Mine water tracing

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Abstract: This paper describes how tracer tests can be used in flooded underground mines to evaluate the hydrodynamic conditions or reliability of dams. Mine water tracer tests are conducted in order to evaluate the flow paths of seepage water, connections from the surface to the mine, and to support remediation plans for abandoned and flooded underground mines. There are only a few descriptions of successful tracer tests in the literature, and experience with mine water tracing is limited. Potential tracers are restricted due to the complicated chemical composition or low pH mine waters. A new injection and sampling method ('LydiA'-technique) overcomes some of the problems in mine water tracing. A successful tracer test from the Harz Mountains in Germany with *Lycopodium clavatum*, microspheres and sodium chloride is described, and the results of 29 mine water tracer tests indicate mean flow velocities of between 0.3 and 1.7 m min^{-1}.

Hundreds of mines have been closed, due to economic or ecological reasons, in the recent past. In many cases, the groundwater table was allowed to rise again as the underground workings flooded. In some remote areas the pollution of surface or underground waters has been taken to be of no serious account, but in most of the developed countries (e.g. United States of America, Europe) polluted mine water must be treated. Mine water treatment, as has been shown by the examples of Picher, Oklahoma, USA (Sheibach *et al.* 1982; Parkhurst 1988), Wheal Jane, Cornwall, UK (Hamilton *et al.* 1997) or Königstein, Germany (Gatzweiler & Meyer 2000), can be extremely expensive, especially if acid mine water is involved. Therefore, the mine owners have to find new, innovative tools to control the hydrodynamic conditions within a flooded mine to minimize the pollution load (e.g. Scott & Hays 1975; Fernández-Rubio *et al.* 1987; Wolkersdorfer 1996; Lewis *et al.* 1997) and to introduce passive treatment techniques at the correct time after mine flooding (Younger 2000).

Techniques must be evaluated prior to applying natural attenuation or passive *in situ* remediation methods. Furthermore, after the chosen method has been applied, its reliability must be proven (Younger & Adams 1999), and tracer techniques are a useful tool to test the remediation method. Finally, tracer tests can also be used in addition to quantitative analyses of rock stability in flooded mines (Hunt & Reddish 1997).

Usually, tracer tests in the vicinity of mines are conducted to find connections between the ground surface and the mine, or vice versa. Typical examples are the tracer tests that accompany numerical models for performance assessment at potential radioactive waste disposal sites (e.g. Lee 1984). All tracer tests in mines can be grouped on the basis of their objectives:

- mine water inrushes/inundations (Skowronek & Zmij 1977; Goldbrunner *et al.* 1982; Wittrup *et al.* 1986; Wu *et al.* 1992; Lachmar 1994);
- optimize mining strategy (Adelman *et al.* 1960; Reznik 1990; Kirshner 1991; Kirshner & Williams 1993; Miller & Schmuck 1995);
- underground waste disposal (non-radioactive; Fried 1972; Himmelsbach & Wendland 1999);
- underground waste disposal (radioactive; Abelin & Birgersson 1985; Brewitz *et al.* 1985; Galloway & Erickson 1985; Cacas *et al.* 1990; Lewis 1990; Birgersson *et al.* 1992 (studies in the STRIPA mine, Sweden, since 1980–numerous papers have been published on the Stripa mine and the tracer tests conducted in the fractured crystalline rocks); Sawada *et al.* 2000);
- subsidence (Mather *et al.* 1969);
- remediation strategies (Aldous & Smart 1987; Doornbos 1989; Aljoe & Hawkins 1993, 1994; Davis 1994*a*, *b*; Wolkersdorfer

From: YOUNGER, P.L. & ROBINS, N.S. (eds) 2002. *Mine Water Hydrogeology and Geochemistry.* Geological Society, London, Special Publications, **198**, 47–60. 0305-8719/02/$15.00

1996; Wolkersdorfer *et al.* 1997; Canty & Everett 1998).

Tracer tests have also been conducted to study 'heat mining' in geothermal projects (e.g. Gulati *et al.* 1978; Horne *et al.* 1987; Kwakwa 1989; Randall *et al.* 1990; Aquilina *et al.* 1998). Because their use is similar to studies in fractured rocks (see Himmelsbach *et al.* 1992; Käß 1998) and energy mining is usually carried out by the use of boreholes only, these studies will not be considered further.

Many tracer tests have not been published in the literature or are only available as academic theses (e.g. Anderson 1987; Bretherton 1989; Doornbos 1989; Diaz 1990; Wirsing 1995). This is often because they were either unsuccessful or the results confidential. Up to now, only a small number of tracer tests have been conducted in flooded underground mines to trace the hydrodynamic conditions within the flooded mine itself (Aljoe & Hawkins 1994; Wolkersdorfer *et al.* 1997; Wolkersdorfer & Hasche 2001). This was mainly due to the fact that no suitable method was available for injection of the tracer into the mine water at predetermined depths or without contaminating the mine water above the injection point. Most tests, therefore, injected the tracer at the surface to flow towards the mine through fractures (e.g. Lachmar 1994) or they used boreholes (e.g. Galloway & Erickson 1985; Cacas *et al.* 1990).

Aims of mine water tracer tests

Tracer tests are well established in groundwater studies where they are commonly used to investigate the hydraulic parameters or interconnections of groundwater flow (Käß 1998). Most of the techniques are well described and, depending on the aims of the tracer test and the hydrological situation, a range of tracers or methods can be chosen.

Published results of tracer tests in abandoned underground mines are not common, as already stated by Davis (1994*a*, *b*). Therefore, in mine water tracing, less experience exists and the expected results of an individual mine water tracer tests cannot always been found. The basic aims are as follows:

- testing the effectiveness of the bulkheads (dams);
- investigating hydrodynamic conditions;
- tracing connections between mine and surface;
- clarifying water inundations;
- investigating mass flow;
- estimating the decrease or increase of contaminants.

Historically, the first tracer tests conducted in mines were simply to reveal connections between ground or surface waters and the mine (e.g. Skowronek & Zmij 1977). One of the first tracer tests in a deep flooded underground mine to investigate the more complex hydrodynamic conditions was conducted in 1995 (Wolkersdorfer 1996).

In future studies, tracer tests should become a prerequisite for the evaluation of remediation strategies used for reclaming abandoned mine sites. Kimball *et al.* (1999) have already provided an example of how to use tracer tests and synoptic sampling of trace metals in surface streams to evaluate the environmental impacts of mine effluents to watersheds.

Possible mine water tracers

Underground mines consist of a number of shafts, adits, raises and stopes, which are similar and comparable to the features found in karstic terrains. Therefore, a flooded mine can be looked on as a karst aquifer in a conceptual model, and numerical models of flow in karst aquifers (e.g. Liedl & Sauter 2000) might also describe the hydrodynamic situation in underground mines. Furthermore, the tracer techniques developed for karst aquifers (e.g. Habič & Gospodarič 1976; Käß 1998) should be appropriate also for flooded mines.

Several classes of tracers have been used in mine water tracing (Table 1). As, usually only successful tracer tests–if at all–are reported, little can be said about tracers that are unsuitable for mine water tracing. In the case of fluorescein, which easily adsorbs to organic materials, there are both successful tests as well as unsuccessful ones.

The chemical composition of mine waters very often tends to be extreme: total dissolved solids (TDS), pH (e.g. Iron Mountain: pH −3.6; Nordstrom *et al.* 2000) or metal concentrations are usually high (Banks *et al.* 1997) and consequently limit the number of tracers that could be used successfully. Even conservative tracers, such as fluorescein, might be unsuitable under certain mine water conditions (e.g. low pH, high suspension load, wooden supports, free chloride radicals). A detailed discussion about the effectiveness, strengths and weaknesses of tracers would go beyond the scope of this paper but can be found in Wolkersdorfer (1996) or Käß (1998).

Laboratory tests using the chosen tracer and typical mine water compositions are essential for

Table 1. *Artificial and natural tracers that have already been used in mine water tracing*

Artificial tracers	
Salts	Chloride (Mather *et al.* 1969; Aljoe & Hawkins 1994; Canty & Everett 1999; Wolkersdorfer & Hasche 2001) Bromide (Doornbos 1989; Kirshner 1991; Wu *et al.* 1992; Kirshner & Williams 1993; Aljoe & Hawkins 1993, 1994) Sulphur hexafluoride (Kirshner 1991; Kirshner & Williams 1993) Lithium (Wu *et al.* 1992) Iodide (Wu *et al.* 1992) Borate (Lewis 1990)
Dyes	Fluorescein, Uranine (Mather *et al.* 1969; Parsons & Hunter 1972; Goldbrunner *et al.* 1982) Rhodamine B (Skowronek & Zmij 1977; Aldous & Smart 1987; Davis 1994*a*, *b*) Rhodamine WT (Canty & Everett 1999)
Solid tracers	*Lycopodium* (Wolkersdorfer 1996; Wolkersdorfer *et al.* 1997) Microspheres (Wolkersdorfer & Hasche 2001)
Radioactive tracers	Lorenz 1973
Neutron activation analysis	Jester & Raupach 1987
Natural tracers	
Lead isotopes	Horn *et al.* 1995
Zinc variations	Bretherton 1989
Temperature	Anderson 1987; Wolkersdorfer 1996
Conductivity	Bretherton 1989; Reznik 1990; Wolkersdorfer 1996
Carbondioxide	Kirschner 1989
Tritium	Parsons & Hunter 1972; Goldbrunner *et al.* 1982; Diaz 1990; Pujol & Sanchez Cabeza 2000
Stable isotopes	Adelman *et al.* 1960; Klotz & Oliv 1982; Wittrup *et al.* 1986; Diaz 1990

obtaining positive results. All tracers have to be selected on their expected or known behaviour in mine water. An important consideration when conducting such tests is the duration of the laboratory test. Mine water commonly flows with mean velocities of 0.3–1.7 m min^{-1} (95% confidence interval of 29 tracer tests investigated, excluding the maximum and minimum value; see Table 6), which can be used for a rough calculation of the expected residence time. The stability of the tracer in the mine water must be at least as long as the duration of the test. Preceding the Niederschlema–Alberoda tracer test, 45 days of laboratory tests, and preceding the Straßberg tracer test, 4 weeks of laboratory tests with regular tracer sampling and visual analyses were conducted to test the stability of the tracers within the mine water (Wolkersdorfer 1996; Wolkersdorfer & Hasche 2001).

The most suitable tracer is chosen on the results of the laboratory tests, the cost of the tracer material, and the cost of analysis. In addition, a detailed hydrogeological investigation is needed to clarify the most suitable injection and sampling points ('conceptual model of test site'). Many tracer tests, even if a suitable tracer has been chosen, have been unsuccessful due to a lack of knowledge about the hydrogeological situation and inappropriate selection of injection and sampling sites.

In the following sections a tracer test in a flooded underground mine will be used to explain the procedures necessary for a mine water tracer test. To understand the aims of the test, a short description of the mine and the hydrogeological situation at the time of the tracer test is given. Some conclusions are drawn, based on the test described, and other tracer tests conducted or described in the literature.

Case study: the Straßberg–Harz underground mine

Description of the mine

Located in the eastern Harz mountains, the Straßberg fluorspar mine is divided into three mining districts (from north to south: Brachmannsberg, Straßberg (Biwender), Glasebach) each connected by two underground adits but with different water chemistries (Table 2).

The surrounding area of the mine consists predominantly of Lower Devonian rocks. In the northern part Lower Carbonian rocks, that are partly influenced by metamorphism of the Ramberg pluton (intrusion age: 290 ± 10 Ma),

Table 2. *Mean composition of the mine water in the Straßberg mine during the time of the tracer test (30 May – 27 July 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

crop out. Galena, sphalerite, pyrite, arsenopyrite, fluorspar and barite occur in veins. The country rock has a permeability of about $k_f = 10^{-6}\,m\,s^{-1}$, and groundwater circulates through fissures, faults, karstic features and galleries (Wolkersdorfer & Hasche 2001). The natural hydrogeological situation has been substantially impacted by the many decades of mining. Pollutants are carried off the mine site by rainwater or drainage water and deposited into rivers, lakes and the groundwater. Mine flooding is believed to be the most economic method for redevelopment of underground mines.

Before its closure, the Straßberg fluorspar mine was the largest fluorspar mine in the German Democratic Republic. 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 Utilization 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 was the most important producer of fluorite in the former GDR (Mohr 1978). Besides fluorite, the hydrothermal polymetallic mineralization of the vein structures comprises several ore minerals of Permian–Cretaceous age (e.g. pyrite, galena, sphalerite, chalcopyrite, arsenopyrite, wolframite, scheelite, siderite; Kuschka & Franzke 1974).

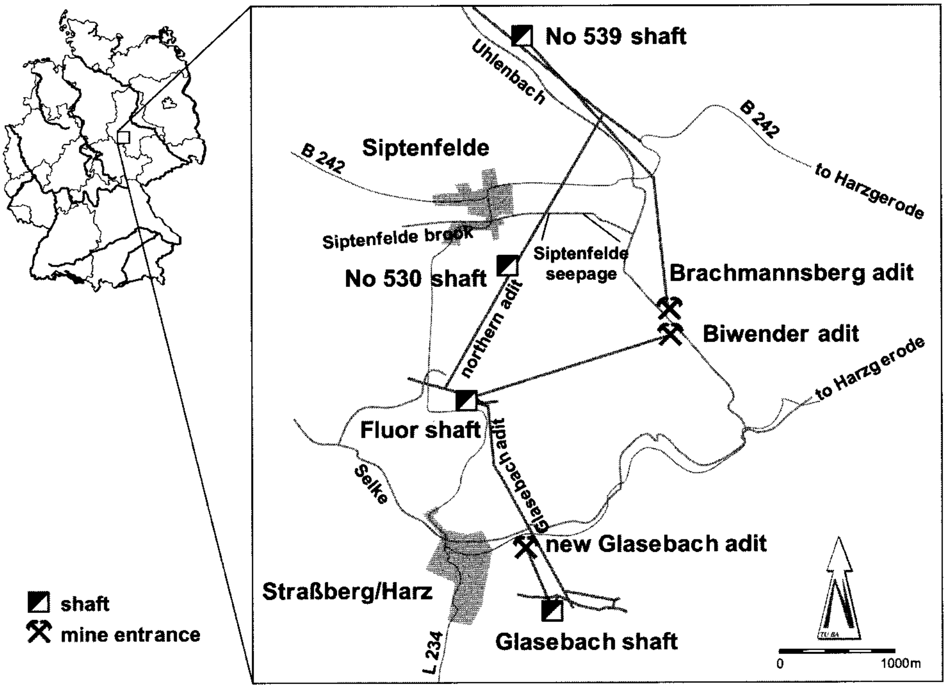

Fig. 1. Map of Germany with the location of the Straßberg mine in the eastern Harz mountains and its main galleries and shafts.

Mining was started more than 1000 years ago when silver, copper and lead were the targets of the miners. From the eighteenth 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 fifth and seventh levels (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 fifth level, the 1.5 km long Glasebachquerschlag (Glasebach adit) connects the Straßberg and Glasebach pits on the seventh level. Ultimately, when the ore reserves in the Brachmannsberg underground pit decreased in the 1980s, a dam was constructed in the northern adit, to separate the Brachmannsberg pit prior to flooding from the Straßberg pit.

On 31 May 1991 flooding of the Straßberg and Glasebach underground pits was started. 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 stratification within the water body was taking place (Kindermann 1998; Rüterkamp & Meßer 2000). Evidence for the stratification were differences in temperature, conductivity and metal-concentration between each of the water bodies (Table 3), with concentrations, particularly of iron, manganese and sulphate, increasing with depth.

Furthermore, the physico-chemical and chemical parameters of the water within the three parts of the mine respectively, showed significant differences, especially in TDS. After an intensive investigation the DMT (German Mining Technology) proposed to construct three new adits (the 'three-adit system') to drain the good quality water. They also predicted the long-term quality of the drainage water and, based on these results, a possible site of the final treatment plant was chosen (Rüterkamp & Meßer 2000). Almost immediately after the three adits were finished, stratification occurred as has been observed elsewhere (Wolkersdorfer 1996). Having analysed the new conditions, the consultant and the mine owners came to the conclusion that the water within the mine was flowing from the south to the north. Consequently, they thought that the mine water quality could be substantially improved by constructing a drainage pipeline from the Straßberg pit to the Glasebach pit.

At this stage, the Department of Hydrogeology at the Technical University Mining Academy Freiberg became involved in the project and proposed a tracer test in the mine. The Straßberg tracer test was designed to answer the following questions:

- How does the water flow between the three pits?
- Is the bulkhead between the Brachmannsberg and the Straßberg pit still effective?
- Does the sewage water from the Siptenfelde brook flow into the mine?
- What are the speeds of the mine water?
- Why did the stratification break down after the installation of the three-adit system?

After careful investigation of the hydrogeological and geochemical situation, as well as the accessibility of potential injection and sampling points, six injection and four sampling points were chosen. One of the injection points finally proved to be unsuitable, and the following injection points were actually used (from north to south): No. 539 shaft, Siptenfelde seepage, No. 530 shaft, Fluor shaft, Glasebach shaft

Table 3. *Selected constituents of the mine waters in the Flour and No 539 shaft in mg l^{-1} before and after the 3-adit system taken in use (after Rüterkamp & Meßer 2000)*

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
c. 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							

* mHN, meters above sea level (Kronstadt elevation).

(Fig. 1). It was important that tracers were injected as deep as possible within the No. 539, Fluor and Glasebach shafts because the three pits are connected to each other by adits at the shaft's deepest points.

As more than one injection point was needed for the test, only a multi-tracer test could be conducted. Owing to the volume of the mine, the use of salts would have required large amounts (e.g. 5–10 t of NaCl). Radioactive tracers would have been a good choice, but their detection is expensive and the German authorities do not allow these tracers to be used in large amounts. As has been shown elsewhere, fluorescent dyes seem to be unstable in mine water due to chemical and physical reactions and, as with salts, relatively large amounts have to be injected. Dyed club moss spores (*Lycopodium clavatum*, 30 μm diameter) and microspheres (15 μm diameter) were chosen because in both cases multiple colours can be used at the same time, and even small quantities contain billions of tracer particles that can be readily detected.

To guarantee reliable results, continuous sampling of the tracer is necessary. Unfortunately, microspheres and club moss spores cannot be sampled continuously, but only 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 groundwater studies. Because of the requirements of 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), a flow cytometer was unfeasible. Therefore, the procedures and filter systems of the LydiA-technique (*Lycopodium Apparatus*; Wolkersdorfer *et al.* 1997) were selected to inject the tracers into the deep flooded mine at the predetermined depths without contamination and to sample the tracers. Owing to a pending patent no more details about the injection technique can be given here.

Tracer amount

It was calculated that 500–600 g of *Lycopodium* and 4×10^7 pieces of microspheres would be required at each injection point to get reasonable concentrations of tracers at the sampling points. In the case of the Siptenfelde Brook an amount of 20 000 l of saturated brine (*c.* 6.2 t of NaCl) was needed to raise the conductivity above background.

The calculations used to estimate the mass of tracer required are similar to those used in karst aquifer tracing (see Käß 1998). They can also be calculated on the assumption that the recovery rate of *Lycopodium* is about 2–7%, that of microspheres is 50–90% and that at least one tracer particle per litre of water must be present, assuming a total mixing of the mine water (Table 4).

During the tracer test, nearly 10 m^3 of water were pumped through the three filter systems that were installed and the filters changed on a 12 hour basis. Consequently, the tracers of 50–100 l of mine water were concentrated within the filter system and, thereafter, used for analyses as described below.

Tracer sampling and analyses

Owing to the characteristics of the tracers, two different sampling techniques were used. The sodium chloride was detected by continuous conductivity measurement at sampling points in 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

Table 4. *Injection points, depth in shafts, and injection times of the seven tracers used*

Injection points (depth)	Tracers	Quantity[†]	Injection time
Siptenfelde seepage	NaCl brine	20 m^3 (6.2 t)	2 June: 9.08 – 10.15
No. 539 shaft (92 m)	Microspheres blue, 15 μm	4×10^7 pcs	5 June: 14.44*
No. 530 shaft (ca. 20 m)	Microspheres orange, 15 μm	4×10^7 pcs	5 June: 9.50 – 10.13
Fluor shaft (247 m)	Microspheres red, 15 μm	4×10^7 pcs	5 June: 12.18*
Fluor shaft (247 m)	Spores malachite green	264.9 g	5 June: 12.18*
Fluor shaft (247 m)	Spores saffron coloured	279.5 g	5 June: 12.18*
Glasebach shaft (4 m)	Microspheres green, 15 μm	4×10^7 pcs	5 June: 8.11*

Add 40 h to the times marked with an asterisk, as *LydiA* (*Lycopodium* Apparatus) opened approximately 40 h later.
[†] pcs, pieces.

systems, each with 100 and 15 μm filters (NY 100 HC, NY 15 HC; Hydro-Bios, Kiel/Germany) for collecting the solid tracers (microspheres, spores), were installed at the No. 539 shaft, Fluor shaft and Glasebach shaft. Mini piston pumps were used for sampling (Pleuger Worthington GmbH, Hamburg/Germany) and installed 5–10 m below the water surface. 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. Edetic acid, as recommended by Käß (1998), if used in chemically unbalanced quantities creates crystals that complicate the counting process (Wolkersdorfer *et al.* 1997). In the laboratory, after at least 1 day of reaction, the filters were carefully rinsed and the solids filtered through 8 μm cellulose nitrate filters (Sartorius, Göttingen, Germany) 47 mm in diameter, Nalgene plastic filters were used for membrane filtering using 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 on glass plates, the fluorescent microspheres and the spores were counted under a fluorescence microscope (Zeiss, Göttingen). Depending on the number of solid particles on the filters, an aliquot part of the whole filter was counted and the totals for the whole sample calculated.

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 and Glasebach shaft) showed a significant change in conductivity that could be attributed to the sodium chloride tracer. During the time of conductivity measurements, the Fluor shaft (30 May–31 July) discharged 3.2 $m^3 min^{-1}$ of mine water resulting in a total tracer recovery of 39% (2.4 t of the 6.2 t injected). Considering the geological and tectonic conditions, this recovery rate is unexpectedly high, suggesting a good hydraulic connection between the Siptenfelde brook and the mine.

After some rainfall events (Fig. 2) the conductivity in the Fluor shaft increased significantly after about 1 day (e.g. 11 June, 7.49 pm; 11 June, 10.28 pm; 3 July, 9.34 pm). Each peak is seen to start quickly and tail out slowly (see inset in Fig. 2). Based on a distance of 2250 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

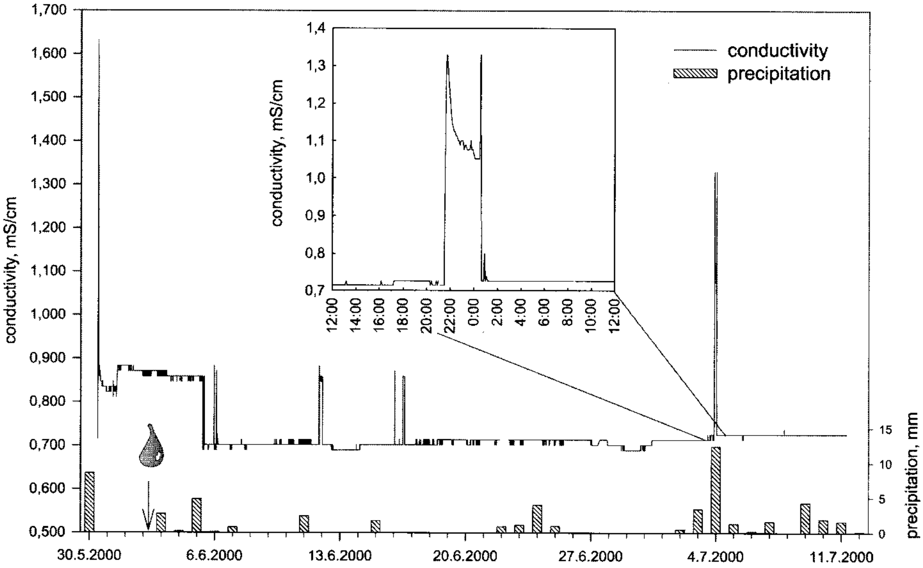

Fig. 2. Plot of precipitation (Siptenfelde station) and conductivity in the Fluor shaft. The arrow marks the time of the injection of the sodium chloride tracer into the Siptenfelde brook. Changes before 6 June are due to moving the conductivity probe upwards in the shaft by 5 m.

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
			(m min^{-1})	(m)
No. 530 shaft	Fluor shaft	Microspheres	0.1	1773
No. 530 shaft	Glasebach shaft	Microspheres	0.3	4798
Fluor shaft	Fluor shaft	Microspheres	0.2	238
Fluor shaft	Fluor shaft	Club moss spores	0.1	238
Fluor shaft	Glasebach shaft	Microspheres	0.3	3180
Fluor shaft	Glasebach shaft	Club moss spores	0.2–1.2	3180
Siptenfelde brook	Fluor shaft	NaCl–brine	1.5	2250

outflow (Table 5). None of these peaks were observed elsewhere, and reasons for these peaks other than the NaCl tracer can be excluded.

Club moss spores (Lycopodium clavatum). Club moss spores were only detected at the Fluor shaft and the Glasebach shaft (Fig. 3). A total of 323,220 spores in the Fluor shaft and 200,820 in the Glasebach shaft could be found after 8 June. 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 Flour shaft, the club moss spores peak reached 199,200 some 2.5 days after tracer injection, and in a relatively short time of 1.5 days decreased to nearly 4000 suggesting a low hydraulic dispersion. A second peak with 6500 spores occurred 6 days after tracer injection. From the injection point to the surface of the water, the spores have to flow 238 m, thus the mean effective velocity calculates to 0.1–0.2 m min^{-1} (Table 5).

It is possible that some of the filter nets used may have been contaminated from storage after an earlier tracer test. Therefore, the results cannot be interpreted easily and it is not clear whether the 1000–6000 spores are due to contamination or not. Nevertheless, 10.5 days after tracer injection is a clear peak with 25 000 spores and another one

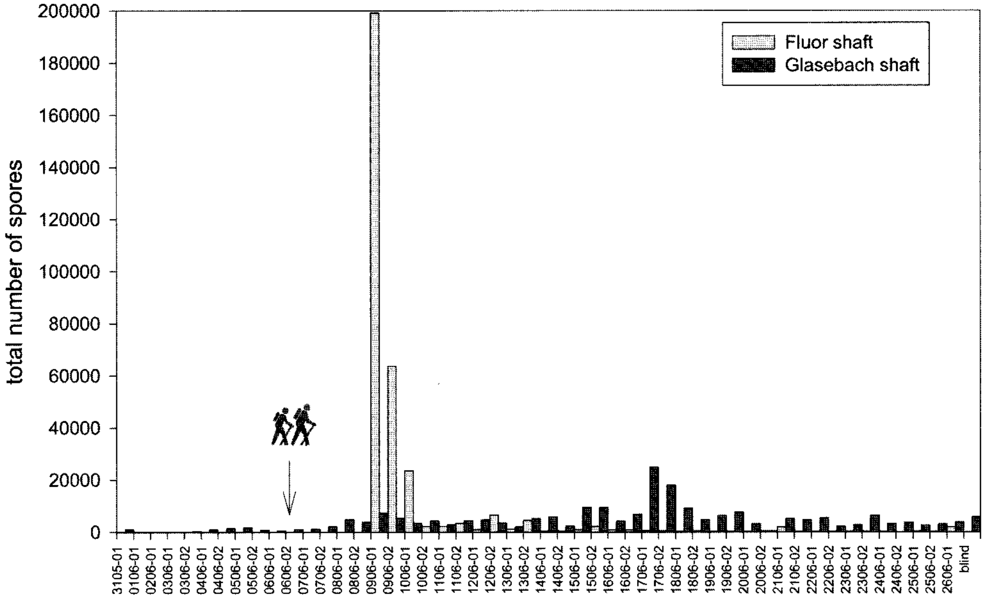

Fig. 3. Breakthrough curves of the club moss spores detected at the Fluor and Glasebach shafts. The arrow marks the time of tracer injection. The abscissa shows the dates of sampling. No spores were detected at the No. 539 shaft. Noticeable amounts of spores at the fluor shaft arrived 2.5 days, and at the Glasebach shaft 11 days, after tracer injection.

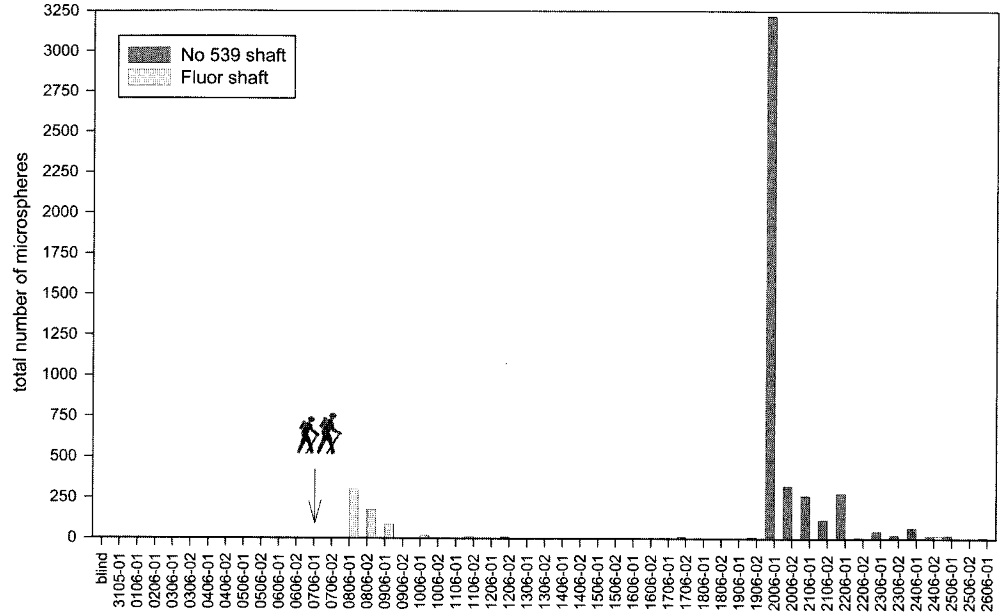

Fig. 4. Breakthrough curves of the microspheres detected at the Fluor shaft. (max.: 3219 microspheres). The abscissa shows dates of sampling. The arrow marks the time of tracer injection.

with 7400 spores 3 days after tracer injection. Once again, the maximum is reached very quickly, with a decline to background within 2 days. Between the injection point in the Fluor shaft and the detection point in the Glasebach shaft, the tracer had to flow 3180 m at the shortest pathway. Taking into consideration the two peaks and the shortest flow distance, the mean effective velocity is 0.2–1.2 m min^{-1} (Table 5).

Microspheres. From the microspheres injected in the No. 539, No. 530, Fluor and Glasebach shafts, only the microspheres from the No. 530 and Fluor shafts could be detected. It cannot be excluded that the LydiAs (*Lycopodium Apparatus*) lowered into the No. 539 and Glasebach shafts did not open properly.

In the Fluor shaft, microspheres from the Fluor shaft and the No. 530 shaft could be detected (Fig. 4). One day after the tracer injection 220 microspheres from the deep part of the Fluor shaft could be detected in the outflow from the shaft. A sharp peak was observed that tailed out within 1.5 days. The other peaks of microspheres from the Fluor shaft are negligible, but 13 days after tracer injection 3219 microspheres from the No. 530 shaft reached the sampling point at the Fluor shaft. A significant tracer signal could still be observed 2.5 and 4 days later. Based on the shortest distances of 238 and 1773 m from the injection to the sampling point, the mean effective velocities are 0.1–0.2 m min^{-1}.

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, were not sufficiently abundant to draw useful conclusions. Some 13 days after tracer injection, 9748 microspheres from the No. 530 shaft arrived at the sampling point at the 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 still be detected. As the distance between the No. 530 and Glasebach shafts is 4798 m, a mean effective velocity of 0.3 m min^{-1} is indicated.

Table 5 summarizes the results of all successful tracer detections during the Straßberg tracer test. From the results obtained, the velocities are consistently around dm min^{-1}, and it can be concluded that similar hydrodynamic conditions exist in the mine, independent of the location.

Straßberg mine: brief conclusions

The general flow direction throughout the tracer test was from north to south, as tracers injected were never found north of their injection point. All parts of the mine are hydraulically well connected, which explains the similar chemical

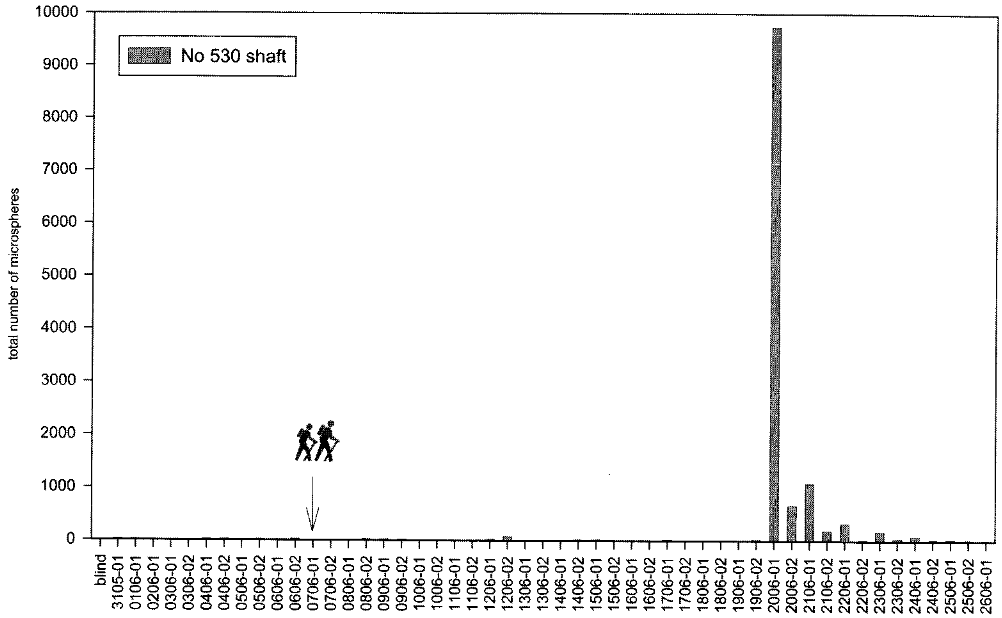

Fig. 5. Breakthrough curves of the microspheres detected at the Glasebach shaft (max.: 9748 microspheres). The abscissa shows dates of sampling. The arrow marks the time of tracer injection.

composition of the mine water in the Fluor and Glasebach shafts. Previous to the tracer test, it was believed that the general flow direction of the mine water was from south to north. Under the current flow regime, with the 3-adit system working, previously observed stratification cannot be re-established.

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 drifts and shafts is 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 six weeks of the tracer test, it must be assumed that there is a good connection between the Siptenfelde seepage and the northern adit. Finally, the tracer test's results confirm that the bulkhead at the northern adit is hydraulically inactive.

Outlook

Tracer tests in partly or fully flooded underground mines are rarely conducted and even less often published. Therefore, the experiences gained in the scientific world are limited until tracer tests in flooded mines become more widespread.

A critical prerequisite for a successful mine water tracer test is a conceptual model of the test site and extensive hydrogeological investigation of the mine and its surroundings, including the geological setting because tracers that are injected close to the surface have to flow through the unsaturated zone. Tracer velocities depend on the hydraulic head and the hydraulic properties of the rock. The mine geometry should be known reasonably accurately from mine plans, although former mine workers may have to be consulted to assist setting up the injection and sampling plan. In many cases, geochemical investigations of the mine water can help to understand the flow regime and trace elements might be useful to support the outcome of the tracer tests.

From the literature review, water velocities range between 0.001 and 11.1 m min^{-1} (Table 6), with a nearly log-normal distribution (24 tracer tests). Interestingly, 99% of all the mean measured velocities are between 0.2 and 1.5 m min^{-1}. Until now, the reasons for that have not been fully understood, but ongoing investigations will provide more details within the next few years.

Tracer tests in mines would benefit from the development of new innovative tracer techniques. Future work, therefore, has to focus on:

- tracer injection into predefined depths;
- measuring of the exact injection time;

Table 6. *Reported distances and mean velocities of worldwide tracer tests in underground mines. The table is given for comparison only, details concerning geological setting and hydraulic parameters are given in the literature cited. Mean of all 29 tracer tests: 0.3–1.7* $\mathrm{m\,min^{-1}}$ *(95% confidence interval, excluding the maximum and minimum value)*

Distance (km)	Mean velocity ($\mathrm{m\,min^{-1}}$)	Author
0.2	0.001	Aljoe & Hawkins 1993*
0.044	>0.004	Aljoe & Hawkins 1993
0.077	0.01	Canty & Everett 1999
0.13	0.01	Aljoe & Hawkins 1994
0.780	0.01	Wolkersdorfer 1996
0.35	0.1	Mather *et al.* 1969
0.077	0.12	Canty & Everett 1999
0.077	0.14	Canty & Everett 1999
0.171	0.17	Canty & Everett 1999
0.283	0.1–0.2	This study
1.773	0.1–0.2	This study
1.7	0.1–0.3	Parsons & Hunter 1972
0.229	0.23	Canty & Everett 1999
3.180	0.2–1.2	This study
3.6	0.3	Aldous & Smart 1987
4.798	0.3	This study
0.15	0.4	Mather *et al.* 1969
0.172	0.4	Wolkersdorfer *et al.* 1997
0.216	0.5	Wolkersdorfer *et al.* 1997
0.220	0.5	Wolkersdorfer *et al.* 1997
0.2	0.6	Mather *et al.* 1969
0.5	1.3	Aldous & Smart 1987
2.250	1.5	This study
0.776	1.6	Wolkersdorfer *et al.* 1997
0.736	1.8	Wolkersdorfer *et al.* 1997
0.780	2.0	Wolkersdorfer *et al.* 1997
2.159	5.7	Wolkersdorfer *et al.* 1997
2.723	7.9	Wolkersdorfer *et al.* 1997
0.5	11.1	Aldous & Smart 1987

* Result probably wrong.

- tracer sampling and counting;
- new tracers, suitable for mine water.

I would like to express my gratitude to A. Hasche for the improvement of the LydiA-technique. H.-J. Kahmann, as well as K. Heinrich, of BST Mansfeld GmbH and the GVV for financial and personal support of the Straßberg tracer test. Also, I would like to thank the staff of the BST Mansfeld, especially the Köhn family, at the Straßberg mine, who spent a lot of time taking care of us. My colleagues at the TU Bergakademie Freiberg supported the work group whenever help was needed. This study had been financially supported by the BST Mansfeld, the DFG Graduate School 'Geowissenschaftliche und Geotechnische Umweltforschung' (speaker: Univ.-Prof. Dr B. Merkel) at the TU Bergakademie Freiberg and the EU Project PIRAMID (contract No. EVK1-CT-1999-00021). I would also like to thank P. Younger for his efforts to make me publish my results! This paper expresses the views held by the author and does not necessarily reflect those held by the BST Mansfeld, the GVV, or any authorities involved.

References

ABELIN, H. & BIRGERSSON, L. 1985. Migration experiments in the stripa mine, design and instrumentation. In: COME, B., JOHNSTON, P. & MÜLLER, A., (eds) *Joint CEC/NEA Workshop on Design and Instrumentation of in situ Experiments in Underground Laboratories for Radioactive Waste Disposal.* Balkema, Rotterdam, **CONF 8405165**, 180–190.

ADELMAN, F.L., BACIGALUPI, C.M. & MOMYER, F.E. 1960. *Final Report on the Pinot Experiment (Colorado)*; Lawrence Radiation Lab Report, Livermore **UCRL-6274**, California University.

ALDOUS, P.J. & SMART, P.L. 1987. Tracing groundwater movement in abandoned coal mined aquifers using fluorescent dyes. *Ground Water, Urbana*, **26**, 172–178.

ALJOE, W.W. & HAWKINS, J.W. 1993. *Neutralization of Acidic Discharges from Abandoned Underground Coal Mines by Alkaline Injection*; Report of Investigations, US Bureau of Mines, Washington, **9468**.

ALJOE, W.W. & HAWKINS, J.W. 1994. Application of aquifer testing in surface and underground coal mines. In: *Proceedings of the fifth International Mine Water Congress*, Nottingham, UK, IMWA **1**, 3–21.

ANDERSON, B.C. 1987. *Use of Temperature Logs to Determine Intra-well-bore flows, Yucca Mountain, Nevada.* Master's Thesis, Colorado School of Mines, Golden, 59.

AQUILINA, L., ROSE, P., VAUTE, L., BRACH, M., GENTIER, S., JEANNOT, R., JACQUOT, E., AUDIGANE, P., TRAN-VIET, T., JUNG, R., BAUMGÄRTNER, J., BARIA, R. & GÉRARD, A. 1998. A tracer test at the Soultzt-Sous-Forets hot dry rock geothermal site. In: *Proceedings of the 23rd Workshop on Geothermal Reservoir Engineering*; Stanford **SGP-TR-158**, 1–8.

BANKS, D., YOUNGER, P.L., ARNESEN, R.T., IVERSEN, E.R. & BANKS, S.B. 1997. Mine-water chemistry: the good, the bad and the ugly. *Environmental Geology*, **32**, 157–174.

BARTELS, C. & LORENZ, E. 1993. Die Grube Glasebach–ein Denkmal des Erz- und Fluoritbergbaus im Ostharz. *Der Anschnitt, Bochum*, **45**, 144–158.

BIRGERSSON, L., WIDEN, H., AAGREN, T. & NERETNIEKS, I. 1992. *Tracer Migration Experiments in the Stripa Mine 1980–1991.* Swedish Nuclear Fuel and Waste Management Co. Stockholm **STRIPA-TR-92-25**.

BRETHERTON, B. 1989. *Near-surface Acid Mine Water Pools and Their Implications for Mine Abandonment, Coeur d'Alene Mining District, Idaho* Master's Thesis, University of Idaho, Moscow.

BREWITZ, W., KULL, H. & TEBBE, W. 1985. In situ experiments for the determination of macropermeability and RN-migration in faulted rock formations such as the oolithic iron ore in the Konrad Mine Design and instrumentation in underground laboratories for radioactive waste disposal. In: Come, B. Johnston, P., & Muller, A. (eds) *Design and instrumentation in underground laborataries for radioactive waste disposal*, Balkema, Rotterdam, 289–302.

Cacas, M.C., Ledoux, E., de Marsily, G., Tillie, B., Barbreau, A., Durand, E., Feuga, B. & Peaudecerf, P. 1990. Modeling fracture flow with a stochastic discrete fracture network: calibration and validation. 1. The flow model. *Water Resources Research*, **26**, 479–489.

Canty, G.A. & Everett, J.W. 1998. Using tracers to understand the hydrology of an abandoned underground coal mine. In: *Proceedings of the Annual National Meeting*. American Society for Surface Mining and Reclamation, Princeton **15**, 62–72.

Davis, M.W. 1994*a*. Identification and Remediation of a Mine Flooding Problem in Rico, Dolores County, Colorado with a Discussion on the Use of Tracer Dyes, *Colorado Geological Survey Open-File Report, Denver* **91-1**, 15.

Davis, M.W. 1994*b*. The Use of Tracer Dyes for the Identification of a Mine Flooding Problem, Rico, Dolores County, Colorado. *Colorado Geological Survey Open File Report, Denver* **91-2**, 1–20.

Diaz, W.D. 1990. *Hydrogeochemistry and Physical Hydrogeology of the Newfoundland Zinc Mine, Daniel's Harbour, Newfoundland*. Master's Thesis, St. John's, Newfoundland.

Doornbos, M.H. 1989. *Hydrogeologic Controls Upon the Water Quality of the Acid Mine Drainage in the Sand Coulee–Stochett Area, Montana*. Master's Thesis, Montana College of Mineral Science & Technology, Butte.

Fernández-rubio, R., Fernández-lorca, S. & Esteban arlegui, J. 1987. Preventive techniques for controlling acid water in underground mines by flooding. *International Journal of Mine Water, Budapest*, **6** (3), 39–52.

Fried, J.J. 1972. Miscible pollutions of groundwater–a study in methodology. In: Biswas, A.K. (ed.) *Modelling of Water Resources Systems*. Harvest House, Montreal **2**, 520–529.

Galloway, D.L. & Erickson, J.R. 1985. Tracer test for evaluating nonpumping intraborehole flow in fractured media. *Transactions of the American Nuclear Society*, **50**, 192–193.

Gatzweiler, R. & Meyer, J. 2000. Umweltverträgliche Stilllegung und Verwahrung von Uranerzbergwerken–Fallbeispiel WISMUT. In: *Proceedings Wismut 2000 Bergbäusanierung Internationale Konferenz, 11–14.7.2000, Schlema*; Wismat Guibit Chemmitz 1–16.

Goldbrunner, J.E., Ramspacher, P., Zojer, H., Zötl, J.G., Moser, H., Rauert, W. & Stichler, W. 1982. Die Anwendung natürlicher und künstlicher Tracer in einem hochalpinen Magnesitbergbau. *Beiträge zur Geologie der Schweiz-Hydrologic, Bern*, **28**, 407–422.

Gulati, M.S., Lipman, S.C. & Strobel, C.J. 1978. Tritium tracer survey at the geysers. *Geothermal Resource Council Annual Meeting: Geothermal Energy–A Novelty Becomes Resource, Hilo, Hawaii, 25–27 July 1978*. Geothermal Resource Council, Davis, CA, **2**, 237–239.

Habič, P. & Gospodarič, R. 1976. *Underground Water Tracing–Investigations in Slovenia 1972–1975*. Institute Karst Research, Ljubljana.

Hamilton, Q.U.I., Lamb, H.M., Hallet, C. & Proctor, J.A. 1997. Passive treatment systems for the remediation of acid mine drainage in Wheal Jane, Cornwall, UK. In: Younger, P.L. (eds) *Mine Water Treatment Using Wetlands*. Chartered Institution of Water and Environmental Management, London, 33–56.

Himmelsbach, T. & Wendland, E. 1999. Schwermetalltransport in Sandsteinen unter Bedingungen einer hochsalinaren Porenwasserlösung–Laborversuch und Modellierung. *Grundwasser, Berlin*, **4**, 103–112.

Himmelsbach, T., Hötzl, H., Käss, W., Leibundgut, C., Maloszewski, P., Meyer, T., Moser, H., Rajner, V., Rank, D., Stichler, W., Trimborn, P. & Veulliet, E. 1992. Transport phenomena in different aquifers (Investigations 1987–1992)–fractured rock test site Lindau/Southern Black Forest (Germany). *Steirische Beiträge zur Hydrogeologie, Graz*, **43**, 159–228.

Horn, P., Hölzl, S. & Nindel, K. 1995. Uranogenic and thorogenic lead isotopes (^{206}Pb, ^{207}Pb, ^{208}Pb) as tracers for mixing of waters in the Königstein uranium mine, Germany. In: *Proceedings of Uranium Mining and Hydrogeology, Freiberg, Germany*. GeoCongress, Freiberg **1**, 281–289.

Horne, R.N., Johns, R.A., Adams, M.C., Moore, J.N. & Stiger, S.G. 1987. The use of tracers to analyze the effects of reinjection into fractured geothermal reservoirs. In: *Proceedings of the fifth Geothermal Program Review, Washington*. Stanford University, CA 37–52.

Hunt, D.J. & Reddish, D.J., 1997. The stability implications of groundwater recharge upon shallow, abandoned mineworkings in the UK. *Engineering Geology and the Environment*. In: Marinos, P.G., Koukis, G.C., Tsiambaos, G.C. & Stouruaras, G.C. (eds) Balkema, Rotterdam, **3**, 2425–2430.

IAEA, Jester, W.A. & Raupach, D.C. 1987. Survey of applications of non-radioactive but neutron activatable groundwater tracers. In: *Isotope Techniques in Water Resources Development. International Symposium on the Use of Isotope Techniques in Water Resources Development, Wien*, IAEA 623–633.

Käss, W. 1998. *Tracing Technique in Geohydrology*. Balkema, Rotterdam.

Kimball, B.A., Runkel, R.L., Bencala, K.E. & Walton-day, K. 1999. Use of tracer Injections and Synoptic Sampling to Measure Metal Loading From Acid Mine Drainage, *Water Resources Investigations Report, Denver* **WRI 99-4018A (1)**, 31–36.

Kindermann, L. 1998. Kontrolle geochemischer Parameter beim Wiedereinbau von Reststoffen in ein stillgelegtes Bergwerk. *Wissenschaftliche Mitteilungen-Sonderheft, Freiberg*, **7**, 196–201.

Kirschner, F.E. 1989. *Ground-surface Delineation of Fractures That Appear to be Connected to Underlying Mined-out Openings Using a Naturally Occurring Gaseous Tracer.* University of Idaho, Moscow.

Kirshner, F.E. 1991. *Hydrogeological Evaluation of an in-situ Leach Cell in Abandoned Mine and Mill Waste at the Kellogg, Idaho Superfund Site Using Tracers.* University of Idaho, Moscow.

Kirshner, F.E. & Williams, R.E. 1993. Hydrogeological evaluation of an in-situ leach cell in abandoned mine and mill waste at the Kellogg, Idaho Superfund site using tracers. In: *International Biohydrometallurgy Symposium, Jackson Hole*, The Minerals, Metals and Materials Society, Warrendale 77–87.

Klotz, D. & Oliv, F. 1982. Verhalten der Radionuklide ^{125}I, ^{85}Sr, ^{134}Cs und ^{144}Ce in drei typischen Sanden Norddeutschlands bei wasserungesättigtem Fließen. *GSF-Bericht, Neuherberg*, **R290**, 395–401.

Kuschka, E. & Franzke, H.J. 1974. Zur Kenntnis der Hydrothermalite des Harzes. *Zeitschrift für geologische Wissenschaften, Berlin*, **2**, 1417–1436.

Kuyumcu, M. & Hartwig, H.-J. 1998. Aufgaben der GVV–Gesellschaft zur Verwahrung und Verwertung von stillgelegten Bergwerksbetrieben mbH. *Bergbau, Gelsenkirchen*, **49**, 18–22.

Kwakwa, K.A. 1989. Tracer results. In: Parker, R.H. (eds) *Hot Dry rock Geothermal Energy; Phase 2B Final Report of the Camborne School of Mines Project.* Pergamon Press, Oxford, 1037–1099.

Lachmar, T.E. 1994. Application of fracture-flow hydrogeology to acid-mine drainage at the Bunker Hill Mine, Kellogg, Idaho. *Journal of Hydrology*, **155**, 125–149.

Lee, W.L. 1984. Performance assessment of nuclear waste isolation systems Shaping our energy future. In: *Proceedings of the Eleventh Annual WATTec Conference and Exposition, Knoxville*, LTM Consultants 59.

Lewis, R.A. 1990. *Borate Adsorption by Some Volcanic Tuffs; Evaluation of Borate as a Potential Tracer for Unsaturated Flow at Yucca Mountain Borate Adsorption by Some Volcanic Tuffs, Evaluation of Borate as a Potential Tracer for Unsaturated Flow at Yucca Mountain* PhD Thesis, Colorado School of Mines, Golden.

Lewis, R.L., Mcgowan, I.R., Hershman, J.I. & Tilk, J. 1997. Numerical simulation of bulkheads to reduce uncontrolled discharge from an underground copper mine. *Mining Engineering*, **49**, 68–72.

Liedl, R. & Sauter, M. 2000. Charakterisierung von Karstgrundwasserleitern durch Simulation der Aquifergenese und des Wärmetransports. *Grundwasser, Heidelberg*, **5**, 9–16.

Lorenz, P.B. 1973. Radioactive Tracer Pulse Method of Evaluating Fracturing of Underground Oil Shale Formations; *Bureau of Mines Report of Investigations: Washington*, **7791**, 33.

Mather, J.D., Gray, D.A. & Jenkins, D.G. 1969. The use of tracers to investigate the relationship between mining subsidence and groundwater occurrence at Aberfan, South Wales. *Journal of Hydrology*, **9**, 136–154.

Miller, N.C. & Schmuck, C.H. Use of a Tracer For in situ Stope Leaching Solution Containment Research; *Bureau of Mines Report of Investigations, Spokane* **RI-9583**, 43.

Mohr, K. 1993. *Geologie und Minerallagerstätten des Harzes*, Schweizerbart, Stuttgart.

Niehren, S. & Kinzelbach, W. 1998. Artificial colloid tracer tests–development of a compact online microsphere counter and application to soil column experiments. *Journal of Contaminant Hydrology*, **35**, 249–259.

Nordstrom, D.K., Alpers, C.N., Ptacek, C.J. & Blowes, D.W. 2000. Negative pH and extremly acidic Mine waters from Iron Mountain, California. *Environmental Sciences and Technology*, **34**, 254–258.

Parkhurst, D.L. 1988. *Mine-water Discharge, Metal Loading, and Chemical Reactions*, US Geological Survey, Reston. Open File Report, **OF 86-0481**, D5–D9.

Parsons, A.S. & Hunter, M.D. 1972. Investigation into the movement of groundwater from Bryn Pit above Ebbw Vale, Monmouthshire. *Water Pollution Control*, **71**, 568–572.

Pujol, L. & Sanchez cabeza, J.A. 2000. Use of tritium to predict soluble pollutants transport in Ebro River waters (Spain). *Environmental Pollution*, **108**, 257–269.

Randall, M.M., Nicholls, J., Willis-richards, J. & Lanyon, G.W. 1990. Evaluation of jointing in the carnmenellis granite. In: Baria, R. (ed) *Hot Dry Rock: Geothermal Energy.* Robertson Scientific Publications, Camborne, 108–123.

Reznik, Y.M. 1990. Determination of groundwater paths using method of streaming potentials. In: Graves, D.H. (ed) *National Symposium on Mining: A New Beginning. Proceedings of the National Symposium on Mining.* University of Kensington, Lexington, 217–221.

Rüterkamp, P. & Meßer, J. 2000. Untersuchungen zur hydraulischen und hydrochemischen Situation in den drei Teilrevieren der gefluteten Flussspatgrube Straßberg: 46. Unpublished report, Deutsche Moutan-technologie (DMT).

Sawada, A., Uchida, M., Shimo, M., Yamamoto, H., Takahara, H. & Doe, T.W. 2000. Non-sorbing tracer migration experiments in fractured rock at the Kamaishi Mine, Northeast Japan. *Engineering Geology*, **56**, 75–96.

Scott, R.L. & Hays, R.M. 1975. Inactive and abandoned underground mines–water pollution prevention and control. In: Michael & Baker Jr. Inc. (eds) US Environmental Protection Agency, Washington, DC **EPA-440/9-75-007**.

Sheibach, R.B., Williams, R.E. & Genes, B.R. 1982. Controlling acid mine drainage from the Picher Mining District, Oklahoma, United States. *International Journal Mine Water*, **1**, 31–44.

SKOWRONEK, E. & ZMIJ, M. 1977. Okreslenie pochodzenia wody wyplywajacej zza obmurza szybu znakowaniem rodamina B. [Determination of the origin of water flowing out from behind a shaft lining traced with Rhodamine B]. *Przegl Gorn, Gliwice, Poland,* **33**, 13-19.

WIRSING, G. 1995. Hydrogeologische Untersuchungen im Grubengebäude des Schauinslandbergwerks–Beurteilung des Grundwasservorkommens und Abgrenzung eines Wasserschutzgebietes für die Quelle 14 der Freiburger Energie- und Wasserversorgungs-AG: 45. Unpublished report Geologisches Laudesaut Buden-Württemberg.

WITTRUP, M.B., KYSER, T.K. & DANYLUK, T. 1986. *The Use of Stable Isotopes to Determine the Source of Brine in Saskatchewan Potash Mines,* Saskatchewan Geological Society, Regina, Special Publication, **8**, 159–165.

WOLKERSDORFER, Ch. 1996. Hydrogeochemische Verhältnisse im Flutungswasser eines Uranbergwerks–Die Lagerstätte Niederschlema/Alberoda. *Clausthaler Geowissenschaftliche Dissertationen, Clausthal,* **50**, 1–216.

WOLKERSDORFER, Ch. & HASCHE, A. 2001. Tracer test in the abandoned fluorspar mine Straßberg/Harz Mountains, Germany. *Wissenschaftliche Mitteilungen, Freiberg,* **16**, 57–67.

WOLKERSDORFER, Ch., TREBUŠAK, I. & FELDTNER, N. 1997. Development of a tracer test in a flooded uranium mine using *Lycopodium clavatum. Tracer Hydrology, 97.* In: KRANJC, A. (ed.) Balkema, Rotterdam, **7**, 377–385.

WU, Q., JIN, Y., TIAN, B., LI, D. & XIA, Y. 1992. An application of artificial tracers in determining vertical groundwater recharge locations in a coal mine. In: *International Symposium on Water Tracing (SUWT), Balkema, Rotterdam,* **6**, 365–367.

YOUNGER, P.L. 2000. The adoption and adaptation of passive treatment technologies for mine waters in the United Kingdom. *Mine Water and the Environment,* **19** (2), 84–97.

YOUNGER, P.L. & ADAMS, R. 1999. *Predicting Mine Water Rebound.* Environment Agency, Bristol.