TRACER TEST IN THE ABANDONED FLUORSPAR MINE STRASSBERG/HARZ MOUNTAINS, GERMANY

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Abstract: After three new water adits were constructed, the water budget of the abandoned Straßberg mine increased substantially. A multi-tracer test was conducted in an attempt to determine why this occurred. Potassium chloride, coloured club moss spores, and microspheres were used to show the hydrodynamic relation between the three mining districts. It was determined that the flow direction is from north to south and that the mean effective flow velocities range 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. Solid tracers, used in conjunction with a reliable injection and sampling technique, proved to be a good means to investigate the hydrodynamic conditions within this abandoned underground mine. However, there is still no good explanation for the increased water budget infiltrating from the Brachmannsberg mining district.

Key words: tracer; abandoned mine; microspheres; hydrodynamics

Introduction

In 1991, economic and environmental reasons caused the closure of the Straßberg fluorspar mine, owned by the 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 (Figure 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 contain several ore minerals, including pyrite, galena, sphalerite, chalcopyrite, arsenopyrite, wolframite, scheelite, and siderite. The mineralisation is of Permian to Cretaceous age (KUSCHKA & FRANZKE 1974).

When mining began at the site, possibly more than 1000 years ago, silver, copper, and lead were targetted. From the 18th century until 1990, mining focused on fluorspar, which was found mainly 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. 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 7th 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 7th level. Ultimately, when the ore reserves in the Brachmannsberg underground pit decreased in the nineteen eighties, a dam was constructed in the northern adit, to separate the to-be flooded Brachmannsberg pit from the Straßberg pit.

On May 31st 1991, the drainage water pumps were stopped and flooding commenced in the Straßberg and Glasebach underground pits (Table 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

Table 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

within the water body was taking place (KINDERMANN 1998, RÜTERKAMP & MESSER 2000). In the Fluor shaft, 3 water bodies were established, separated from each other at the 2nd (328 mHN) and 5th (243 mHN) levels. Only 2 water bodies, separated by the 4th (357 mHN) level, could be recognised in the No. 539 shaft. Stratification was indicated due to differences in temperature, conductivity, and metal concentration between each of the water bodies (Table 2), with the uppermost always low in contaminants and the lowermost most 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; Figure 1), to drain and treat the contaminated mine water within the uppermost water bodies at a water level of 357,7 mHN (RÜTERKAMP & MESSER 2000). These three adits were built between 1995 and 1998. 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.

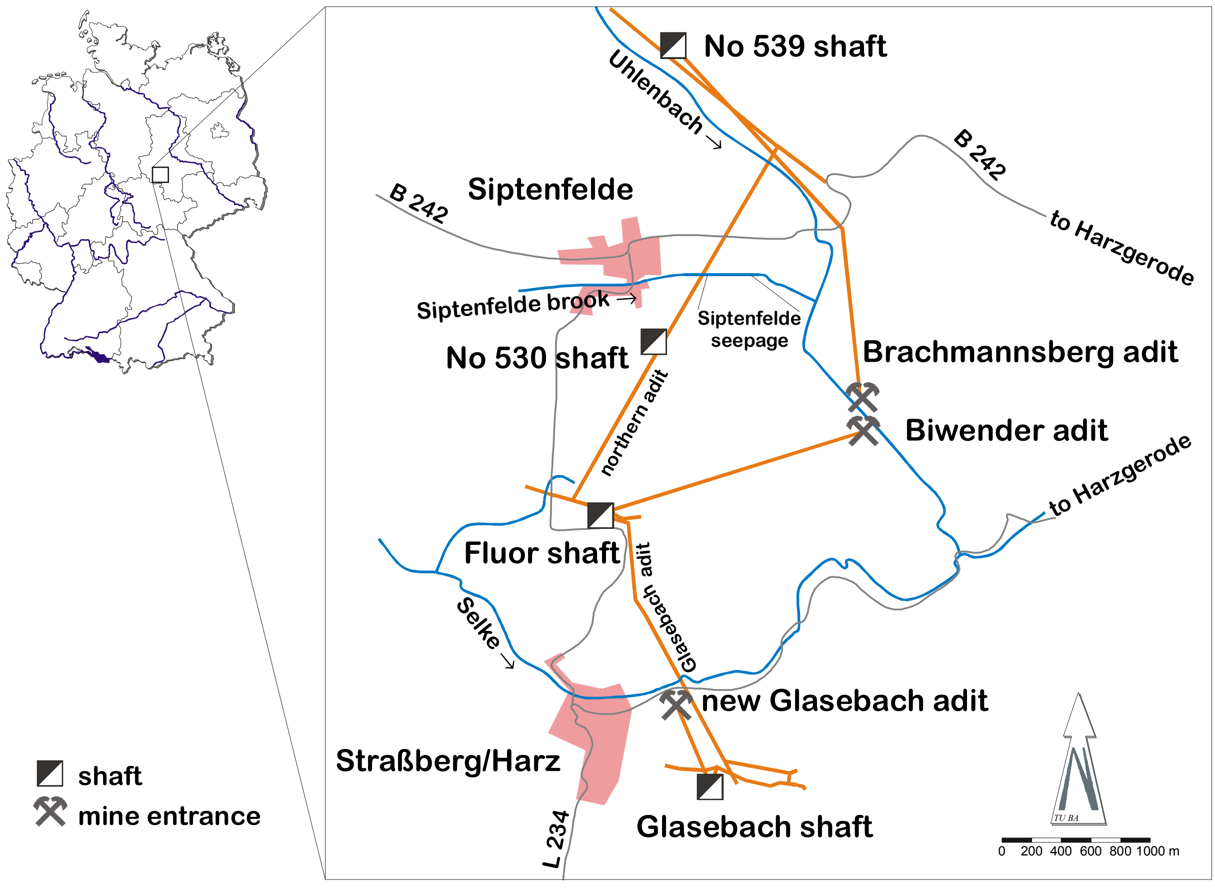

Figure 1: Location of the Straßberg Mine in the eastern Harz Mountains and its main galleries and shafts.

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, appendices 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 flow system was 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 what had occurred after installing the 3-adit system, the mine's owner suggested conducting 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 indicate if there was a connection between a small brook, used locally as a sewer, and the underground mine. A multi-tracer test with sodium chloride, microspheres, and club moss (*Lycopodium clavatum*) spores was therefore carried out (WOLKERSDORFER 2000). This paper describes the implementation and the results of that tracer test at the abandoned Straßberg mine, which was conducted in June 2000.

Methods

Previous Tracer Tests 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 by injecting a fluorescent dye tracer into the surrounding overburden. Another tracer test with fluorescent dyes was performed in a flooded mine near Rico, Dolores County, Colorado by DAVIS (1998). A yet unpublished tracer test with discontinuous sampling of microspheres (0,4 µm diameter) was carried out in the Königstein Mine (Elbtalzone/Germany; KÄSS, pers. comm. 2000). However, microspheres have 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 is necessary. Unfortunately, microspheres and club moss spores cannot be sampled continuously, only quasi-continuously using filters that have to be changed regularly (KÄSS 1998). NIEHREN & KINZELBACH (1998)

Table. 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).

Depth, mHN	Fluor shaft						Depth, mHN	No. 539 shaft					
	25.8.1997			24.2.2000				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
134, 204	52	19	600	50	18	525							

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 method, 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 the north-south and 2 km in the east-west direction, several injection and sampling points were needed (Figure 1, Table 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. At one, coloured club moss spores (Sigma-Aldrich Chemie GmbH, Deisenhofen/Germany) were also used. In addition, 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 injection times can be found in Table 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. It was determined that a successful test would require 40 mL of microspheres per injection point, 500 g of spores and 20,000 L of saturated brine.

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, three LydiAs (a Lycopodium Apparatus 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 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.

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}. It flows into the Uhlenbach Brook, which in turn flows into the Selke River. During summer, the flow decreases and when the flow is less than 300 L min^{-1},

Table 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) was 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“, 15 µm	40 mL	June 5th: 14:44 *
No. 530 shaft (ca. 20 m)	microspheres „orange“, 15 µm	40 mL	June 5th: 9:50-10:13
Fluor shaft (247 m)	microspheres „red“, 15 µm	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“, 15 µm	40 mL	June 5th: 8:11 *

Table 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

the Siptenfelde Brook does not reach its mouth. About 350 m east of Siptenfelde, 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 had trickled away 150 m downstream.

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

Tracer Sampling and Analysis

Due to the tracers' characteristics, two different sampling techniques were used. The sodium chloride was detected by continuous 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 100 µm and 15 µm filters (NY 100 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 using mini piston pumps (Pleuger Worthington GmbH, Hamburg/Germany), which were installed 5-10 m under the water surface (Table 4). Every 12 hours, the filter system was changed. 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 47 mm diameter, 8 µm cellulose nitrate filters (Sartorius, Göttingen/Germany), 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 (Zeiss, Göttingen). 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 (Table 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). None of the other sampling points (Uhlenbach Brook, No. 539 shaft, Glasebach shaft) showed the 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 rainfalls, the conductivity in the Fluor shaft increased significantly for periods lasting 1 minute to 247 minutes, The highest peak occurred on July 3rd (185 minutes). Each peak started quickly and tailed out slowly (see inset in Figure 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 can be calculated for the meteoric and mine water flowing between the brook and the shaft's outflow (Table 5).

Club moss spores (Lycopodium clavatum)

Club moss spores were only detected at the Fluor shaft and the Glasebach shaft (Figure 3). 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}.

Unfortunately, within the Glasebach shaft, a very high level of contamination occurred. The reason for this is unclear. Even before the first tracer injection and in the blind sample, 1,000-6,000 spores were present. As some 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

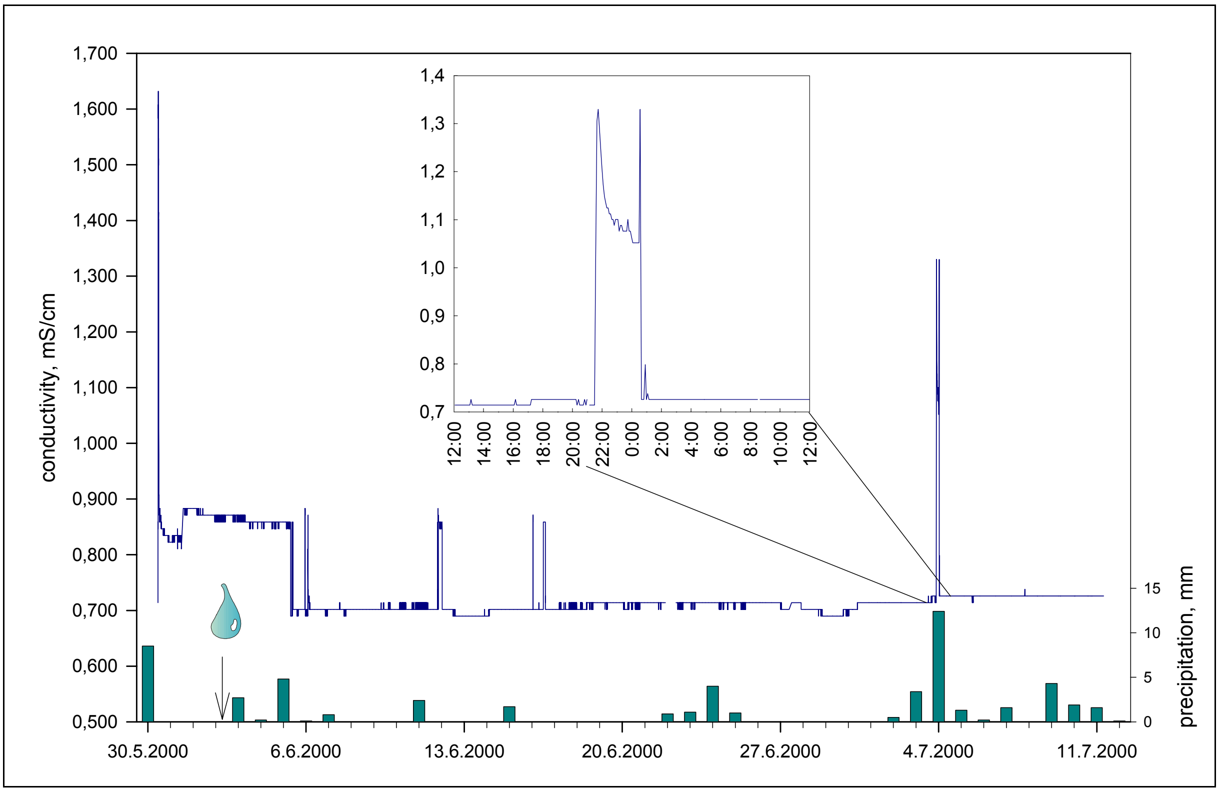

Figure 2: Plot of precipitation (Siptenfelde station) and conductivity in the Fluor shaft. The arrow marks the time of the injection of the sodium chloride tracer into the Siptenfelde brook. Changes before June 6th are due to moving the conductivity probe upwards in the shaft by 5 m.

Table 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

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 there is another one with 7,400 spores 3 days after tracer injection. Once again, the maximum was reached very quickly, and then the peak tailed 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 was calculated to be 0.2-1.2 m min^{-1}.

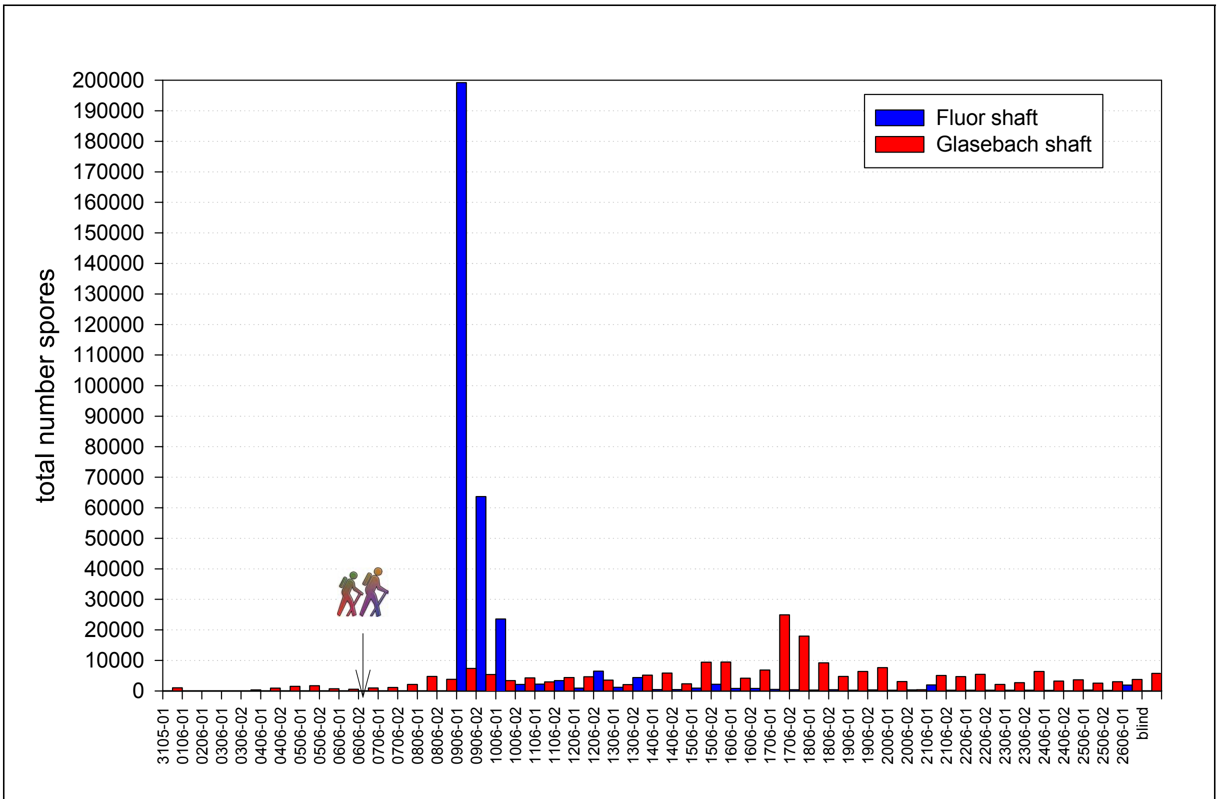

Fig. 3: Breakthrough curves of the club moss spores detected at the Fluor and Glasebach shafts. Arrow marks time of tracer injection. No spores were detected at the No. 539 shaft. Noticeable amounts of spores arrived at the Fluor shaft 2.5 days and at the Glasebach shaft 11 days after tracer injection.

Microspheres

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 (Figure 4). 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. Thirteen days after tracer injection, 3,219 microspheres from the No. 530 shaft reach the sampling point at the Fluor shaft. A significant tracer signal could still be observed 2.5 days and 4 days later. Based on the shortest distances of 238 m and 1,773 m, the mean effective velocities were calculated to be 0.1-0.2 m min^{-1}.

Only Microspheres from the No. 530 shaft could be detected at the Glasebach shaft (Figure 5). All the other microspheres, including those injected into the Glasebach shaft itself, could not be found in enough abundance to draw useful conclusions. Thirteen days after tracer injection, 9,748 microspheres from No. 530 shaft occurred at the sampling point at 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} was calculated.

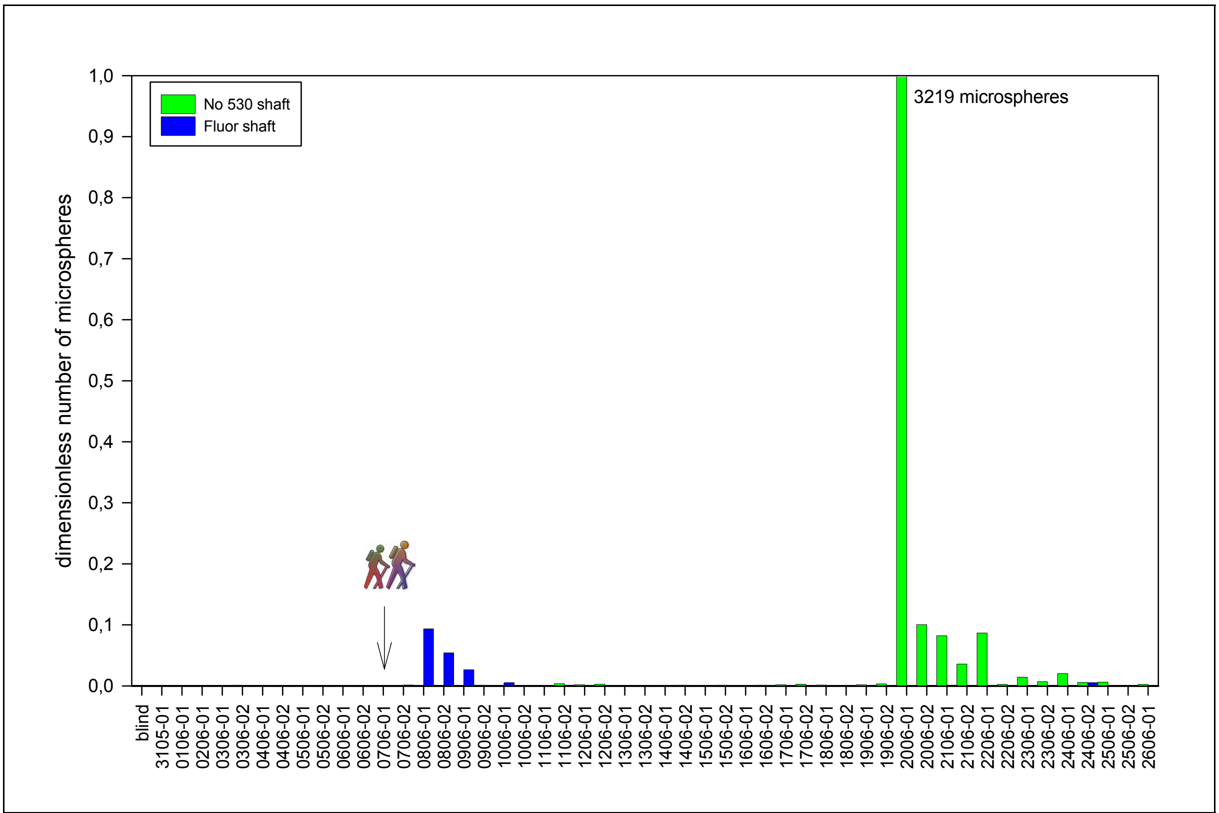

Figure 4: Breakthrough curves of the microspheres detected at the Fluor shaft. (max.: 3,219 microspheres). Arrow marks time of tracer injection.

Conclusions

All of the tracers positively injected into the 5 injection points could be detected at one or more of the 4 sampling points. Therefore, both the injection and sampling methods proved to be suitable for the Straßberg mine. Unfortunately, the tracer test did not answer the question of why the mine's total water budget increased by $2 \cdot 10^6$ m³ after installing the 3-adit-system.

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 a 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 problems. From the breakthrough curves, showing a small hydraulic dispersion, it is more

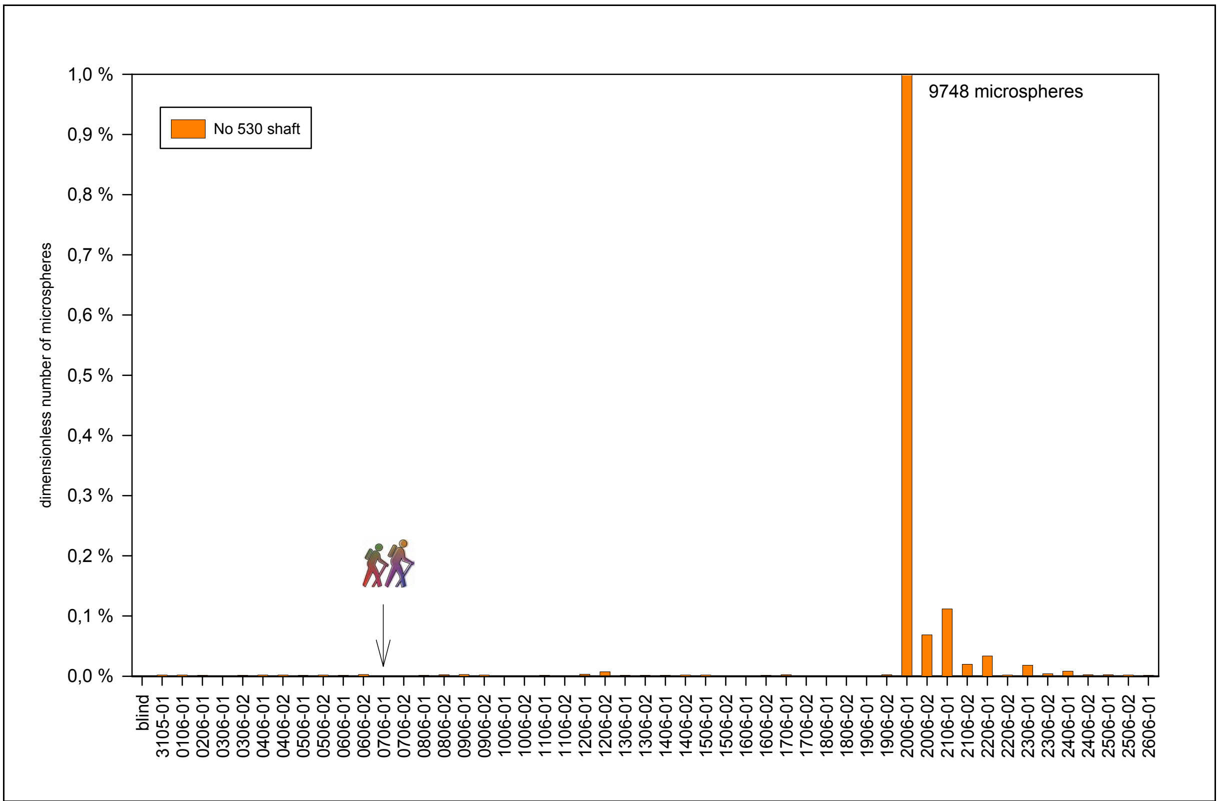

Fig. 5: Breakthrough curves of the microspheres detected at the Glasebach shaft (max.: 9,748 microspheres). Arrow marks time of tracer injection.

likely that the tracers pass through a broken pipe in the dam than the surrounding rock. Consequently, all the results indicate that the dam is hydraulically ineffective.

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 proved that the modified injection and sampling techniques used for the Straßberg tracer test are a good means for hydrodynamic investigations in flooded mines.

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