Hydrodynamics in a flooded underground limestone mine

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Abstract This paper describes a mine water tracer test in a flooded Germany underground limestone mine. Uranine was injected at two locations and the tracer concentration measured with an on-line fluorimeter. The breakthrough curve shows two peaks, relating to the two injection sites. Background values were reached after 24 months making this tracer test the longest mine water tracer test ever. Mean effective velocities range between 0.1 and 0.5 m d^{-1} indicating a slow water circulation. The paper concludes that low effective velocities are an indication for mines with a simple geometry and that simple mine geometries facilitate stratification and a lower pollution potential.

Keywords tracer test; *Felsendome Rabenstein*; Saxony; hydrodynamics, abandoned mine

Introduction

In contrast to hydrogeochemical investigations related to mine water, the number of hydrodynamic investigations of the water flow within a mine is rather restricted. One reason might be that taking samples and conducting physico-chemical investigations of mine water is relatively simple compared to conducting hydrodynamic investigations in mines. Hydrodynamic investigations usually require access to the mine water at more than one location which is not always possible, unless bore holes are drilled, shafts reopened or discharge adits made accessible. In addition, the injection of tracer substances and their analysis is not a standard method and therefore does not belong to the investigations carried out as often as physico-chemical analyses. Another reason might be that mining operators, researchers, and authorities consider the quality of mine water draining out of a mine as "given" and consequently focus on the chemistry rather the flow of the water through the mine. But, as we will show, the flow of water in mines depends on the mine's geometry and this knowledge might be used to plan remediation strategies for underground mines before their flooding.

Mine operators or researchers initiate relatively few investigations relating to the flow of the mine water itself (Semmler 1937; Merritt & Angerman 1972; Wolkersdorfer & Hasche 2001). In those cases, where a tracer test is conducted the key question is usually if two or more locations are hydraulically connected rather than identifying the hydrodynamics within the mine itself. First investigations of the hydrodynamics of flooded mines were conducted by Wolkersdorfer *et al.* (1997) and optimised thereafter (Wolkersdorfer 2008). The potential for stratification in flooded underground mines was investigated by several researchers based on the hydrogeochemistry or physico-chemical parameters of the mine water (*e.g.* Wolkersdorfer 1996; Kories *et al.* 2004; Nuttall & Younger 2004; Wolkersdorfer & Merkel 2005; Rapantova *et al.* 2009; Reichart *et al.* 2011).

Our own tracer investigations and the investigations of others revealed three facts:

- the mean effective velocity of water in flooded underground mines is in a relatively narrow range of 0.3…1.6 m min^{-1} (95 % confidence interval of 42 tracer tests; Wolkersdorfer 2008)
- several mines have a relatively fast effective velocity of the mine water (6…11 m min^{-1})
- some mines have a very slow effective velocity of the mine water (10^{-4}…10^{-2} m min^{-1})

The hypothesis resulting from those facts was that mines where the shafts are hydraulically well connected with each other show faster velocities (‘multiple shaft mines’), while mines with only one or two poorly connected shafts show slower effective velocities (‘single shaft mines’). To prove this hypothesis we conducted two tracer tests in mines with only one or two shafts that we assumed are poorly connected with each other. One of those mines was the Austrian *Georgi Unterbau* and the other one the German *Felsendome Rabenstein*. In this paper we are presenting the results of the latter tracer test. Preliminary results of the first one are published elsewhere (Wolkersdorfer *et al.* 2002, Wolkersdorfer 2008).

A quasi-stagnant situation is typical for ‘single shaft mines’ where the geothermal gradient is not high enough to start free convection, nor does a major regional forced convection exist. Water in the shaft flows very slowly and it can be assumed that there is a laminar Poiseuille flow situation in the upper part of the shaft and diffusive flow in the lower part of the shaft. Therefore, this shaft was selected for a tracer test in a mine with a low vertical flow characteristic and a simple mine geometry.

Location and mining history of the *Felsendome Rabenstein*

The *Felsendome Rabenstein* is a former underground limestone mine located in Rabenstein/Germany, a suburb of Chemnitz/Saxony consisting of four worked mine levels (Fig. 1). Since the beginning of the 20th century the two lowermost levels have been flooded and the mine started to become a local tourist attraction in 1936 (Geißler *et al.* 1984). During the

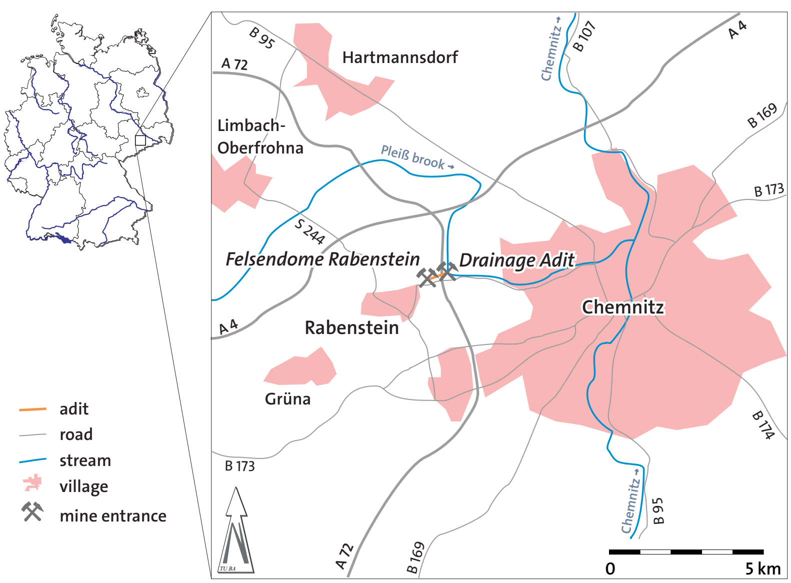

***Fig. 1** Location of the Felsendome Rabenstein abandoned underground limestone mine.*

last two decades, the site was converted into an attractive recreation area, and the underwater part is now extensively used by divers (Meier & Meier 2007).

First underground limestone mining in the area began in medieval times (Riedel 1993). In 1834, the Rabenstein underground mine opened and 40 years later, the 35 m deep *Maschinenschacht* (machine shaft) was sunk, connecting the three lowermost levels with each other (15, 22, and 27 m below the surface; Fig. 2). At the end of the mine's lifetime, four levels existed: the upper and lower level as well as the 1st and 2nd deep levels (level 3 and 4), extending over an area of 250 × 100 m with caverns ranging from 6–8 m in height. An underground drift adit in the *Grüne Grotte* (green grotto) and the *Maschinenschacht* connected the two deeper levels with the lowest level. To dewater the mine, a 220 m long drainage adit to the Pleiß brook was constructed in 1855, which still dewaters the mine from the lower level, with daily mean discharges between 3 and 40 $^{-1}$. Extreme precipitation can induce total discharges up to 120 $m^3\ d^{-1}$. During active mining, the water from the 1st and 2nd deep levels was pumped into the adit. In 1902, six years before the closure of the mine, the two deepest levels were allowed to flood and since then the connecting shaft has been filled with a 15.8 m high water column. Based on available data, the volume of the *Maschinenschacht*, the *Grüne Grotte* incline, and the flooded 1st and 2nd deep levels is 124, 120, and 2,100 m^3, respectively. Only the parts that were thought to be relevant for the tracer test were used in the calculation. The total volume of each level must be another 20–30,000 m^3. Using that data, a total flooding time of several years can be estimated. However, Dietrich (1965) calculated a flooding time of 12 weeks for the two underground levels, which seems to be rather low considering a mean flow of 12 $m^3\ d^{-1}$.

At two locations the flooded part of the mine is accessible: the *Grüne Grotte* and the *Maschinenschacht*, which are 140 m apart from each other. Between 2002 and 2005, when the tracer test was conducted, the electrical conductivity of the mine water was relatively constant at 1,190…1,260 µS cm^{-1}, with a pH of 6.5…8.9, an E_H of 350…510 mV, and a temperature of 7.5…8.7 °C. Slightly different values prevailed at the *Grüne Grotte*: electrical conductivity 800…1,000 µS cm^{-1}, pH 7.1…8.7, E_H 340…510 mV, and a temperature of 4.8…6.8 °C.

According to the known records of the *Felsendome Rabenstein* mine and the reports of divers, the flooded and partly backfilled *Maschinenschacht* (machine shaft) is con-

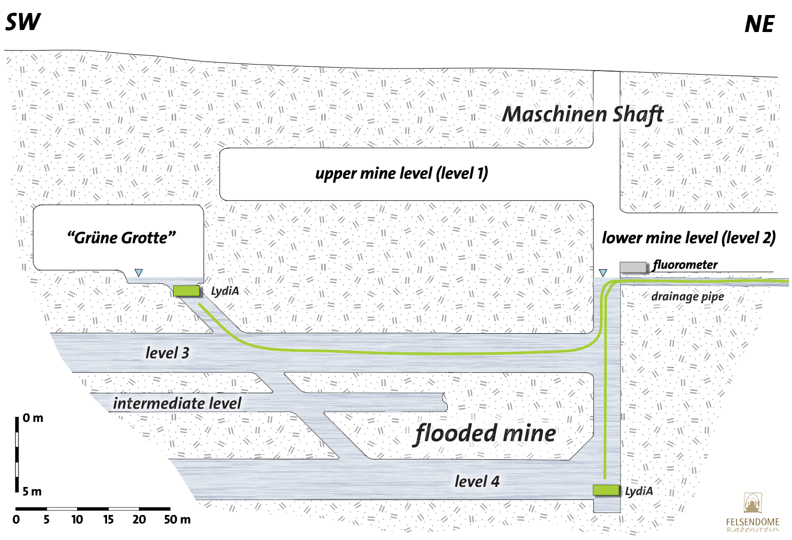

Fig. 2 *Cross section through the partly flooded Felsendome Rabenstein limestone mine showing the injection and sampling sites as well as the proposed flow path of the uranine tracer. Scales only correct for the flooded mine parts. Not to scale above the water table.*

nected to the 1st and 2nd deep levels at depths of 6 and 12 m below the mine water surface. Several small blind shafts and the incline within the *Grüne Grotte* connect the 1st deep level with the 2nd deep level. No precise data are available about the shaft's outflow, but it was estimated with an area velocity measurement to be in the range of 1…2 L min^{-1}. Only a poorly developed thermal stratification can be found in the *Maschinenschacht*. The temperature in the shaft is relatively constant at 7.9 °C and small temperature fluctuations can be observed at the two onsetting stations (Fig. 3).

Outline of the Geological Situation

Geologically, the mine is located in the Rabenstein-Formation within the Schist Cover of the Saxonian Granulite Massiv and the rocks are assumed to belong to the Cambrian Series 2…3. Primarily, the mined strata comprise metamorphosed limestone, a coloured calcite marble in combination with phyllites, alum shale-like black phyllites, and amphibolites. Pyrite occurs frequently in the limestone and especially in the phyllites, and copper pyrite (chalcopyrite), often oxidised to malachite, can be found in vugs. The whole formation is slightly folded with northwest striking folding axes, and faults in a northeastern direction with offsets in the range of 5 m are common (Dietrich 1965; Freyer *et al.* 1982; Geißler *et al.* 1986). Some of the faults are hydraulically active, as water penetrates from the surface to the mine during high precipitation periods (*e.g.* a fault between the *Blauer Salon* and the *Gnomengang*). Divers have reported that they can regularly see bead-like air bubbles moving in straight lines from the 2nd deep level through the rock into the 1st deep level.

Methods and Investigations

In 2002, the flooded part of the mine was investigated hydrogeologically and the potential for a mine water tracer test was evaluated. The water analysis did not indicate potential problems for a tracer test and the pH was circumneutral, suggesting that no decomposition of the tracer, uranine (sodium fluresceïn), would be expected. A discontinuous temperature log in the *Maschinenschacht* showed a small temperature variation at the two flooded onsetting stations with no temperature shift. Later, continuous temperature logs revealed a small positive temperature shift of about 0.05 K/10 m (Fig. 3).

Between 2002 and 2005, the mine was visited 16 times and the physico-chemical on-site parameters were measured regularly. One full analysis of the mine water was conducted, showing that the water is of the Ca-Mg-SO_4-

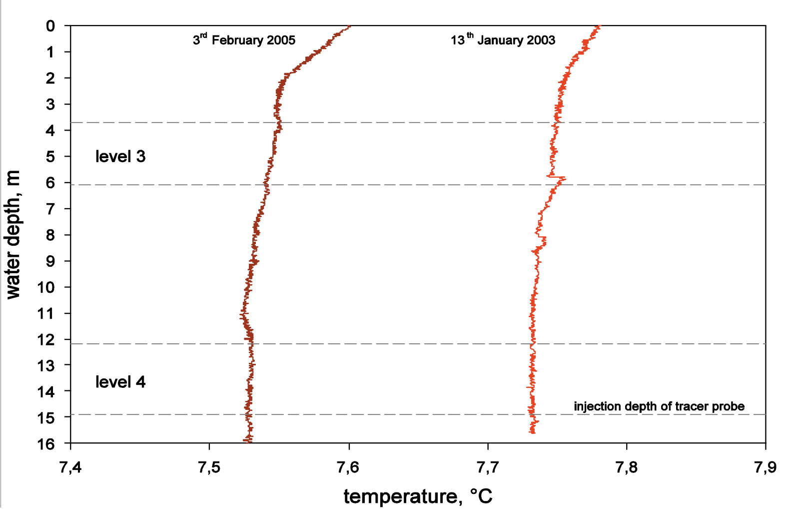

Fig. 3 *Temperature–depth profile in the Felsendome Rabenstein Machinenschacht before and after the tracer test.*

HCO_3-type. Five temperature and electrical conductivity logs were conducted in early 2003 and 2005 before and after the tracer test with uranine.

On 21 March 2003, the tracer test with uranine, scheduled for a duration of about 3 months, was started. With a tracer probe (LydiA; Wolkersdorfer *et al.* 1997), 15 g of uranine were lowered to a depth of 15 m into the *Maschinenschacht* and 250 g at a depth of 2…3 m within the incline of the *Grüne Grotte* (Fig. 2, 4). The recommendations about the use of tracer amounts summarised in a later paper by Wolkersdorfer & LeBlanc (2012) were followed. After 96 weeks, the tracer concentration came down to background values and was therefore brought to an end. Thus, the *Felsendome Rabenstein* Tracer test has the unique distinction of being the longest lasting tracer test ever conducted in an underground mine (Fig. 5). Due to a malfunction of the piezometer that measured the total flow of the mine water no recovery rates can be given at this stage of the investigation.

To clarify which of the two peaks belongs to which injection place, the vertical distribution of the tracer in the shaft was measured four times in the *Maschinenschacht* and once in the *Grüne Grotte* incline.

Results and Interpretation

Our investigations in the *Felsendome Rabenstein* showed that there is only a minor stratification of 0.1 K which is not strong enough to prevent the flow from the lowest mine level to the shaft's drainage point. Furthermore, the mine has only two main shafts which are connecting the two flooded levels. Based on the flow measurements in summer 2002 and assuming a mean flow of 0.3…1.6 m min^{-1} a duration of 1…2 months was calculated for the concentration of the tracer to return to background levels. Yet, the tracer concentrations did not decrease to the background values even after 19 months into the test period. From the tracer's maximum at about 3 months after the tracer test's beginning it can be calculated that the effective velocities between the injection and sampling points are about 0.1–0.4 m d^{-1} (Wolkersdorfer 2005, 2008).

No relevant stratification could be observed in the *Felsendome Rabenstein* mine. Neither the temperature nor the electrical conductivity plots show signs of stratification, though small fluctuations in the area of the onsetting stations were observed. While the temperature slightly increases (by about 1.5 K) from bottom to top, the electrical conductivity decreases by about 100 µS cm^{-1}, proving a

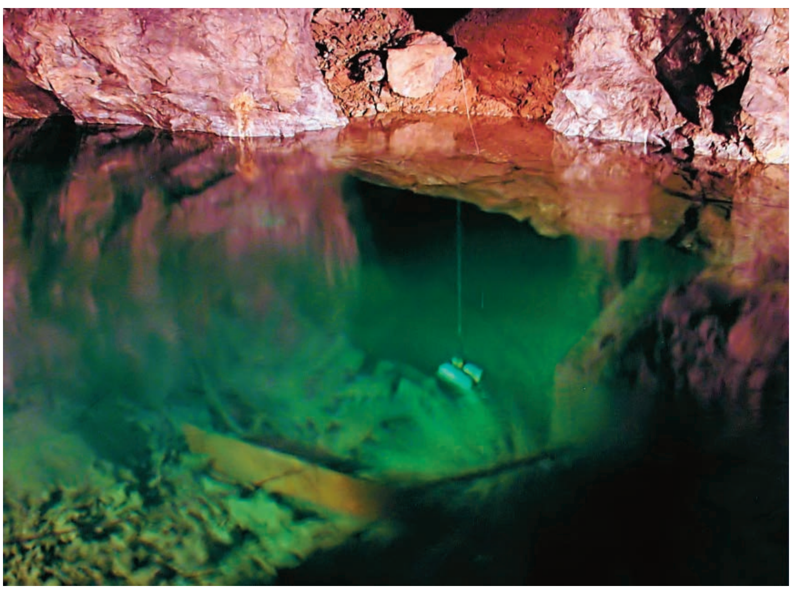

Fig. 4 *Tracer probe in the Grüne Grotte incline. The green colour of the water is from the uranine still in the mine water.*

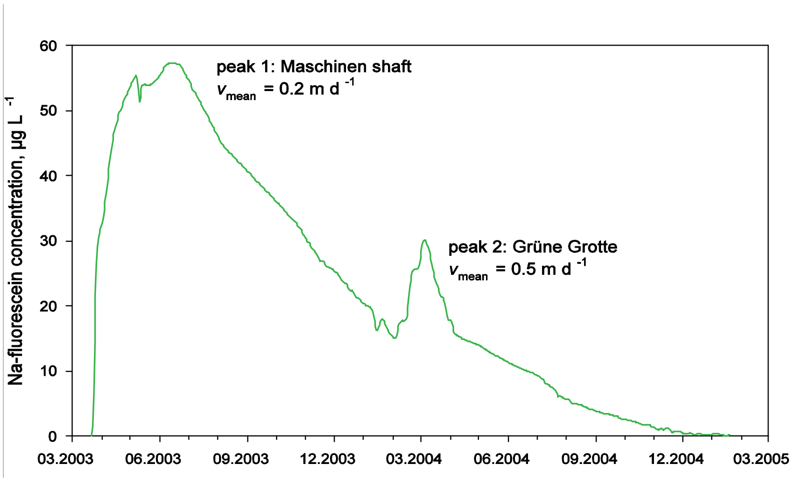

Fig. 5 *Breakthrough curve of the 2003–2005 Felsendome Rabenstein tracer test with uranine.*

mainly diffusion-based flow scenario in the *Maschinenschacht*, with only a small advective component.

In the breakthrough curve, two tracer peaks could be observed, the first one after 65 days, the second one 350 days after the tracer injection (Fig. 5, Table 1). Our hypothesis is that the first peak results from the tracer injected at a depth of 15 m in the *Maschinenschacht*; the second one from tracer injected 171 m away in the *Grüne Grotte* incline. From that data, an effective velocity v_{eff} of 0.10^{-1} was calculated for peak 1 and 0.48 m d^{-1} for peak 2. The smaller peak after peak 2 might have been induced by divers training in the flooded underground mine.

In contrast to the first peak, which has an extremely long tail of about 620 days, the second one has a tail of only 120 days, indicating a larger calculated longitudinal dispersion coefficient of 7.1 · 10-6 m^2 s^{-1} for peak 1 and a smaller one of $1.3 \cdot 10^{-6}$ m^2 s-1 for peak 2. From the vertical tracer distribution in the *Maschinenschacht*, it became clear that the first peak results from the tracer injected into the *Maschinenschacht* and the second one from the tracer in the *Grüne Grotte*. The long tail of the first peak shows that the mass transport from the 2nd deep level to the surface is possibly diffusion-based and the flow from the *Grüne Grotte* must be via the connecting adit between the incline and the *Maschinenschacht* on the 1st level. If the water had followed the connecting adit at the 2nd level, a tailing similar to peak 1 would have been observed. It can be concluded that the transport from the 2nd level

	Effective velocity v_{eff}			Mean velocity v_{mean}		
Peak	Time d	Distance m	Velocity m d^{-1}	Time d	Distance m	Velocity m d^{-1}
1	149	15	0.10	65	15	0.23
2	356	171	0.48	350	171	0.49
2’	320	165	0.53	314	165	0.52

Table 1 *Results of the Rabenstein tracer test. Peak 2’ is the reconstruction of the travel times for the* Grüne Grotte *tracer from the* Grüne Grotte *to the onsetting station of the 1st deep level at the* Maschinenschacht. *It has been calculated from the travel times and distances of Peak 2 less the distance to the onsetting station and the mean travel times calculated from peak one and the mean of the effective and mean velocities of peak 1. Velocities are based on the data given in this table. No extensive modelling has been used.*

into the region of the 1st deep level is probably diffusion-dominated whereas the shaft above the 1st deep level shows Poiseuille-dominated flow.

Conclusions

The *Felsendome Rabenstein* tracer test proved our hypothesis that slow effective velocities in flooded underground mines are a result of restricted hydrodynamic connections of the mine workings. Only one larger diameter shaft and an incline as well as two minor shafts are connecting the two flooded levels with each other which does not induce an overall convective flow regime in the mine. The effective velocities in the mine water range between 0.1 and 0.5 m d^{-1} and are therefore in the lowest range of effective velocities ever measured in a flooded underground mine. Obviously, the mine is not very deep, but in conjunction with the *Georgi Unterbau* tracer test results, where a 100 m deep shaft is connecting the levels, we cannot reject our hypothesis that a simple mine geometry prevents convective flow in flooded underground mines.

In combination with the results of previous tracer tests we therefore draw the following conclusions:

- simple mine layouts abet slow effective mine water velocities
- modifications of the mine layout prevent an overall convective flow in the mine
- modifications of the mine layout before a mine is flooded reduce the effective velocity of the mine water
- a reduced effective velocity and convective flow regime hamper the spreading of the potential contaminants throughout the mine

Because the higher contaminated parts of a mine can usually be found in the deeper parts of the mine (*e.g.* Frost *et al.* 1977; Kories *et al.* 2004; Wolkersdorfer 2008) we therefore recommend to prevent an overall convective flow by modifying the mine layout before flooding starts. This might induce a stratification in the mine and the contaminant load draining out of the mine will be reduced.

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