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MONITORING OF FLOODED UNDERGROUND MINES – USING MINE DRAINAGE DENSITY STRATIFICATION AS AN EXAMPLE

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ABSTRACT

Geochemical and hydrodynamic processes in acid and circumneutral mine drainage that occur during and after underground mine flooding have not been fully understood so far. While there are often physico-chemical data of the discharged mine drainage available, there are rarely data on the underground mine pool itself. Typically, the discharged mine drainage quality or the water in the upper part of the mine pool, specifically the shaft, differs from the quality of the mine drainage at greater depths. This fact is important, for example, if highly acidic mine drainage is encountered in deeper parts of the mine, if a geothermal use, or mine drainage pumping is envisioned. In this assessment of several decades of own investigations and literature data, a comprehensive synopsis of density stratification in flooded underground mines will be given. Methods to investigate the entire mine pool with pH values sometimes as low as 2 include depth profile measurements using depth-dependent sampling, camera surveys and tracer tests. In general, the parameters temperature and electrical conductivity are relevant for depth profile measurements, as they are indicators for density stratification. This study used these parameters to identify and discuss the occurrence of density stratification in flooded underground mines.

Keywords: Stratification, Layering, Mine water, Underground mine, Flooding

1.0 INTRODUCTION

After the closure of an underground mine, mine water usually discharges from the mine, having very low pH values in some instances (Wolkersdorfer 2008; Younger et al. 2002). However, it is often not known that the water quality at the discharge point differs from the rest of the mine pool. With suitable monitoring methods, such as depth profile measurements, the mine pool can be examined over the entire depth. In most cases, a density stratification can be detected in the mine pool, meaning that there are water bodies with different physical and chemical properties. The occurrence of stratification has for example, recently been of relevance at the abandoned mines in Witwatersrand, South Africa. If stratification is present, the need for mine water treatment can be reduced or even omitted (Mugova and Wolkersdorfer 2022).

Preferably, in order to harness the potential benefits of stratification, monitoring of the mine pool should already take place during the flooding process. If stratification can be observed during flooding, measures can be taken to prevent it from being disrupted. First stratification investigations in flooded underground mines date back to the 1960s. In a mine that had already been flooded, water samples were taken from different depths using buckets (Stuart and Simpson 1961). At greater depths, lower pH values were detected. First precise measurements of density stratification were carried out by Uerpmann in 1980 (Uerpmann 1980). He measured a depth profile over 300 m in 1 m steps. In the early 1990s, Wolkersdorfer investigated the flooding process of the former WISMUT company uranium mines in Niederschlema-Alberoda, Germany through depth profile measurements of temperature and electrical conductivity (Wolkersdorfer 1996). These measurements continue to be carried out by the WISMUT company long after flooding has been completed. This long-term monitoring allows good insight on any changes in the water quality in the flooded mine pools.

2.0 METHODOLOGY

2.1 Depth dependant measurements with down-hole probes and depth samplers

Down-hole probes or dippers are most used to record depth profiles (Coldewey et al. 1999; Cutright 1979; Czolbe et al. 1992; Ladwig et al. 1984; Melchers et al. 2019). Thereby, the parameters temperature and electrical conductivity are recorded over depth at small intervals. If sudden parameter changes occur in the profile, this is an indication that stratification is present. When there is a jump from one water body to another, the temperature, electrical conductivity or both suddenly rise or fall sharply. An intermediate layer separates the water bodies from each other.

Water samples should be taken from different depths only after the depth profile measurement has been conducted. This order of procedure is important, as the depth profile must be recorded without prior interference (Mugova and Wolkersdorfer 2022). Suitable for this purpose are special depth samplers, such as Kemmerer point samplers (Bao 2018; Snyder 2012), Van Dorn plastic point samplers (Snyder 2012), ball-valve operated samplers (Coldewey et al. 1999; Gzyl and Banks 2007; Snyder 2012), Ruttner samplers (Chudy et al. 2020; Uerpmann 1980; Wieber et al. 2016) or bailers, like point-source bailers (Toran 1987).

Ideally, the measurements should be repeated over several months or years in order to more accurately interpret the behaviour of the stratification (Mugova and Wolkersdorfer 2022). In addition, the first flush can be observed from the repeated depth profile measurements, providing further information about the improvement in water quality over time during and after flooding.

2.2 Use of shaft cameras

High-resolution shaft cameras equipped with powerful lamps provide detailed insights while investigating and monitoring flooded underground mines and can reveal stratification. In many cases, water bodies can be distinguished from each other by differences in turbidity (Figure 1) (Stemke et al. 2017). In addition, particle flow can be observed on the camera recordings. Research has been carried out to determine the flow direction and flow velocity through particle flow.

Fig. 20: Stratification in a flooded underground mine taken with a shaft camera. The camera is just slightly below the transition from a murky to clear water (courtesy: Thorsten Gökpinar; image optimized with colour and contrast enhancement, image width ≈ 1 m; from Mugova and Wolkersdorfer 2022).

Another innovation is the development of underwater robots, which autonomously explore the flooded mines. These are equipped with cameras, as well as other measuring devices such as scanners, temperature and pressure sensors, and allow access to areas which can no longer be reached with traditional measuring devices and cameras attached to ropes. One underwater robot initiative is part of the EU project UNEXMIN (Fernandez et al. 2019; Žibret and Žebre 2018).

2.3 Tracer test to identify stratification

Tracer tests are commonly used in flooded underground mines to identify flow paths and flow velocities. For instance, drift tracers like microspheres, dyed spores (Wolkersdorfer 1996) or fluorescent dyes such as Na-fluorescein (Wolkersdorfer 2008) can be used.

Research is in progress to determine whether tracer tests using fluorescent dyes could also be used to detect stratification within a mine. Since stratification has a barrier effect, there is hardly any exchange between the water bodies. Hence, the tracer does not permeate through the intermediate layer which is the boundary between two water bodies. With use of special depth fluorometers, such as those used in cave research, the stratification can be detected, in a similar manner to the depth profile measurement with down-hole probes.

3.0 RESULTS AND DISCUSSION

Upon the authors having carried out depth profile measurements themselves, as well as having evaluated literature covering more than 60 mines worldwide (Table 1), it was determined that both AMD and other mining influenced water in flooded underground mines are generally stratified (Mugova and Wolkersdorfer 2022). Usually, an upper water body (CF, cold/fresh water body) with a relatively better water quality and one or several lower water bodies (WM, warm/mineralized water body) with relatively poorer quality resulting from (di-)sulfide weathering are present. In most cases, mine water that drains from the point of discharge has a much better quality than mine water at greater depths. Meaning mine water treatment can be reduced or is not necessary at all if a stable density stratification is maintained. Such is the case at the former Portuguese Urgeiriça uranium mine (Figure 2). Due to the stable stratification, a highly mineralized deeper water body (WM water body) and a much less mineralized upper water body (CF water body) exist. Only the water from the upper water body discharges and can be treated passively. Without such stratification, passive treatment would not be possible due to poor discharge water quality.

Tab. 1: Selection of flooded underground mines investigated on density stratification

mine	***shaft***	***commodities***	***country***	***stratification***
Felsendome Rabenstein	Maschinen Schacht (Maschinen shaft)	limestone	Germany	yes
Friedlicher Nachbar	Schacht 2 (shaft 2)	coal	Germany	yes
Georgi Unterbau	Blindschacht (blind shaft)	ore	Austria	yes
Groverake	No 2 shaft	ore	Great Britan	yes
Grube Georg	Schacht 2 (Schaft II)	ore	Germany	yes
Grube Meggen	Sicilia Schacht (Sicilia shaft)	ore	Germany	yes
Grube Merkur	Weidtmann-Schacht (Weidtmann shaft)	ore	Germany	yes
Grube Stahlberg	Schacht II (shaft II)	ore	Germany	yes
Grube Velsen	Gustav 2 (Gustav 2 shaft)	coal	Germany	yes
Hancock Mine	Shaft 2	ore	USA	yes
Leopold-Louise	Otto-Wolff Schacht (Otto-Wolff shaft)	ore	Germany	no
Metsämontu	MS2 shaft	ore	Finland	yes
Metsämontu	MSD shaft	ore	Finland	yes
Nikolaus-Bader-Schacht	Nikolaus-Bader-Schacht	ore	Austria	yes
Rosice-Oslavany coal basin	Jindřich II (Jindřich II shaft)	coal	Czech Republic	yes
Rosice-Oslavany coal basin	Kukla	coal	Czech Republic	yes
Roudný	Aleška (Aleška shaft)	ore	Czech Republic	yes
San Vicente	Pozo El Entrego (El Entrgo shaft)	coal	Spain	yes
San Vicente	Pozo El Sorriego (El Sorriego shaft)	coal	Spain	maybe 2008
Siège Simon	Simon 5 (Simon 5 shaft)	coal	France	yes
Grube Straßberg	Flourschacht (Flour shaft)	ore	Germany	yes
Grube Straßberg	Ü539	ore	Germany	yes
Urgeiriça mine	St Babara (St Babara shaft)	ore	Portugal	yes
Vouters mine	Vouters 2 (Vouters 2 shaft)	coal	France	yes

West Rand	Shaft No 8	ore	South Africa	yes
Zeche Glückaufsegen	Glückaufsegen 3 (Glückaufsegen 3 shaft)	coal	Germany	yes
Zeche Hermann	Hermann 1 (Hermann 1 shaft)	coal	Germany	yes
Zeche Hermann	Hermann 2 (Hermann 2 shaft)	coal	Germany	yes
Felsendome Rabenstein	Maschinen Schacht (Maschinen shaft)	limestone	Germany	not clear

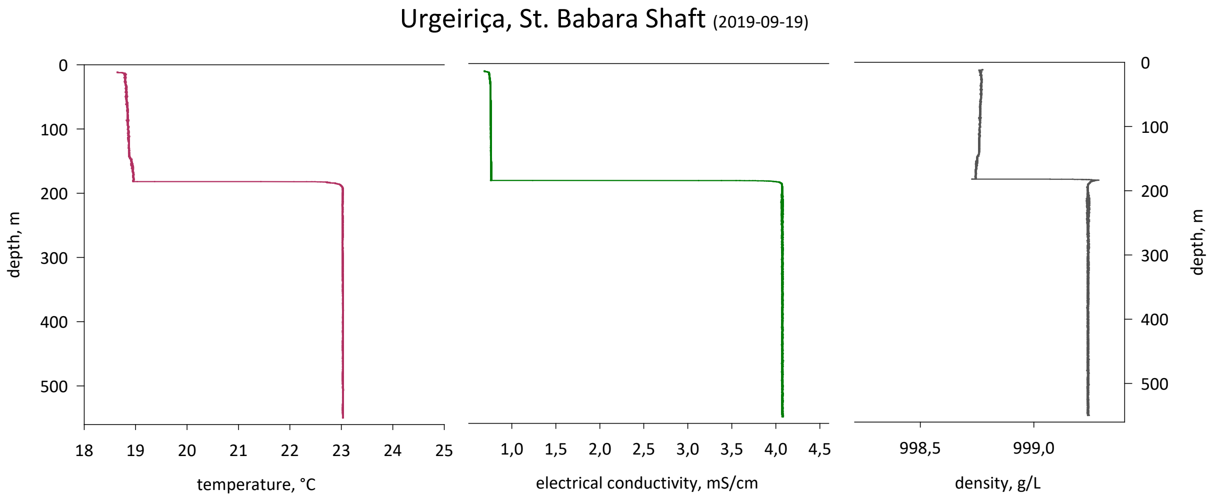

Fig. 21: Depth profile of St. Barbara Shaft at the Urgeiriça Mine, Portugal; temperature and electrical conductivity measured, density calculated with the UNESCO formula (Fofonoff and Millard Jr 1983)

4.0 CONCLUSIONS

Investigations on stratification in flooded underground mines have shown, that it is of great importance not only to bear the composition of the discharging mine water in mind, but also to understand the water chemistry in the underground mine pool. Where stratification is present, which is the case in the majority of flooded underground mines worldwide, only the water from the upper water body will discharge with better quality instead of water with lower quality and sometimes low pH values caused by (di-)sulfide oxidation. When stratification collapses, for whatever reason, severe quality deteriorations of the mine water will usually occur, sometimes resulting in AMD discharges into receiving water courses. This possibility is particularly of relevance when pumps are envisioned for mine water geothermal applications. Should the distance between the intermediate layer (boundary between two water bodies) and the pump not be considered adequately, the stratification may break down and the discharged water quality may worsen. Therefore, it is of utmost importance to investigate the mine water body over its entire depth before interfering with the hydraulic system of a flooded underground mine. Existing stratification should not be destroyed, to ensure the stratified mine pool remains intact.

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