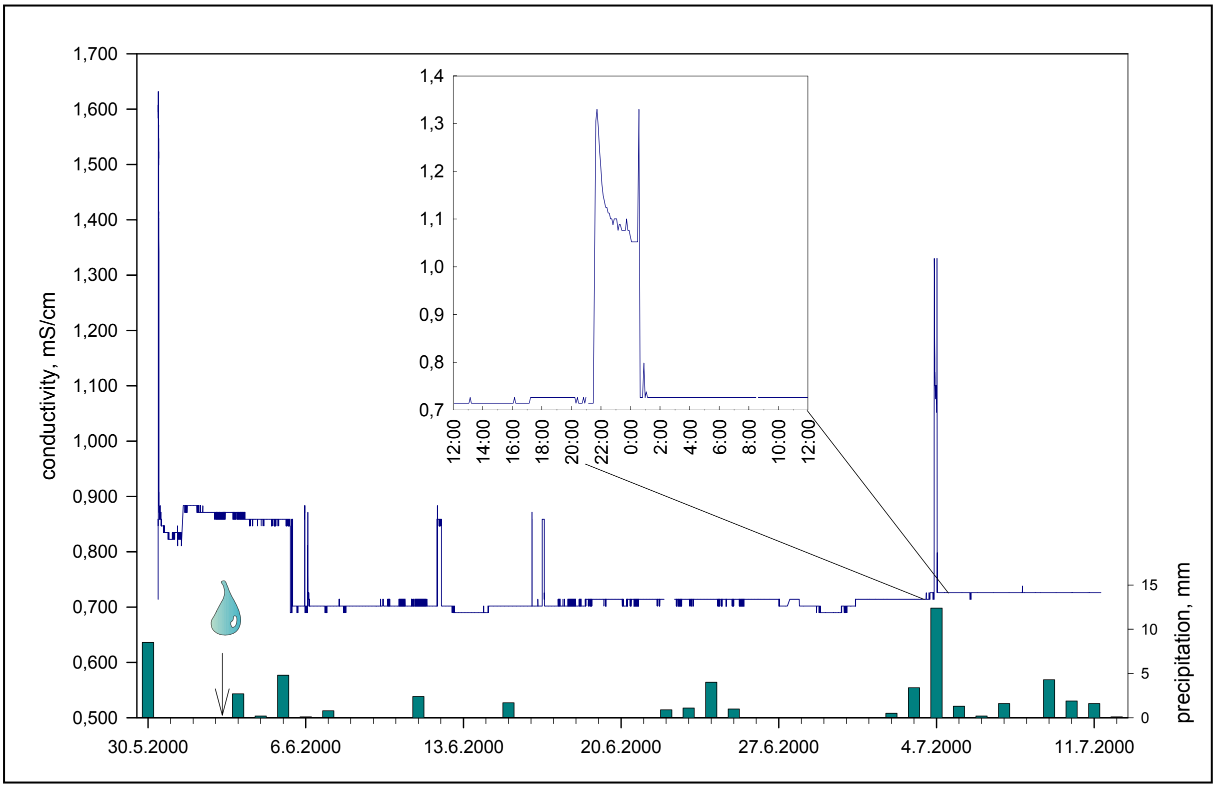

Fig. 2: Plot of precipitation (Siptenfelde station) and conductivity in the Fluor shaft. The arrow marks the time of the injection of the sodium chloride tracer into the Siptenfelde brook. Changes before June 6th are due to moving the conductivity probe upwards in the shaft by 5 m.

Unfortunately, within the Glasebach shaft, a very high contamination occurred, the reason for it being unclear. Even before the first tracer injection and in the blind sample, 1,000–6,000 spores were present. As there a bulk of unused filter nets from another tracer test was used, it might be possible, that these filter nets had been contaminated during their storage. Which of the peaks are due to contamination or to different flow paths, cannot be solved with the data available. Taking into account the complicated mine geometry between the Fluor and Glasebach shafts, the latter possibility cannot be fully excluded. Nevertheless, 10.5 days after tracer injection a clear peak with 25,000 spores exists and another one with 7,400 spores 3 days after tracer injection. Once again, the maximum is reached very quickly, whilst the peak is tailing out within 2 days. Between the injection point in the Fluor shaft and the detection point in the Glasebach shaft, the tracer had to travel 3.180 m at the shortest pathway. Taking into consideration the two peaks and the shortest travel distance, the mean effective velocity calculates to be 0.2–1.2 m min^{-1}.

Microspheres

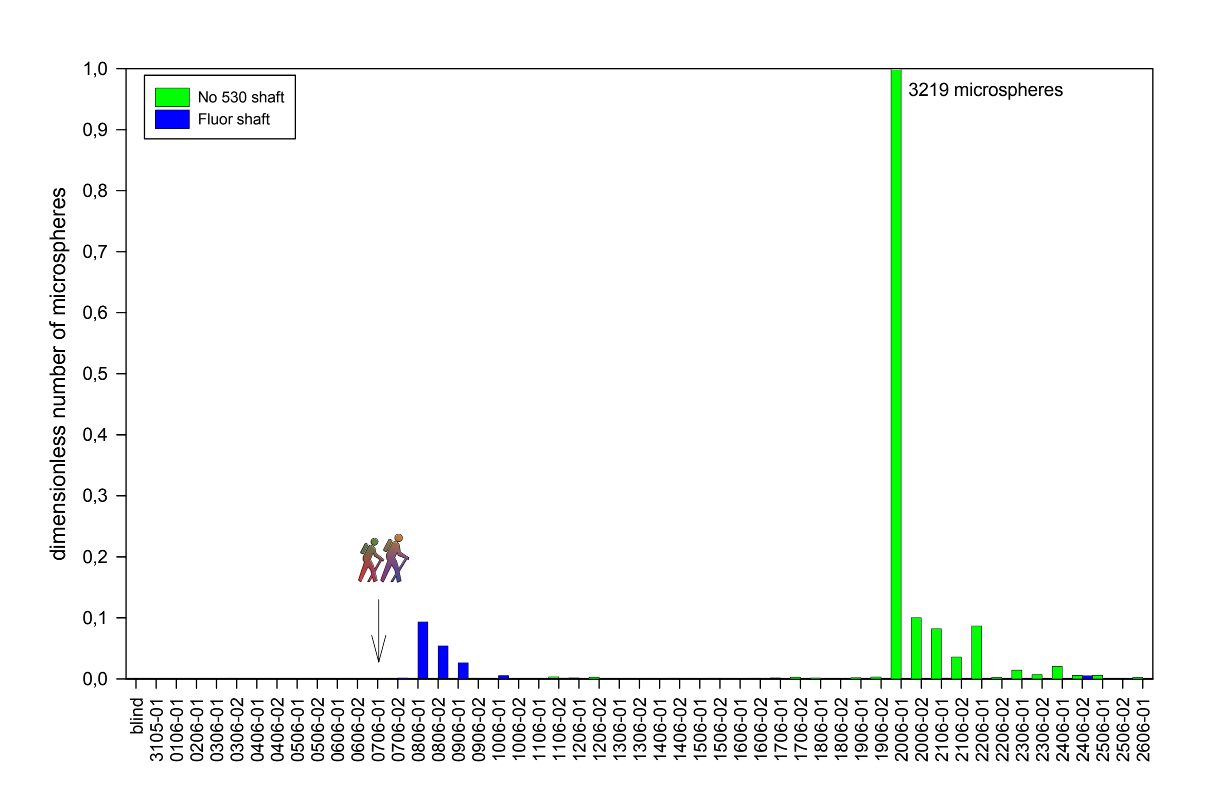

Fig. 3: Breakthrough curves of the microspheres detected at the Fluor shaft. (max.: 3,219 microspheres). Arrow marks time of tracer injection.

From the microspheres injected in the No 539, No 530, Fluor, and Glasebach shaft, only the microspheres from the No 530 and Fluor shaft could be detected. It cannot be excluded that the LydiAs lowered into the No 539 and Glasebach shaft did not open properly.

In the Fluor shaft, microspheres from the Fluor shaft and the No 530 shaft could be detected (Fig. 3). 1 day after the tracer injection, 220 microspheres from the deep part of the Fluor shaft could be detected at the shafts' outflow. As already observed, the peak sets in very quickly and tails out within 1.5 days. The other peaks of microspheres from the Fluor shaft are negligible. 13 days after tracer injection, 3,219 microspheres from the No 530 shaft reach the sampling point at the Fluor shaft. Still 2.5 days and 4 days later a significant tracer signal could be observed. Based on the shortest distances of 238 m and 1,773 m, the mean effective velocities are 0.1–0.2 m min^{-1}.

Tab. 5: Mean effective velocity of mine water in the Straßberg mine. No tracer from No 539 shaft could be detected anywhere.

from	to	tracer	velocity v_{eff}	distance
No 530 shaft	Fluor shaft	microspheres	0.1 m min^{-1}	1,773 m
No 530 shaft	Glasebach shaft	microspheres	0.3 m min^{-1}	4,798 m
Fluor shaft	Fluor shaft	microspheres	0.2 m min^{-1}	238 m
Fluor shaft	Fluor shaft	club moss spores	0.1 m min^{-1}	238 m
Fluor shaft	Glasebach shaft	microspheres	0.3 m min^{-1}	3,180 m
Fluor shaft	Glasebach shaft	club moss spores	0.2–1.2 m min^{-1}	3,180 m
Siptenfelde brook	Fluor shaft	NaCl-brine	1.5 m min^{-1}	2,250 m

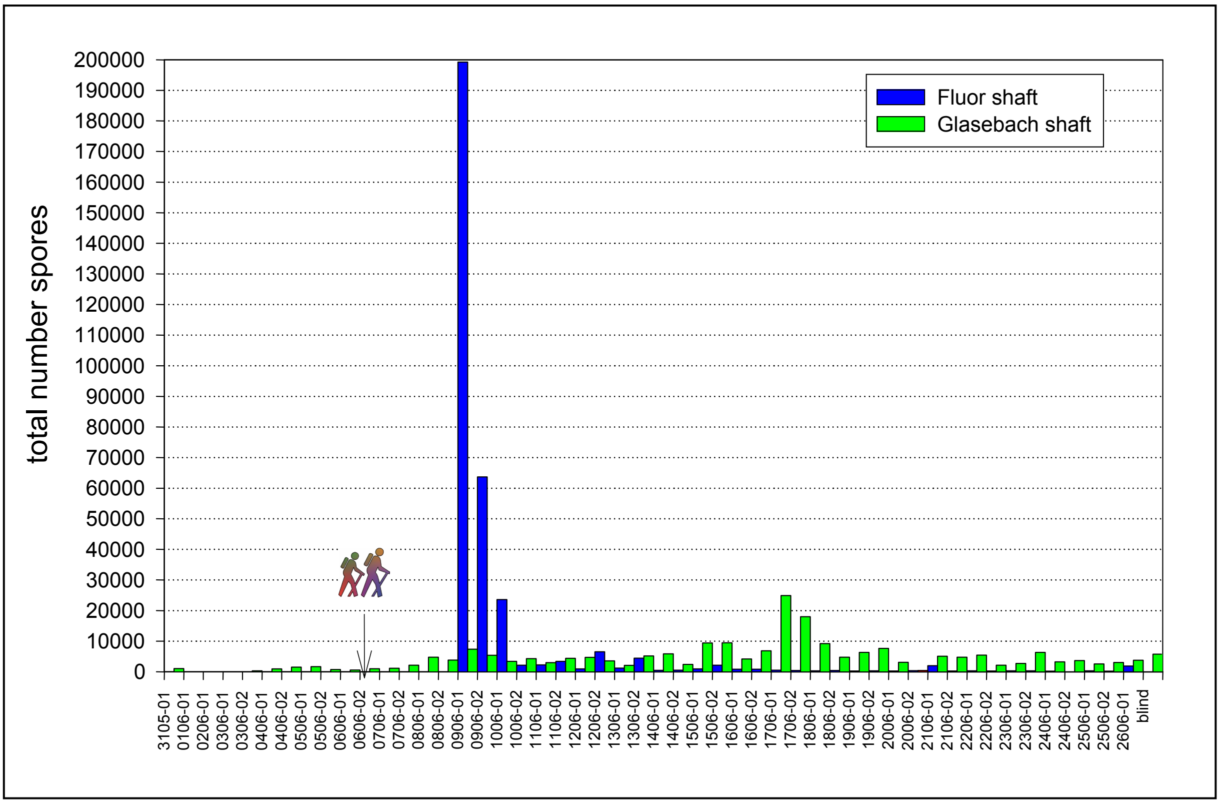

Fig. 4: Breakthrough curves of the club moss spores detected at the Fluor and Glasebach shafts. Arrow marks time of tracer injection. No spores were detected at the No 539 shaft. Noticeable amounts of spores at the Fluor shaft arrive 2.5 days and at the Glasebach shaft 11 days after tracer injection.

Only Microspheres from the No 530 shaft could be detected at the Glasebach shaft (Fig. 5). All the other microspheres, including those injected into the Glasebach shaft itself, could not be found abundant enough to draw useful conclusions. 13 days after tracer injection, 9,748 microspheres from No 530 shaft occurred at the sampling point Glasebach shaft. As already observed in the Fluor shaft, the peak tails out slowly and even 3 days later a significant amount of microspheres could be detected. As the distance between the No 530 and Glasebach shafts is 4,798 m, a mean effective velocity of 0.3 m min^{-1} calculates.

Conclusions

All of the tracers positively injected into the 5 injection points, could be detected by at least one of the 4 sampling points. Therefore, both, the injection and sampling methods, proved to be suitable for the Straßberg mine. Unfortunately, the tracer test gave no results to the question, why the mine's total water budget increased by $2 \cdot 10^6$ m³ after installing the 3-adit-system.

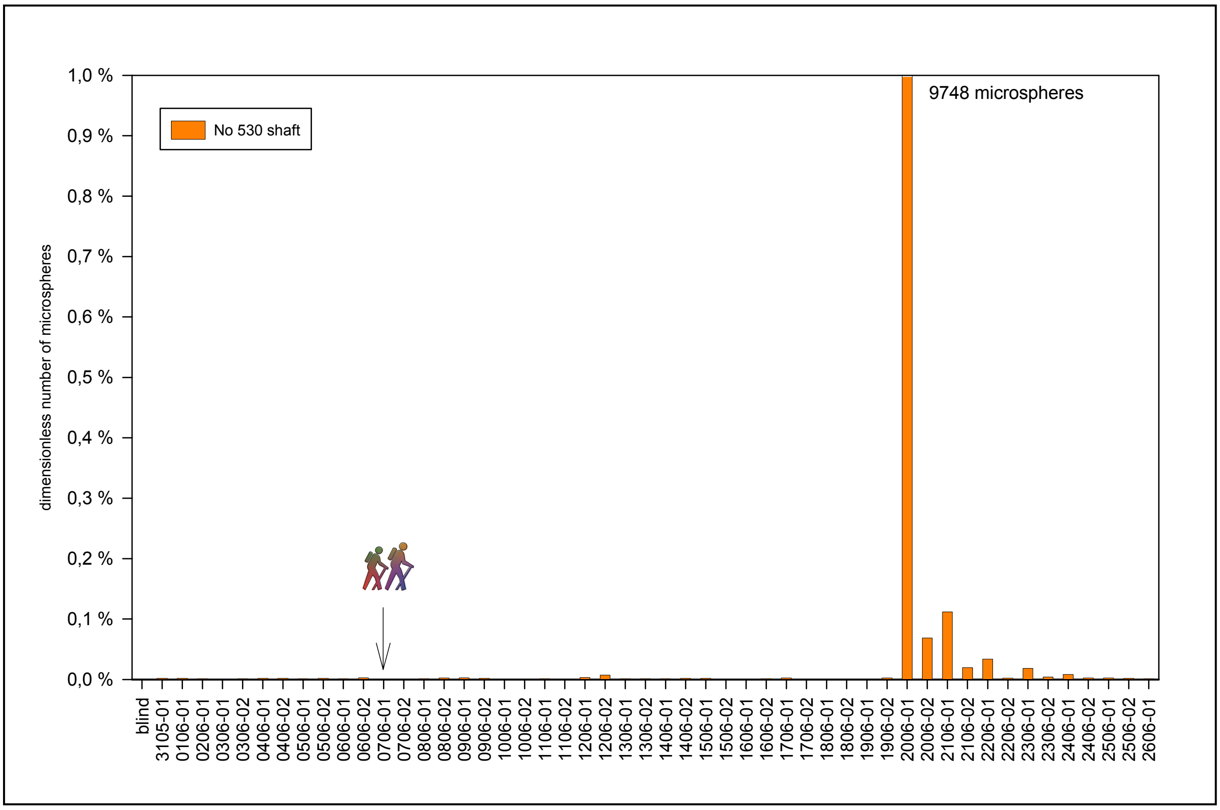

Fig. 5: Breakthrough curves of the microspheres detected at the Glasebach shaft (max.: 9,748 microspheres). Arrow marks time of tracer injection.

From the results it is clear now, that all parts of the mine are hydraulically well connected. Generally, the flow direction throughout the tracer test was from north to south, thus explaining the similar chemical composition of the mine water in the Fluor and Glasebach shafts. This was a new result, because previous to the tracer test, it was believed, that the general flow direction of the mine water was from south to north. Finally, under the current flow regime, with the 3-adit-system working, no stratification will be achieved again.

Furthermore, the sodium chloride tracer confirmed the assumption, that there is a connection between the Siptenfelde seepage and the mine. The breakthrough curves clearly show, that the hydraulic dispersion within the flow path through the partly unsaturated fissured aquifer and the mine's drifts and shafts is rather small and that the tracer is transported after rainfall events only. Because more than one third (39 %) of the injected sodium chloride tracer was recovered within the 6 weeks of the tracer test, it must be assumed that there is a good connection between the Siptenfelde seepage and the northern adit. Comparing the velocities of the microspheres arriving from the No 530 shaft (0.1–0.2 m min^{-1}) and the sodium chloride tracer (1.5 m min-1), the transport from the Siptenfelde seepage into the mine (approx. 180 m) must be very fast.

Both tracers pass the dam in the northern adit or at least the fissured rock around it, without having problems. From the breakthrough curves, showing a small hydraulic dispersion, it is more likely, that the tracers pass a broken pipe in the dam, than the surrounding rock. Consequently, all the results show, that the dam is hydraulically ineffektive.

Comparing the numbers of tracers arriving from the No 530 and Fluor shaft, the composition of the water leaving the Fluor and Glasebach shafts can be explained. Water leaving the Fluor shaft, is composed of water from the Brachmannsberg pit and the Straßberg pit whilst water leaving the Glasebach shaft consists of water from all three pits: the Brachmannsberg, Straßberg and Glasebach pit. No water from the Glasebach pit flows north into the Straßberg pit and no water from the Straßberg pit flows north to the Brachmannsberg pit.

Finally, the results clearly proofed, that the modified injection and sampling techniques used for the Straßberg tracer test is a good means for hydrodynamic investigations in flooded mines.

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