Hydrodynamic Investigation of a Density-Stratified Underground Mine – Tracer Test Challenges and Results in the Georgi-Unterbau Mine, Tyrol, Austria

Christian Wolkersdorfer

South African Research Chair for Acid Mine Drainage Treatment, Tshwane University of Technology (TUT), Private Bag, X680, Pretoria, 0001, South Africa, christian@wolkersdorfer.info, ORCID 0000-0003-2035-1863

Abstract

Understanding hydrodynamics in stratified underground mines is critical for effective mine water management. In Tyrol's Georgi-Unterbau mine, density stratification in a subvertical shaft between levels 20 and 40 enabled the study of flow and tracer dispersion using four solid tracers and a fluorescent dye introduced at varying depths. An inclined rise connected to the shaft required adding table salt as a tracer, disrupting the delicate density layering with a 0.1–0.2 K difference. While flow paths and velocities were measured, the stratification breakdown caused by the injected brine highlighted the sensitivity of such systems. This study underscores the challenges of external interventions and provides insights for managing stratified mine water.

Keywords: Mine water tracer test, Tyrol/Austria, underground mine, density stratification, lessons learned

Introduction

Density-stratified underground mines typically discharge Mining Influenced Water (MIW) with better water quality than non-stratified mines. This is because cooler and fresher mine water is superimposed on warmer, mineralised mine water in the deeper parts of the mine. To understand the process causing this density stratification and the subsequent layering of mine water into cold fresh (CF) and warm mineralised (WM) water bodies, research in flooded underground mines is required (Mugova and Wolkersdorfer 2022). This research needs to investigate the hydrodynamics, chemistry, geochemical reactions and physico-chemical parameters in the MIW. Tracer tests in flooded mine pools are part of these investigations, as the velocity of the tracer or its flow path is an indication of the mine water hydrodynamics (Wolkersdorfer 2005). Understanding the processes that cause density stratification will allow mines or mine closure procedures to be designed to minimise the discharge of polluted MIW, as illustrated by the cases of the abandoned Metsämonttu, Finland and Urgeiriça, Portugal mines (Mugova and Wolkersdorfer 2022, 2024). In these mines, the highly mineralised mine water in the WM water body is overlaid by the better water quality of the CF layer, which ultimately discharges into the receiving water courses.

Initial measurements of temperature and electrical conductivity (EC) in the 100 m deep sub-vertical shaft ("Blindschacht") of the Austrian Georgi-Unterbau mine showed stable stratification at the three working levels connected to the shaft (Unger 2002; Wackwitz 2002). This was indicated by a temperature jump of 0.1 to 0.2 K of the 8.5–8.6 °C warm, circum neutral MIW and a more or less constant EC of 280 to 340 µS/cm (Wolkersdorfer et al. 2002). The persistence of this density stratification over a three-month period prompted an investigation of the stratification. This included measurements of temperature and EC, water chemistry and a multi-tracer test using microspheres, a fluorescent dye and a water-soluble salt. The injection locations of the various artificial tracers were determined during preliminary investigations of the 38,200 m^3 mine pool, where six locations were identified for the injection of microspheres and uranine.

During the preparation of the multi-tracer test, a rise (possibly an ore chute) from level 20 to the level of the Georgi-Unterbau was discovered. This was overseen in the pre-investigation as it was not mapped in the digital map provided, but was later identified in supplement 30 of Krischker (1990). An additional tracer, sodium chloride (NaCl), was to be injected into this rise to determine its role in the density stratification. This additional tracer, which had not been considered during the planning phase of the survey, ultimately made part of the results difficult to interpret.

This paper describes the results of the August 2001 multi-tracer test in the Austrian Georgi-Unterbau mine and the implications of the incorrectly injected uranine and NaCl tracers. It will describe the characteristics of the used tracers and the local conditions encountered during the tracer tests.

Location and Investigation

The Georgi-Unterbau is an access adit to the Großkogl mine ("Bergbau Großkogl") in the Brixlegg mining district, which mined for fahlore (silver, copper) and barite within the Reither Kogel mountain range east of St. Gertraudi in the Austrian Inntal valley. It is 38 km ENE of Innsbruck and geologically dominated by the Devonian Schwazer Dolomit of the Oberalpin (Zentralostalpin) Grauwackenzone (Pirkl 1961; Schmidegg 1953; Schönlaub 1980). Mining in this Kogel complex dates back to the 19th century when the Georgi-Unterbau adit was started in 1887, and the sub-vertical shaft therein was sunk after 1900. After baryte mining until 1968 (Hanneberg and Schuster 1994; Mutschlechner 1984) the operations temporarily closed ("gefristet"). At the time of the author's investigations, the sub-vertical shaft had been flooded since at least 1990 (pers. comm. Peter Gstrein, 2001), meaning that the hydraulic system had been in equilibrium (stationary conditions) for at least a decade at the time of the tracer test. In 2021 the shaft was dewatered down to level 40 for research purposes (pers. comm. Armin Hanneberg, 2025). To reach the sub-vertical shaft ("Blindschacht"), a 320 m long adit had to be followed. The shaft itself is a 100 m deep two-compartment shaft connected to levels 20, 40, 70 and 100 of the mine (Fig. 1)

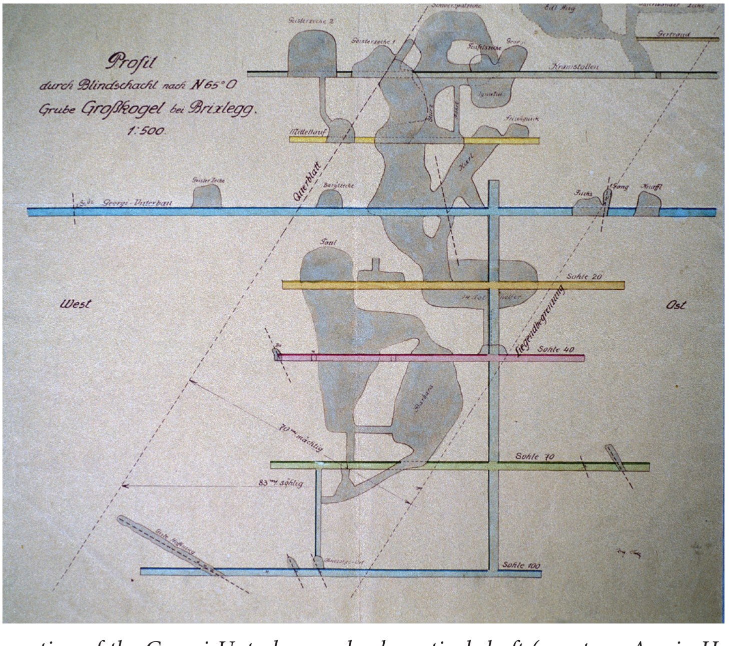

Figure 1 *Cross section of the Georgi-Unterbau and sub-vertical shaft (courtesy: Armin Hanneberg; from former Berghauptmannschaft Innsbruck, today Montanbehörde; IRIS register MB 30205).*

with a cross-sectional area of 6.23 m². Other hydraulic connections exist with the older workings of the "14 Nothelfer" and "Barbara" pits, an ore shoot and the "Large" and "Small" lakes (the latter resulting from the connection of the two aforementioned pits with the "Schwerspat" pit). Prior to the start of the tracer test, the temperature and EC within the shaft were measured using a 6-parameter borehole probe (DL1-512, Login Gommern GmbH, Gommern, Germany), and 12 mine water samples were taken within the shaft and its underground surroundings. These samples were analysed for major ions (unfiltered and unacidified samples) and trace elements (0.45 µm filtered and acidified samples). At all sites, temperature, pH, EC, redox and oxygen concentrations were measured in situ with an Ultrameter 6P (MyronL Company, Karlsbad, USA) and an OxiCal SL oxygen probe connected to a WTW Multiline P4 (WTW Weilheim, Germany).

Three different tracer classes were used to investigate the hydrodynamic and stratification conditions of the mine: a fluorescent dye (uranine, CAS 518-47-8), particle tracers (15 µm fluorescent microspheres, FluoSpheres, Triton Technology, San Diego, USA) and a water-soluble salt (sodium chloride, NaCl, CAS 7647-14-5; animal food grade: 98.3% NaCl, 1.2% SO_4, 0.47% Ca, 0.03% Mg). All of them are considered ecologically safe (Behrens et al. 2001). For the tracer test in August 2001, 900 g of uranine powder were filled into a LydiA injection probe (Wolkersdorfer et al. 1997), 4 times 20 mL of microspheres (yellow, orange, red, green, $1 \cdot 10^6$ per colour) into three LydiAs as well as the large lake and 200 kg of NaCl (dissolved in 600 L of mine water) directly into the rise. These tracers were injected on 5 August 2001 between 8:02 and 10:10 o'clock using the LydiAs (10, 30 and 85 m below surface for microspheres, 55 m below surface for uranine), green microspheres into the large lake and pouring the NaCl solution via Dirac injection (300 g/L, 68 minutes injection time to avoid immediate disturbance of the stratification) into their respective injection locations.

Microspheres were collected from the mine water using a specially designed filter set, uranine was measured photometrically (HACH DR/2500 Scanning Spectrophotometer, Loveland CO, USA) at a wavelength of 489 nm (experimentally determined), and NaCl was measured with an EC probe at a depth of 0.66 m below the shaft water surface (DL1-512, Login Gommern GmbH, Gommern, Germany). Additionally, measurements were taken down the shaft before and after the tracer test. Two Pleuger Worthington mini submersible pumps were used to extract the mine water from a depth of 10 cm in the sub-vertical shaft. The flow from the shaft to the dewatering gully was measured every ≈ 11 h with a calibrated V-notch weir, as were the pumping rates through the photometer and the microsphere filter sets (volumetric method, every ≈ 47 h).

Results

The flow rate of mine water leaving the shaft increased from 9.8 to 31.4 L/min (average 22.3 L/min, error range 7%) during the 16-day tracer test. The pump rate for the microsphere filters was 0.26 L/min and the photometer 0.04 L/min (error range 1–3%). This increased flow rate from the shaft was due to three intense rain events with a cumulative rainfall of 103.1 mm (meteorological station Rotholz, 5 km W of mine adit) during the tracer test (August 4, August 9 and August 16). The filtered water totalled 4.57 m³ and the water flowing through the photometer was 0.84 m³, compared to 511.41 m³ discharged from the shaft during the tracer test.

All three tracer classes were detected at the shaft outlet, but at substantially different concentrations and satisfaction. The LydiA filled with 900 g of uranine powder was only partially opened, resulting in average uranine concentrations between 50 and 100 µg/L at the shaft outlet (theoretically a concentration of 1.4 mg/L would have been expected). Measurement of the uranine concentration at 10 m intervals along the first 90 m of the shaft showed that the uranine is close to a Gaussian normal distribution around the injection point at 55 m, with a maximum concentration of 563 µg/L at the injection point (curve fitting showed that the distribution is closer to a Weibull distribution with r^2 = 0.956, but as the number of data points is small, the simpler Gaussian distribution with r^2 = 0.946 describes the data well enough; in both cases

$p < 0.0005$). This result corresponds to 109 to 114 g of uranine being released into the shaft (12% release rate). When the LydiA injection probe was lifted, the reason for the low uranine concentration at the photometer and in the shaft, and hence the very low recovery rate, became clear: the two halves of the probe were stuck together because the uranine had agglutinated as soon as the shaft water entered the partially opened LydiA probe. It took a chisel and hammer to remove the uranine block from the probe (≈ 870 g of uranine were recovered this way, but it was not possible to fully dry the block even after five months).

Despite this negative result, the uranine tracer distribution in the shaft allowed the calculation of a longitudinal dispersion coefficient D_L of 0.015 m^2/min and an effective velocity of 0.009 m/min (Tab. 1). These data give a Peclet number Pe ≈ 34, indicating advective flow of the tracer (diffusive flow was assumed in previous reports, but a recalculation updated this assumption). In the time between tracer injection and shaft measurement, approximately 220 m^3 of water flowed past the probe, which is about half of the outflow at the shaft. If this water would have come predominantly from below the level 40, the tracer would not have shown a Gauss distribution around the injection location, but an upward skewed distribution, indicating an upward flow. Yet, the tracer distribution is indicative of convective upward and downward flow of the MIW in the section of the tracer injection. This could be proven by a numerical model with ANSYS FLOWTRAN which showed low flow between levels 40 and 70 but upward advective flow above level 40 (Unger 2002).

Microspheres were injected at four locations: three in the shaft at 10, 30 and 85 m depth and into the large lake. Only microspheres from the large lake and 10 m depth could be identified during the tracer test. Considering the result of the uranine test, which calculated the time from 55 m depth to the discharge to be 100 h, it would have been expected that the microspheres from the 30 m injection point would also have been found. However, combined with the microspheres from 10 m depth, which arrived 10 days after injection, it may be that the sampling time was too short, and the tracers injected below 10 m depth were not detected. This also means that the tracers from the 85 level did not arrive during the sampling period. Similarly to the uranine tracer, the green microspheres from the large lake had a mean effective velocity of 0.017 m/min with a D_L of 0.016 m/min.

The results for the NaCl tracer were disappointing, as the increase in EC at the shaft outlet was not as high as expected. Assuming equal dilution of the salt in the 623 m^3 of shaft water, an increase in EC of 580 ± 30 µS/cm would have been expected. Yet, the EC increased by 71 ± 1 µS/cm, which relates to a flow based NaCl discharge of 3.9 ± 0.2 kg, representing a recovery rate of 1.9 ± 0.2%. Depth dependent measurements of EC, Na, Cl and Ca showed a statistically significant increase in these chemical parameters with depth. Electrical conductivity at 90 m increased from 410 to 449 µS/cm, Na from 0.7 to 15 mg/L, Cl from < 0.7 to 20 mg/L and Ca from 60 to 65 mg/L. This result indicates that the high density NaCl brine (ρ ≈ 1.18 g/L) sank to the deeper parts of the shaft and did not mix uniformly with the MIW therein.

Two measurements of on-site parameters in the shaft after tracer injection showed that the initial stratification which the project was designed to investigate had broken down. Instead of two layers before NaCl injection, there were three distinct water bodies with different average EC values of ≈ 360, 390 and 470 µS/cm. They were separated by levels 40 and 70, confirming the flow conditions previously identified and used in the numerical modelling.

During the tracer test in February 2002, the on-site and chemical parameters were analysed again. It was shown that the Cl concentration was still higher than before the NaCl injection, but substantially lower than immediately after the 2001 tracer test. Before the injection it averaged ± 1 mg/L, after the test 20 mg/L at a depth of 90 m and 5 mg/L at 55 m, all other sites had pre-injection concentrations. In 2002, five months after injection, all eight sampling points in the shaft and the three lakes were around 4 mg/L, showing (1) that the stratification had broken down and (2) that the accessible MIW appears to be well mixed and to be rising from deeper parts of the mine to the shaft surface.

Discussion and Conclusions

Based on preliminary measurements in the sub-vertical Georgi-Unterbau, a stable mine water stratification with a temperature difference of 0.1–0.2 K was observed. The aim of the 2001 tracer test was to investigate the reasons for this stratification and the hydrodynamics in this flooded Großkogl underground mine. The conceptual model before the tracer test assumed a stable stratification at level 40 with flow from the "Schwerspat" pit into the "14 Nothelfer" pit and from there via level 40 into the sub-vertical shaft. Below level 40, convective, possibly free flow driven by the geothermal gradient through the shaft and the Barbara pit was assumed (Fig. 1 has geometric details). To verify the conceptual model, a multi-tracer test was carried out in 2001 using uranine, microspheres and rock salt (NaCl).

It was shown that the conceptual model had to be adjusted and that the tracer test design had three weaknesses that rendered the tracer test partially unusable, which are described here:

1. The mass for the uranine tracer was not only too high, but the injection method was also inappropriate. Assuming a uniform dilution of uranine in the 623 m³ of shaft water, the concentration would have been 1.4 mg/L, well above the visibility limit of 10 to 100 µg/L. A yellow to greenish plume would most likely have been visible for several kilometres in the receiving water courses of the Geyerbach and Inn rivers. Therefore, it was ultimately a favourable situation for tracer design weakness 2. to occur. Also the assumption that the tracer would spread into the whole mine pool and the uranine concentration being 23 µg/L was, under the given hydrodynamic circumstances, wrong.
2. The uranine was injected as a powder into the LydiA injection probe. Water was allowed to slowly seep into the probe at a depth of 55 m before the tracer was released. This probe was completely filled with the uranine and therefore the water seeping into the probe did not find enough pore volume to dissolve the tracer, causing the uranine to clump. This procedure contradicts most of the recommendations in tracer testing guidelines to dissolve the powder before injecting it into the water course (e.g. Benischke et al. 2007). Why this recommendation was not followed in the tracer test design could not be determined anymore at the time of the first evaluation and article in 2002 (Wolkersdorfer et al. 2002).
3. The application of an almost saturated NaCl solution with a density of 1.18 g/L directly into a slightly stratified system caused a rapid breakdown of the initial stratification. This resulted in a newly stratified system where the density of each new layer overprinted the initial conditions.

Although the 2001 tracer test failed in verifying the initial conceptual model, it was possible to use the results to interpret the hydraulics in the Georgi-Unterbau (Tab. 1). However, the conclusions – and they are not new *per se* – are that the tracer masses must be carefully selected based on the real situation, for example using the EHTD code (Field 2003). This code gave good results in all tracer tests subsequently carried out by the author. In addition, water-soluble tracers must always be dissolved before the tracer

Table 1 *Effective velocities of the MIW in the sub-vertical shaft of the Georgi-Unterbau based on various evaluation methods.*

Test Conditions	$\bar{v}$, m/min	v_{max}, m/min	D_L, m²/min
Model set 1	0.008	0.017	–
Model set 3	0.029	0.058	–
Uranine 2001, 55 m	0.009	–	–
green Microspheres 2001, 20 m	0.017	0.024	0.016
Uranine 2002, 10 m	0.049	0.078	0.07
Average	0.022	0.044	–

test and mixed outside the test area to avoid contamination. Finally, when using saturated brine, it is essential that it does not sink into areas where it could become trapped or negatively affect the initial conditions of the mine. In the author's other tracer tests using saturated brine, the injection points were chosen so that the brine could flow into the mine workings without affecting the system or hydrodynamics too much.

Acknowledgements

The investigations described were carried out by Thomas Wackwitz and Kati Unger. Access to the underground mines was provided by Montanwerke Brixlegg (Robert Stibich) and accommodation as well as logistical support during the tracer tests by "Team 2000" (now: "Bergbau Aktiv Team"). Thanks to Armin Hanneberg for his continuous support and excellent historical information. Additional support was provided by Gerold Sturmmeier, Andrea Hasche, Andreas Hechenblaikner, Leopold Weber and Erwin Schinner. Part of the project was financed through the EU project PIRAMID (EVK1-CT-1999-00021).

References

Behrens H, Beims U, Dieter H, Dietze G, Eikmann T, Grummt T, Hanisch H, Henseling H, Käß W, Kerndorff H, Leibundgut C, Müller-Wegener U, Rönnefahrt I, Scharenberg B, Schleyer R, Schloz W, Tilkes F (2001) Toxicological and ecotoxicological assessment of water tracers. Hydrogeol J 9(3):321–325. https://doi.org/10.1007/s100400100126

Benischke R, Goldscheider N, Smart C (2007) Tracer techniques. In: Goldscheider N, Drew DP (eds) Methods in Karst Hydrogeology. Taylor & Francis, London, p 147–170. https://doi.org/10.1201/9781482266023

Field MS (2003) Tracer-Test Planning Using the Efficient Hydrologic Tracer-Test Design (EHTD) Program. vol EPA/600/R-03/034. U.S. Environmental Protection Agency – Office of Research and Development; National Center for Environmental Assessment, Washington

Hanneberg A, Schuster H (1994) Geschichte des Bergbaus in Schwaz und Brixlegg. Mineralien Magazin, Lapis 19(7-8):13–21

Krischker GA (1990) Die Baryt-Fahlerz-Lagerstätte St. Gertraudi/Brixlegg. Unveröff. Dipl.-Arb. Univ. Innsbruck, Innsbruck

Mugova E, Wolkersdorfer C (2022) Density Stratification and Double-Diffusive Convection in Mine Pools of Flooded Underground Mines – A Review. Water Res 214:118033. https://doi.org/10.1016/j.watres.2021.118033

Mugova E, Wolkersdorfer C (2024) Advancing sustainable mine water management through understanding stratification in flooded underground mines. Paper presented at the West Virginia Mine Drainage Task Force Symposium & 15th International Mine Water Association Congress, Morgantown, WV, USA:471–472.

Mutschlechner G (1984) Erzbergbau und Bergwesen im Berggericht Rattenberg. Eigenverlag Gemeinden Alpbach Brixlegg Rattenberg und Reith im Alpbachtal, Innsbruck

Pirkl H (1961) Geologie des Trias-Streifens und des Schwazer Dolomits südlich des Inn zwischen Schwaz und Wörgl (Tirol). Jb Geol B-A 104(1):1–150

Schmidegg O (1953) Die Erzlagerstätten am Reiter Kopf und am Reiter Kogel. Schlern-Schr 101:17–25

Schönlaub HP (1980) Die Grauwackenzone. In: Oberhauser R (ed) Der geologische Aufbau Österreichs. Springer, Wien, p 265–289. https://doi.org/10.1007/978-3-7091-3744-4_16

Uerpmann E-P (1980) Hydrogeologische Fragen bei der Endlagerung radioaktiver Abfälle. Unveröff. Diss. TU Clausthal, Clausthal-Zellerfeld

Unger K (2002) Hydrodynamische Verhältnisse im gefluteten Unterbau des Bergwerks Großkogel/Tirol – Numerische Modellierung mit ANSYS-FLOTRAN [Hydrodynamic conditions in the flooded substructure of the Großkogel mine/Tyrol – Numerical modelling with ANSYS-FLOTRAN]. Unveröff. Dipl.-Arb. TU Bergakademie Freiberg, Freiberg

Wackwitz T (2002) Multitracerversuch im gefluteten Blindschacht des Bergwerks Großkogel/Tirol: Vorbereitung, Durchführung und GIS unterstützte Auswertung [Multitracer test in the flooded subvertical shaft of the Großkogel mine/Tyrol: preparation, implementation and GIS-supported evaluation]. Unveröff. Dipl.-Arb. TU Bergakademie Freiberg, Freiberg

Wolkersdorfer C (2005) Tracer Tests as a Mean of Remediation Procedures in Mines. In: Merkel BJ, Hasche-Berger A (eds) Uranium in the Environment. Springer, Heidelberg, p 817–822. https://doi.org/10.1007/3-540-28367-6_84

Wolkersdorfer C (2006) Acid Mine Drainage Tracer Tests. ICARD 2006. vol 7. Proceedings 7th International Conference on Acid Rock Drainage (ICARD), St. Louis, p 2490–2501 [CD-ROM]. https://doi.org/10.21000/JASMR06022490

Wolkersdorfer C, Hasche A, Unger K, Wackwitz T (2002) Tracer Techniken im Bergbau – Georgi-Unterbau bei Brixlegg/Tirol. Wiss Mitt Inst Geol 19:37–43

Wolkersdorfer C, Trebušak I, Feldtner N (1997) Development of a Tracer Test in a flooded Uranium Mine using Lycopodium clavatum. In: Kranjc A (ed) Tracer Hydrology 97 – International Symposium of Underground Water Tracing. vol 7. Balkema, Rotterdam, p 377–385. https://doi.org/10.1201/9781003078142-62