HYDRODYNAMICS OF THE FLOODED FREIBERG/SAXONY UNDERGROUND MINE

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Abstract
This paper describes the hydrodynamic processes within the flooded underground mine of Freiberg (Himmelfarth Fundgrube) and quantifies the amount of mine water which rises in the Reiche Zeche Shaft up to the Rothschönberg adit.
Due to inaccessibility of the flooded part of the shaft Reiche Zeche between 229 m and 724 m below the surface, passive methods were used for determining flow direction and velocity. Five tracer tests were conducted with Na-fluorescein (uranine) which was injected depth-orientated into the mine water by use of the LydiA-technique. A first test 40 m below the water table confirmed the obvious upwelling of the water. From the injected Na-fluorescein, 80 % (11.98 g) could be detected with a fluorimeter. The mean velocity was calculated to be 0.74 m min^{-1}. Three more tracer tests at depths of 65 m and 324 m below the water table and a previous one in 2002 did not increase the concentration of Na-fluorescein at the outflow. As failing of the opening mechanism of the LydiAs can be excluded, it must be assumed that no water from those depths is upwelling in the shaft.

Introduction
The Freiberg/Saxony mining district (Fig. 1) once belonged to the richest silver deposits in Europe (Jobst et al., 1994). In 1168 AD mining started at a small place called Christiansdorf which later became a part of Freiberg. Due to economical reasons the last mine producing in Freiberg was closed in 1969 and thereafter the uncontrolled flooding of the mine workings started. Because the deepest dewatering adit is the 128 years old Rothschönberger Stollen, all the mine water drains through that adit into a northerly direction and discharges 18 km north of Freiberg into the rivers Triebisch and Elbe. According to different sources, the total flooded mine volume is about $2\text{-}5{\cdot}10^6$ m³ (Kolitsch et al., 2001) and the discharge volume 400-1100 L s^{-1} (Weyer, 2003). Since the adit has been finished in 1877 the mine water is discharging into the Triebisch without further treatment and even after the collapse in 2002 nothing changed.
Below the flooding level, which is the Rothschönberger Stollen, there are 494 m of flooded mine workings which were driven into the polymetallic ore veins of the Erzgebirge (Oelsner, 1958). Therefore, the water penetrates through the flooded shafts, galleries, backfilled veins and open veins and gets enriched in nearly all metals of the periodic table, as can be seen from the chemical analyses (e.g. Baacke, 1999). Despite the fact that the Rothschönberger Stollen is the main drainage gallery, several other drainage galleries for isolated parts of the mine exist, there under the Königliche Verträgliche Gesellschaft Stollen and the Fürstenstollen, which dewater into the Freiberger Mulde river (Becke et al., 1986).
Though numerous studies have been conducted about the Freiberg mine waters, no comprehensive hydrogeological investigation has been done so far. This is mainly due to the fact that only a small part of the mine is accessible from the surface and underground but also due to the complicated responsibilities concerning the mine and the flooded part of the mine. This paper will describe the results of tracer tests in the mine's central shaft, conducted in 2002 and 2006.

Hydrodynamics
Some of the already existing publications gave a conceptual model of the hydrogeological situation in the flooded and the non-flooded part of the Freiberg mining district (e.g. Baacke and Degner, 2000; Fig. 2). Based on that conceptual model the authors conducted a tracer test in the Reiche Zeche Schacht in 2002 but were not able to detect any tracer, though the existing models predicted that a tracer should be found at the shafts outfall.
From a hydrodynamic point of view the existing conceptual model is impossible in that way, that water can not flow down a shaft against the hydrostatic pressure. Water always flows in the direction of the lowest hydrodynamic pressure. Furthermore, water can flow in fluid loops if the hydrodynamic situation allows fluid loops or it can flow through flooded levels in the direction of the lowest hydrodynamic pressure. Moreover, the water flow can split in one of two directions relative to the different hydrostatic pressures at each of the end-

points of the possible flows (Wolkersdorfer, 2006). Tracer tests conducted by the Hydrogeology Department of Freiberg University in other mines (e.g. Wolkersdorfer and Hasche, 2001) clearly showed that the conceptual model of the Freiberg mine needs relevant amendments. After the catastrophic flooding of the mine as a result of the heavy rainfalls in summer 2002, the mine was not accessible for repeating the tracer test until the end of 2006. This short paper will outline the results of our 2002 and 2006 tracer test in the Freiberg underground mine.

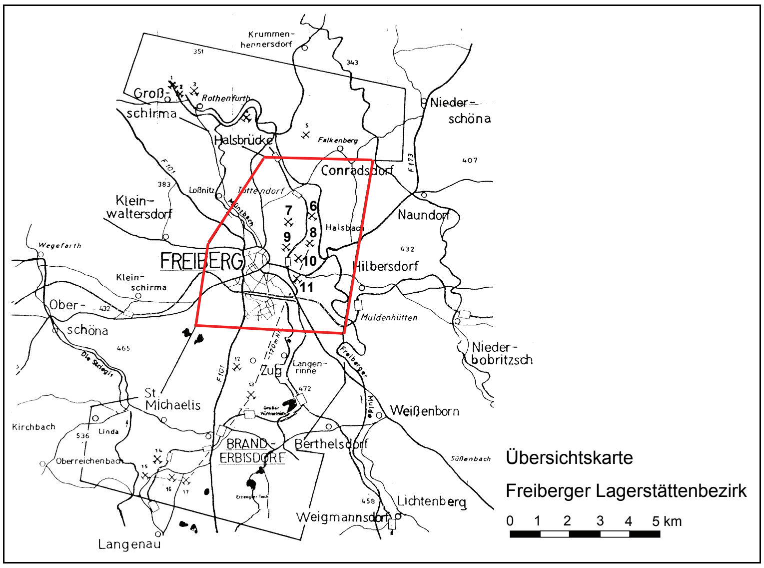

Figure 1. Overview of the Freiberg mining district (modified from Jobst et al., 1994). Shafts in the central part of the Freiberg mine: 6 Ludwig Schacht, 7 Reiche Zeche Schacht, 8 David Schacht, 9 Alt Elisabeth Schacht, 10 Abraham Schacht, 11 Thurmhof Schacht.

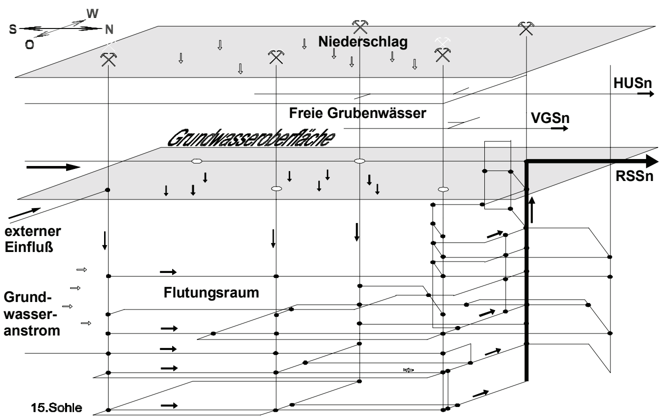

Figure 2. Obsolete conceptual hydrodynamic model of the Freiberg underground mine according to Baacke (2000).

Methods

Na-fluorescein was mixed with 2 L of tab water in the laboratory the day before the start of the tracer tests. In each case the tracer amount was calculated in that way that the tracer peak should be around 100 µg L^{-1}. Two methods, an analytical method and the software EHTD (Field, 2003) were used. To make sure that the entire tracer is diluted in the water, the bottles were shaken in an overhead mixer for 24 hours each. All bottles were cooled until the start of the tracer test and stored in a dark place to avoid decomposition of the tracer. One bottle was prepared in the same way but used for the calibration of the Na-fluorescein probe.

All tracers were injected with the LydiA probe at the predefined depths. Na-fluorescein concentrations were measured with an on-line probe and the probe cleaned from iron hydroxide coatings every 2 to 10 days. Furthermore, the flow of the water and the on-site parameters were measured regularly.

A total of five tracer tests with Na-fluorescein in four different depths were conducted in the Reiche Zeche shaft (Table 1). For the first test in 2002, at a depth of 75 m below the mine water table, 150 g of Na-fluorescein were injected and the tracer concentration measured for 17 days. No tracer could be detected during that test. The first test in 2006 was conducted 7 m above the first flooded mine galleries (level ½ 5), at a depth of 40 m with 15 g of Na-fluorescein and lasted one day during which a clear tracer peak could be measured. Tracer for the tests 2 / 2006 and 3 / 2006 were injected between the first (level ½ 5) and second (level 6) flooded mine galleries at a depth of 65 m below the mine water table. While test 2 / 2006 lasted 14 days, test 3 / 2006 was stopped after 6 days, both tests without a tracer peak. Finally, a last test was conducted between levels 11 and 12 at a depth of 324 m below the mine water table with 250 g of Na-fluorescein.

Flow measurements were conducted in three ways: salt dilution method, impeller method and with a water pressure meter. On site parameters were measured with a WTW Oximeter and Myron L Ultrameter 6P.

Table1. Data of the 4 tracer tests in 2006 and the 2002 tracer test.

Test No.	Test Name	Depth m below water surface	Volume of water m³	Amount of tracer g
1 / 2006	Tracertest 2	40	180	15
2 / 2006	Tracertest 3	65	293	20
3 / 2006	Tracertest 4	65	293	20
1 / 2002	Tracertest 1	75	338	150 ± 5
4 / 2006	Tracertest 5	324	2,500,000	250

Results and Discussion

During the tracer tests in 2006 the water flow out of the shaft into the Rothschönberger Stollen (Rothschönberg adit) ranged between 39 and 84 L s^{-1} (0.05 and 0.95 percentiles) with a mean of 62 L s^{-1} and a standard deviation of 14 L s^{-1}. Those data are in the range of outflows reported by other authors (e.g. Autorenkollektiv, 1992). Off the five tracer tests conducted so far, only one ("Tracertest 2") yielded positive results and all other tracer tests did not result in a tracer peak during the tests' duration.

At the beginning of "Tracertest 2" on May 15th 2006, a background concentration of 0.04 µg L^{-1} of Na-fluorescein could be measured which is close to the detection limit of the fluorimeter. 18 minutes after the LydiA probe released the tracer into the mine water, the tracer arrived at the fluorimeter and 44 minutes later the peak flow of the tracer ended. Yet, the background concentration was not reached another 260 minutes later which is due to the shaft installations and the wall roughness, causing also turbulent flow conditions within the shaft. Based on the tracer concentrations and the flow rate a recovery rate of roughly 80% was achieved. The maximum velocity that can be calculated from this data is 1.74 m min^{-1}, the median velocity 0.74 m min^{-1} and the velocity for the last tracer arrival 0.13 m min^{-1}. This differs significantly from velocities measured *in-situ* with down-hole probes and thermal diffusion flowmeters by Kolitsch et al. (2005) who reported only upward velocities of 1.1 – 3.5 m h^{-1} (0.02 – 0.06 m min^{-1}) under similar flow conditions. In 1988 Zittnan et al. (1990) measured the flow velocities by means of a radioactive flowmeter ranging between 0.0 and 0.5 m min^{-1} with both upward and downward flows. They are in a similar range than those derived from the tracer velocities.

All other tracer tests in the shaft were conducted below the first flooded mine galleries, which are connected to the level ½ 5. None of those tracer tests resulted in a tracer detection. Tracertest 5 was designed in that way that the amount of tracer injected should be detectable as an increase in the background concentration from 0.04 to 0.1 µg L^{-1} if a uniformly mixing in the whole mine water body ($2.5 \cdot 10^6$ m³) can be assumed. Even after 58 days no increase in the background concentration was measured by the fluorimeter.

Conclusions

Our results clearly prove that the conceptual model of the flow situation in the Reiche Zeche shaft published so far (e.g. Baacke and Degner, 2000; Baacke, 2000; Kolitsch et al., 2005) must be significantly modified. According to the 2006 tracer tests no water from levels deeper than level ½ 5 reaches the outflow of the Reiche Zeche shaft. Water below that level therefore belongs to another hydraulic regime and does not mix with water flowing on the level ½ 5. This complies with results from other tracer tests and hydrodynamic investigations (summarized in Wolkersdorfer, 2006). Tracertests 1, 3 and 4, with tracer injected between level ½ 5 and 6, clearly prove that the water in this part of the shaft is flowing downward as no tracer reaches the outfall of the shaft, a fact already observed in 1988 by Zittnan et al. (1990).

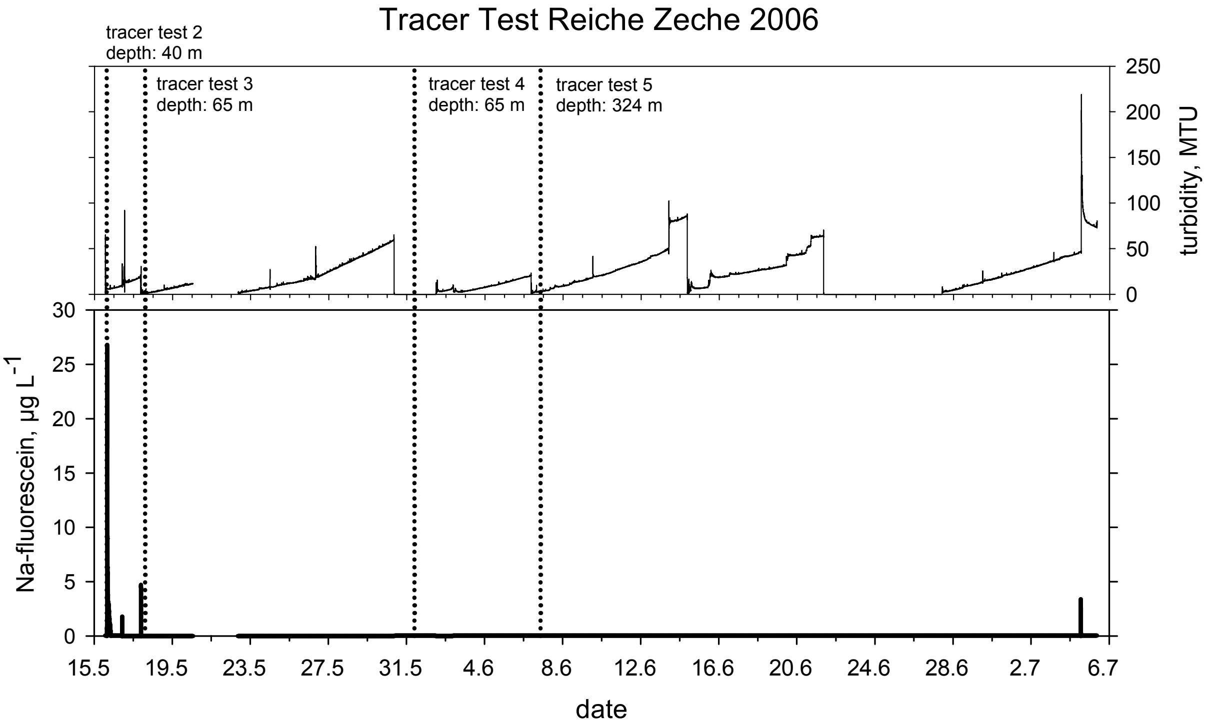

Figure 3. Results of the 4 Reiche Zeche mine water tracer tests conducted in 2006. Tracer could only be detected for the Tracertest 2.

A simplified explanation is that the water infiltrating from the upper, unflooded levels of the mine reaches the water table of the flooded mine parts. This water is usually lower mineralized than water from the deeper parts of the mine and therefore, even if this water's temperature might be lower, has a lower density than the highly mineralized water in the flooded mine parts. Therefore the water can not flow against the hydrostatic pressure into the deeper mine parts and "floats" on the water already in the mine. In the case of the Reiche Zeche shaft the infiltration water percolates through the level ½ 5, possible only in some isolated shafts or blind shafts also down to the level 6 (which is not directly connected to the Reiche Zeche shaft) and through convection loops back to level ½ 5 and to the Reiche Zeche shaft.

All the water deeper than the level ½ 5 flows either up- or downwards in the shaft or takes part on smaller or larger convection loops. It can be concluded that the deep mine water is separated from the shallower mine water and that, according to the observed stratification patterns, no mixing between the separate water bodies occurs. Most of the developments in the mine which, for example, result in the temperature equilibrium in the mine shaft, between the shallow and the deep mine water body are controlled by diffusive processes, while the flow within the mine water bodies seems to be a turbulent convective flow.

To evaluate the new conceptual model of the Freiberg underground mine it would be necessary to gain access to other flooded parts of the mine. Furthermore, the Na-fluorescein concentration should be measured at the portal of the Rothschönberger Stollen. Yet, as the tracer concentration would need to be higher than the one used in the 2002 and 2006 tracer tests, a proper calculation of the tracer amounts is essential.

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