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Understanding the influence of stratification for mine water management: a comparative study

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Managing mine water in the best possible way is of great importance and depends on various factors like environmental protection, regulatory compliance and human health. To understand the complex chemical and hydrodynamic processes within the mine pool, it is critical to establish effective practices and management strategies. This study focuses on the characterisation of hydrodynamic processes affecting flooded underground mines, emphasising the importance of density stratification. The investigation of 29 ore and coal mine shafts and their corresponding physico-chemical depth profile measurements was aimed to compare the profiles with each other, while also taking into account the shaft geometry and the layout of the mine. Finding cross-links between the profiles, which allow universal statements on stratification in flooded underground mines, was the main objective. Results of this study indicate that stratification occurs in almost all flooded underground mines, and the uppermost stratified water body is usually located in the area of the first or second connected level. Furthermore, stratification is often responsible for considerably better quality of the uppermost water body. Hence, stratification is fundamental to mine water management and has a direct influence on the quality of the discharged water. This knowledge is invaluable in developing strategies to optimise mine closure, mine water management, treatment planning and future mine layouts.

Keywords Mine water, Flooding, Mine water rebound, Mine water management, Density stratification

Motivation and scope

After mine closure and the termination of all extraction work as well as pumping activity, underground mines are usually allowed to flood. After the mine water gradually filled the mine workings, it will eventually reach the hydraulically lowest point of the mine and discharge into receiving water courses like streams or lakes. As the discharged mine water can be polluted it might cause (semi)-metal contamination and acidification. Consequently, this can lead to a deterioration in water quality, which might have a negative influence on the aquatic ecosystem in the discharge area and downstream[1,2]. When stratification occurs in a flooded mine, meaning the separation of different water bodies without a considerable exchange between them, the discharged water is usually fed from the uppermost water body with better quality and the negative influence of deep, higher mineralised water at the discharge point is lower. However, if stratification collapses, for example due to pumping activities, in most cases the water quality at the discharge point deteriorates due to forced upward flow of deep mineralised mine water. In order to understand the development of water quality in flooded mines, but also the potential deterioration due to interventions in the hydrodynamic system, it is of major importance to examine and better understand mine water density stratification. On the one hand, this concerns mine water management, specifically pumping operations for dewatering. On the other hand, it also applies to the possible application of geothermal exploitation.

This paper´s scope includes a comparison of 29 shafts with the corresponding depth profiles of temperature and electrical conductivity. Through the comparison, it is intended to find features that are characteristic for the occurrence of stratification and which can be transferred to flooded mines in general. The aim is to create awareness of stratification in flooded underground mines by using the various examples, as well as consider density stratification in mine water management.

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Density stratification in flooded underground mines

Water bodies with different densities and temperatures can be identified not only in lakes[3–6], but also in flooded underground mines[7]. An intermediate layer usually separates water bodies with different physico-chemical properties, whereby in most cases a colder water body with better water quality (CF water body, cold freshwater) overlies a WM (warm mineralized) water body with restricted mass and energy exchange between the different water bodies. Density stratification in flooded underground mines occurs in all types of mines and has been studied since the early 1960s. First investigations originate from the USA, carried out by Stuart and Simpson[8], who discovered "the presence of layering of the acid water" and in Germany by Semmler[9]. The latter describes a temporal stratification due to freshwater injection. Research by Cairney and Frost[10], Cutright[11] and Sanders & Thomas Inc.[12] continued to study stratification in flooded underground mines in the UK and USA in the 1970s. Uerpmann[13] carried out stratification experiments with dyes, described convection cells and the barrier effect between two water bodies, both in real mines and laboratory studies. Ladwig, et al.[14] used downhole probes for shaft profiles as well as sampling water in the mine pools and concluded that higher mineralised water accumulates deeper in the mine. In 1989, Herbert[15] undertook an extensive study at the Hope salt mine in Germany to identify stratification and to investigate turbulent flow conditions in the flooded shafts. In the 1990s and 2000s, first results were published about modelling stratification in flooded underground mines[16–19] and the application of tracer tests to investigate stratification[20]. More recent research has focused on geothermal applications[21–24], the barrier function of stratification[25–30] and stratification investigation in laboratory scale[31]. Mugova and Wolkersdorfer[7] published a review paper about stratification in flooded underground mines. Coldewey, et al.[32] carried out a comparison of several depth profile measurements and stratification therein and described the formation of the individual water bodies, which differ from each other in their physicochemical properties (especially temperature and mineralisation). Through the different examples, they could show that stratification occurs in both steady-state and unsteady systems, i.e. in mines that are already flooded, but also in mines that are still being flooded. Coldewey, et al.[32] also emphasised that stratification occurs preferentially at on-setting stations and emphasized the barrier effect that stratification can have.

However, the majority of investigations about stratification in flooded underground mines refer to individual mines or shafts. So far, comprehensive comparative studies are missing in the literature, although understanding stratification in flooded underground mines is important, as knowledge about it may ensure much better water quality (lower mineralised water) in the upper part of the mine. Predicting the development of density stratification, but also to understand possible factors that leads to stratification breakdown is crucial. If stratification is destroyed, the CF and WM water bodies will mix and a deterioration of the water quality is likely. This paper aims to determine if the occurrence and breakdown scenarios as well as the long term stability of stratification can be generalized and transferred to other mines. It will be investigated whether correlations between the mine layout and the stratification can be proven.

Methods

Depth profile measurements

To investigate stratification in decommissioned, flooded underground mines, down hole probes or dippers are commonly used. By measuring physico-chemical parameters, usually temperature and electrical conductivity, stratification can be detected due to a sudden change of the measured values over depth. In most cases, the upper CF (cold fresh) water body has a lower electrical conductivity and lower temperature compared to the WM (warm mineralised) water body or bodies below. In between, the intermediate layer varies in thickness from centimetres to decimetres[7,11,27,32]. Generally, density can be calculated using the UNESCO equation[33] in order to determine the difference in density between the water bodies. Moreira, et al.[34] presented a more accurate density calculation method for lakes. For this method it is first required to have lake water chemistry data, which allows the calculation of two coefficients to be used with the measured electrical conductivity. Since the chemical data of mine water is not always know, and in most cases the density difference is more relevant than the exact density, the authors of the present paper used the UNESCO equation (Eq. 1) for all calculations:

$$\rho\ (S,t,p) = \frac{\rho\ (S,t,0)}{1 - \frac{p}{K(S,t,p)}} \tag{1}$$

with

ρ = density.
S = salinity.
t = temperature.
p = pressure.
K = secant bulk modulus.

The thickness of the intermediate layer is a function of the velocity differences in the two layers above and below and often shows a staircase characteristic, indicating either double diffusive conditions or internal waves[1].

Data acquisition for evaluation

The authors compiled depth profile measurements from flooded underground mines, resulting from literature data, their own measurements and data provided by colleagues. Main focus was on depth profile measurements of temperature and electrical conductivity, as these parameters best reveal density stratification and are more often measured. For this study, 24 mines with 29 shafts were evaluated in detail (cross sections and depth profiles of the mines are provided in the electronic appendix). These include 12 coal mines and 17 ore mines, some in the flooding process but most completely flooded (Table 1). For some shafts, repeated measurements over several months or even years were available, and therefore, 87 depth profiles were evaluated in total.

Data analysis

Data storage and evaluation were performed using MS Excel (Microsoft Corporation, Redmond), which allowed for a structured and easily accessible dataset for subsequent analyses. Built-in functions such as mean, median and range were applied. Excel´s sorting and filtering capabilities were utilized to arrange and isolate specific subsets and compare the type of mine and number of water bodies within the depth profiles. In order to examine the temperature and electrical conductivity distribution in more detail, 55 distinct depth profiles were selected, each with two or three clearly identifiable water bodies. Those profiles were also chosen to characterise the intermediate layer, i.e. the stratification itself. Descriptive statistical analysis was carried out on the profiles with two or three water bodies by calculating the mean (Eq. 2), standard deviation (Eq. 3), median, minimum and maximum values

$$\mu = \frac{1}{n} \sum {}_{i=1}^{n} x_i \tag{2}$$

$$\sigma = \sqrt{\frac{1}{n} \sum {}_{i=1}^{n} (x_i - \mu)^2} \tag{3}$$

Mine	Shaft	Commodities	Country	Reference	Figure in supplementary material
Vouters	Vouters 2	coal	France	[35]	S 1, S 2
Siège Simon	Simon 5	coal	France	[35]	S 3, S 4,
Rosice-Oslavany coal basin	Kukla	coal	Czech Republic	pers. comm. J. Zeman (2020)	S 5, S 6, S 7
Rosice-Oslavany coal basin	Jindřich II	coal	Czech Republic	[36] pers. comm. J. Zeman (2020)	S 8
Zeche Hermann	Hermann 1	coal	Germany	[32,37,38]	S 9, S 10
Zeche Hermann	Hermann 2	coal	Germany	[32]	S 11
Grube Velsen	Gustav 2	coal	Germany	[38]	S 12, S 13
Zeche Glückaufsegen	Glückaufsegen 3	coal	Germany	[32]	S 14, S 15
Friedlicher Nachbar	Schacht 2	coal	Germany	[32]	S 16, S 17
San Vicente	Pozo El Entrego	coal	Spain	pers. comm. HUNSA (2019), own measurements	S 18, S 19
San Vicente	Pozo El Sorriego	coal	Spain	pers. comm. HUNOSA (2019), own measurements	S 20
Horden	S40 Horden South Shaft	coal	Great Britain	pers. comm. Coal Authority (2023)	S 21
Grube Merkur	Weidtmann-Schacht	lead	Germany	own measurements	S 22, S 23
Straßberg	Flourschacht	fluorspar	Germany	[37,39] own measurements	S 24, S 25, S 26, S 27
Straßberg	Ü539	fluorspar	Germany	[40] own measurements	S 28, S 29, S 30
Grube Meggen	Sicilia Schacht	pyrite, barite, limonite, lead, zinc, poly-metallic VMS	Germany	[32,37]	S 31, S 32
West Rand	Shaft No 8	gold	South Africa	own measurement	S 33, S 34
Leopold-Louise	Otto-Wolff Schacht	iron	Germany	[41]	S 35, S 36
Hancock Mine	Shaft 2	copper	USA	[22,42]	S 37, S 38
Grube Georg	Schacht 2	iron	Germany	[41,43]	S 39, S 40
Grube Stahlberg	Schacht 2	iron	Germany	own measurements	S 41, S 42
Urgeiriça	St Barbara	uranium	Portugal	own measurements	S 43, S 44
Metsämontu	MSD shaft	Pb Zn Cu Ag, polymetallic VMS	Finland	own measurements	S 45, S 46
Metsämontu	MS2 shaft	Pb Zn Cu Ag, polymetallic VMS	Finland	own measurements	S 47
Aijala	Aijala	Pb Zn Cu Ag, polymetallic VMS	Finland	own measurements	S 48, S 49
Georgi Unterbau	Blindschacht	silver, copper	Austria	own measurements	S 50, S 51, S 52
Nikolaus-Bader-Schacht	Nikolaus-Bader-Schacht	gold	Austria	own measurements	
Groverake	No 2 shaft	fluorspar	Great Britain	[1,44]	S 53, S 54
Roudný	Aleška	gold	Czech Republic	pers. comm. J. Zeman (2021)	S 55, S 56

Table 1. Overview of the evaluated mines.

with

μ = mean.

n = number of data points.

x_i = each individual data point.

σ = population standard deviation.

In addition, comparative analysis was also calculated to evaluate a potential relationship between the depth of the shaft profile and that of the uppermost intermediate layer using the Pearson correlation coefficient (Eq. 4).

$$r = \frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum (x_i - \bar{x})^2} \sqrt{\sum (y_i - \bar{y})^2}} \tag{4}$$

with

r= Pearson correlation coefficient.

x_i= each individual value of variable.

y_i= each individual value of variable.

$\bar{x}$ = mean of the -values.

$\bar{y}$ = mean of the -values.

All depth profiles were plotted with the scientific graphing and data analysis software SigmaPlot (Grafiti LLC, Palo Alto) to ensure a consistent and comparable visualisation of the data (Figs. 1 and 4, electronic appendix). To compare the depth profiles with each other and to relate them to the layout of the mine, cross sections of the mines were illustrated uniformly (Fig. 3, electronic appendix).

Limitations

This study was subject to several limitations that should be considered when interpreting the available data. Salt mines were not included due to the distinct properties of the mine water, specifically the higher mineralisation, which differs considerably from coal or ore mine water. The selection of mines from similar climate zones introduced another limitation. For example, flooded mines from arid climate zones were not considered in detail due to the lack of data. Depth profiles of temperature and electrical conductivity were not always measured across the complete depth of the shafts, with sometimes incomplete coverage. In addition, there is not always an exact match between the depths of the mine cross sections and the depth profile measurements. Lastly, inaccuracies during the measurement itself cannot be excluded. Possible error sources are the missing acclimatisation of the probe before measuring or lowering down the probe too quickly in the shaft. Additional errors could arise from wrongly calibrated conductivity probes, different temperature compensation coefficients or scaling of probes[1].

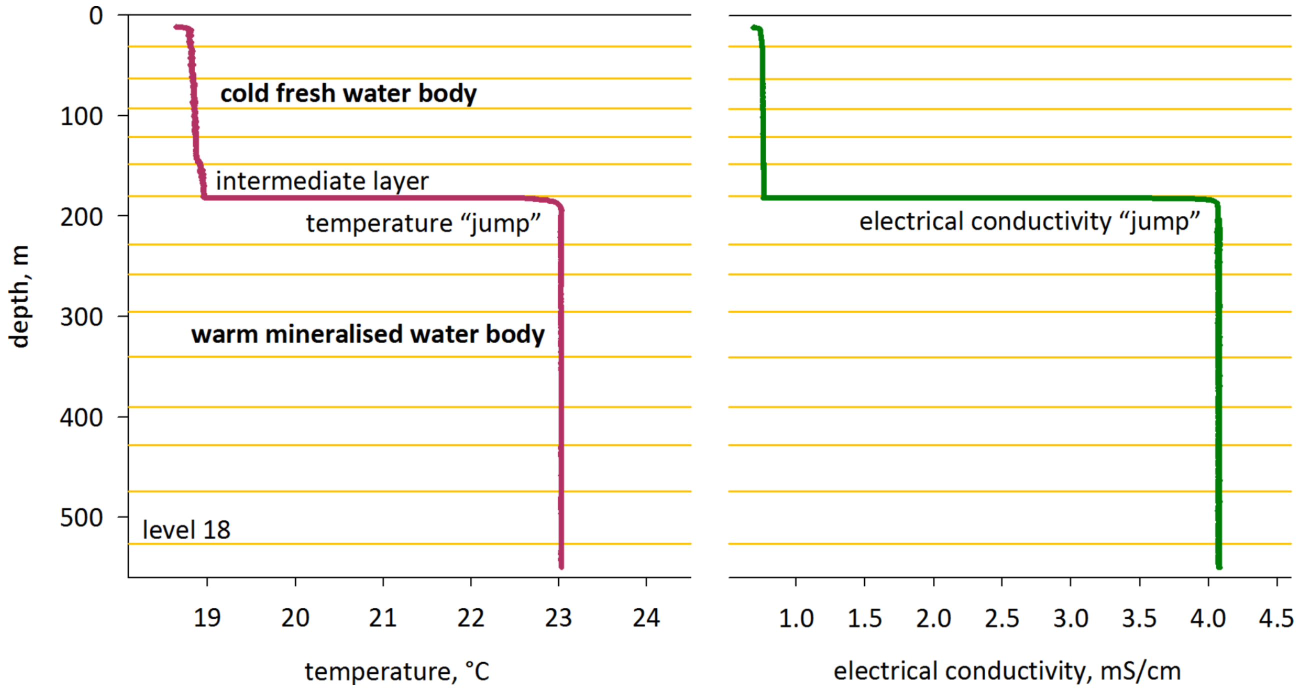

Fig. 1. Temperature and electrical conductivity profile of the St. Barbara Shaft, Urgeiriça Uranium Mine in Portugal.

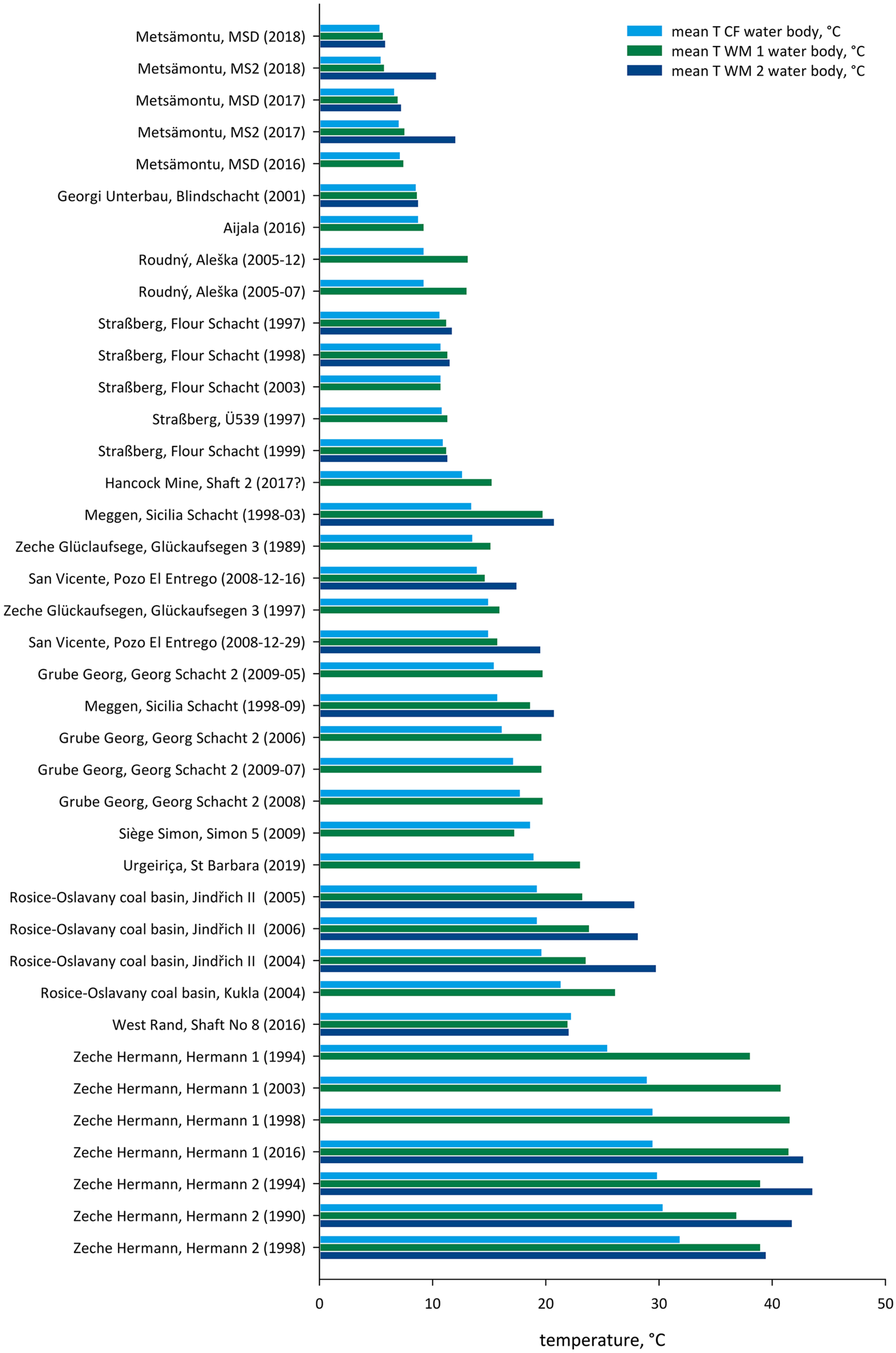

Fig. 2. Mean temperatures for 39 selected depth profiles with two or three different water bodies (out of 55 only 39 profiles had temperature recordings available). WM 1 water body is the upper warm mineralised water body and WM 2 water body is the lower warm.

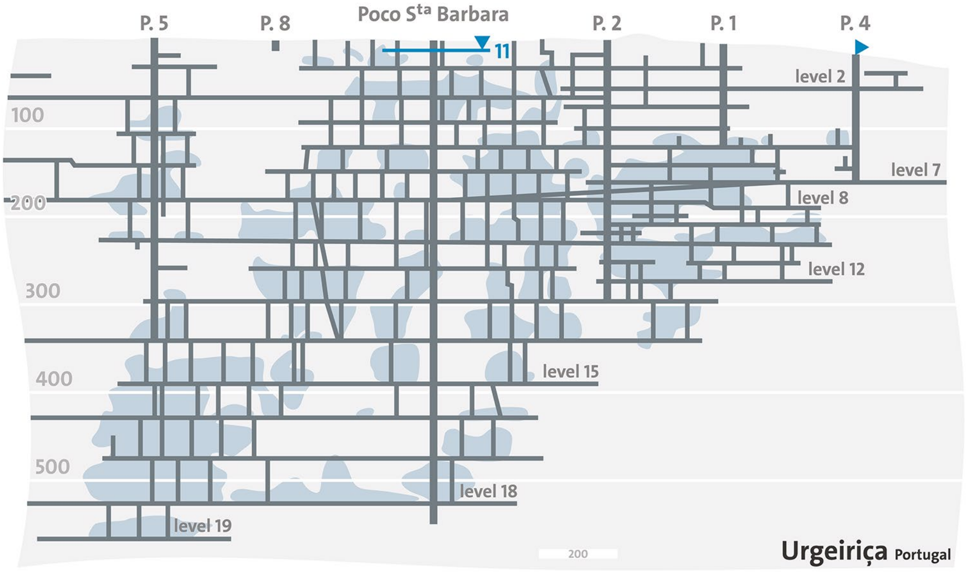

Fig. 3. Cross section of the Urgeiriça Uranium Mine in Portugal, the St. Barbara Shaft and outflow at shaft P4; orange arrow on level 8 indicates position of stratification in the St. Barbara Shaft.

Results

Comparison of depth profiles

In all shafts (with the only exception being Shaft No. 8, West Rand, South Africa), the CF water body overlays the underlying WM water body (Fig. 1). Evidence of this can be seen from the depth profiles of temperature and electrical conductivity, but more specifically from the calculated density profiles (Fig. 4). Six mines are single shaft mines *sensu* Wolkersdorfer[1], the rest are multiple shaft mines with hydraulic connections between the shafts. There is no correlation between the mine type (single shaft or multiple shaft mine) and the number of stratified water bodies. In 28 of the 29 shafts, the water bodies could be differentiated from each other through the immediate change of temperature, electrical conductivity or both. Out of the 87 depth profiles investigated, 14% showed no stratification, 36% had two distinct water bodies, 29% three of them and 22% four or more. Larger amounts of water bodies are subject to inaccuracies, as in some shafts staircase profiles occur (Fig. 2). These staircase profiles are caused by either double-diffusive convection or internal waves[1,45–47].

Most of the 78 investigated profiles show varying "grades" of stratification (Table 2). From the 55 profiles with two or three distinct water bodies, temperatures vary between 5.3 °C and 43.5 °C, electrical conductivities vary between 0.1 mS/cm and 189.6 mS/cm. Mean and median temperatures in the WM water bodies are typically higher with a higher standard deviation, compared to the CF water bodies with lower standard deviation (Fig. 2). Additionally, the electrical conductivities in the WM water bodies are considerably higher (with a much higher standard deviation) than in the CF water bodies (with a lower standard deviation; Fig. 5). It becomes apparent that the temperature and electrical conductivity differences between the individual CF and WM water bodies can vary greatly. For example, in the St. Barbara shaft of the Portuguese Urgeiriça mine, individual water bodies differ by a temperature difference of 4 K and an electrical conductivity difference of 3 mS/cm (Fig. 1). However, the range in the 55 examined profiles with two and three water bodies is very large. Maximum temperature difference between two water bodies is 11.7 K and the minimum is 0.1 K. The electrical conductivity "jump" ranges from a maximum of 163 mS/cm (Hermann 2 shaft) to a minimum of 0.1 mS/cm between the individual water bodies.

In the 55 profiles with two or three water bodies, the shafts are between 100 and 1500 m deep. The shortest depth profile is 98 m deep (at shallowest shaft, Georgi Unterbau), the longest one 1450 m deep (at deepest shaft, Rosice-Olsavany coal basin). In most cases, measurements were taken over almost the entire shaft depth, therefore most profiles reflect a good representation of the flooded shaft column (Fig. 6).

Location of the intermediate layer

In relation to the 55 profiles with two or three water bodies, the topmost intermediate layers (boundary between CF water body and WM 1 water body) are located between 31 and 850 m below the surface, with a median depth of 162 m (mean depth 270 m) (Fig. 6). Where present, the second intermediate layers (boundary between WM 1 and WM 2 water body) are located between 69 and 1215 m, with a median depth of 287 m (mean depth 475 m). A Pearson correlation coefficient of 0.73 indicates a linear relationship between the depth of the shaft and the depth of the topmost intermediate layer. Hence, this suggests that in deeper mines, the interface between the CF and WM water bodies is at a greater depth. Additionally, the intermediate layer is mainly located at the first or second connected level in the shaft (Fig. 7, table with description provided in electronic appendix). Out of the profiles with two or three water bodies (except Horden S40 South shaft where no cross section was available), the topmost intermediate layer is located 26 times at the first connected level to the shaft. Sixteen times, the topmost

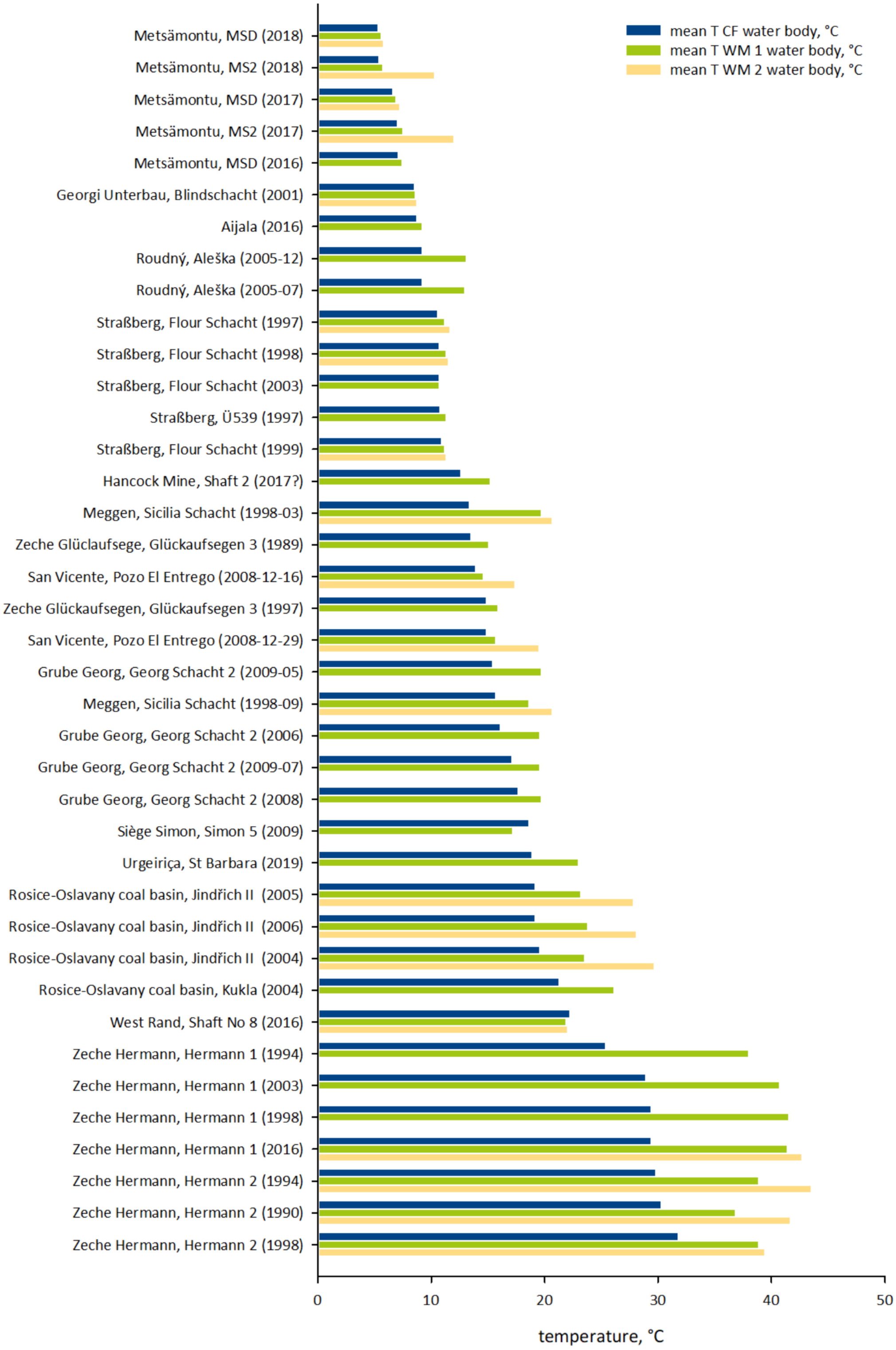

Fig. 4. Depth profiles of the Vouters 2 shaft, Vouters mine (France); staircase-like profile below level 1036. (modified from Reichart[35]).

intermediate layer is located at the depth of the second connected level to the shaft. As can be seen, the uppermost stratification is mostly found in the upper part of the mine. Only in nine profiles, the boundary between the CF water body and WM 1 water body is located deeper in the shaft and at deeper horizontal connections to the shaft. Furthermore, there is a weak negative correlation (Pearson correlation coefficient −0.14) between the position of the topmost intermediate layer (1st, 2nd or deeper connected level) and the depth of the shaft. In case of the Hancock Mine, Shaft 2, no clear statement can be made, as presumably the depths of the profiles do

Water body and parameter	Mean	Median	Minimum	Maximum	Standard deviation
water body 1 (CF), upper temperature, °C	15.8	14.9	5.4	31.4	7.2
water body 1 (CF), lower temperature, °C	16.1	14.9	5.3	32.2	7.7
water body 2 (WM), upper temperature, °C	19.4	17.2	5.6	41.4	10.8
water body 2 (WM), lower temperature, °C	19.6	17.1	5.7	41.6	11.0
water body 3 (WM), upper temperature, °C	21.6	20.1	5.7	43.5	12.5
water body 3 (WM), lower temperature, °C	21.6	20.1	5.8	43.5	12.5
water body 1 (CF), upper electrical conductivity, mS/cm	2.6	1.4	0.1	10.8	2.7
water body 1 (CF), lower electrical conductivity, mS/cm	2.7	1.4	0.1	13.8	3.0
water body 2 (WM), upper electrical conductivity, mS/cm	26.3	2.4	0.4	170.9	53.4
water body 2 (WM), lower electrical conductivity, mS/cm	26.2	2.5	0.4	170.9	52.9
water body 3 (WM), upper electrical conductivity, mS/cm	31.7	4.7	0.5	189.3	58.9
water body 3 (WM), lower electrical conductivity, mS/cm	31.6	4.8	0.5	189.6	58.7

Table 2. Mean, median, minimum, maximum and standard deviation for temperature and electrical conductivity (55 profiles with two or three water bodies).

not correspond with the cross section. Furthermore, the position of the deeper intermediate layer can partly be explained by convection loops with other shafts due to hydraulic connections. In some cases, the upper levels might also be sealed or collapsed, but no evidence can be found for this. Not included in the 55 profiles, but included in this study, are a few shafts with a deviating explanation for the location of the stratification. Either the shaft is too shallow (Nikolaus Bader shaft, Austria), the shaft lining has changed (Gustav 2 shaft, Germany) or the existing cross sections are probably faulty.

Depth profiles without density stratification

Some shafts without stratification show an inclined course of the temperature or electrical conductivity profile, which indicates diffusive transport within the water body[48]. However, the reason why there was no stratification at the Otto-Wolff shaft (Leopold-Louise mine, Germany) cannot be identified with certainty due to the one-time measurement at the shaft. At the El Sorriego shaft (San Vicente mine, Spain) stratification existed a decade before the last measurement in 2019, the connecting galleries might have broken down in the meantime. In eight other shafts, breakdown of the stratification could also be documented, whereby the reasons for this can always traced back to the disturbance of the stratified water bodies. For instance, at the Georgi Unterbau mine, the stratification was disturbed by a tracer test where a saturated sodium chloride solution was injected into the shaft. As long as a mine is in the flooding process, stratification can breakdown as well. The system is not stable and new convection loops may develop, preventing the re-formation of stratification[7,20]. Such is the case at the Sicilia shaft in Meggen (Germany) and the two French Simon and Vouters shafts. A special case is the Straßberg mine in the Harz Mountains (Germany), where hydraulic conditions substantially changed after newly constructed dewatering adits connected to the flooded shafts. This resulted in convection, causing a breakdown of the existing and stable stratification. Another unusual example is the Nikolaus-Bader-Shaft in Austria. Due to the shallow depth of only about 10 m, seasonal influences have a strong effect. However, stratification collapses and builds up again in the course of the year[7]. The reason for only one water body at the Maschinen shaft (Felsdome Rabenstein, Germany) is related to its shallow depth on the one hand and the flow of water from the lowest level to the discharge gully on the other hand.

Special attention must be paid to pumping in flooded mines. This can destroy density stratification, hence eliminating the separation of the CF and the WM water bodies. Such an example is described by Farr, et al.[49] for the British Horden Mine, S40 South Shaft. Stratification breakdown due to pumping can also be assumed for the two French shafts Simon 5 and Vouters. Although not listed in the investigated mines for this study, because no measurement are available, Jacques Whitford & Associates Limited[50] describe the deterioration of water quality resulting from pumping at the Canadian Springhill Mine. The authors conducted their own measurements at a mine in South Africa, where the water level had been kept at a certain level by pumps. After several months without pumping, due to the failure of the pumps, stratification had developed. Shortly after the pumps were restarted, the stratification collapsed. Another case, where pumping deteriorated the water quality, is the Australian Blinman mine. After initial investigations in the flooded mine shaft, good water quality was found. Jet, when pumping for drinking water started, the quality deteriorated and bad quality water reached the pumps. The undertaking, consequently, had to be stopped.

Discussion

By comparing the profiles and cross sections of various physico-chemical shaft profiles, it became evident, that there are various scenarios in which density stratification occurs but also gets destroyed (Fig. 8). In most flooded underground mines around the world, mine water discharges naturally from the mine at the location with the lowest hydraulic head. The investigated mine shafts in this study indicate, that the uppermost intermediate layer, i.e. the change from the CF to the WM water body, mostly occurs in the upper part of the mine, mainly at the first or second connected level to the shaft. Based on the observations made, the boundary between the CF and WM water bodies is mainly determined by infiltration water, which enters the mine pool predominantly via the

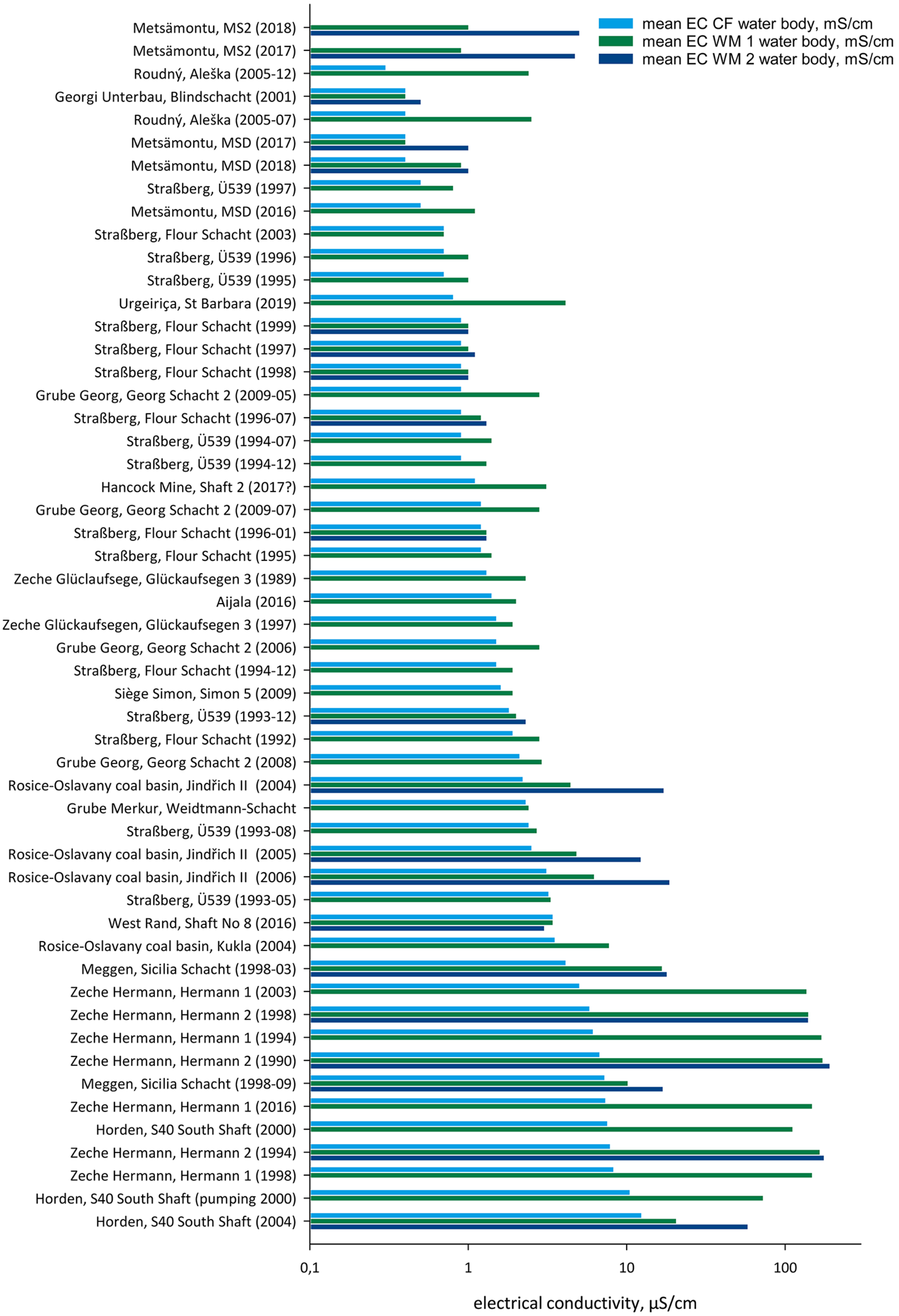

Fig. 5. Mean electrical conductivity (with logarithmic scale for x-axis) for 53 selected depth profiles with two or three different water bodies (out of 55 only for 53 profiles with EC recordings were available). WM 1 water body is the upper warm mineralised water body. WM 2 does not exist in all shafts/depth profiles.

galleries and voids. This area usually covers the uppermost 200–400 m below ground[20,51], often the area where the topmost levels connect to the shafts. To a lesser extent, influxes from other mine areas from deeper parts of the mine or large-scale groundwater flows are seen as reasons for the development of the CF–WM density transitions. Within the individual water bodies (CF and WM), the flow is dominated by convective flow (Fig. 9)[7].

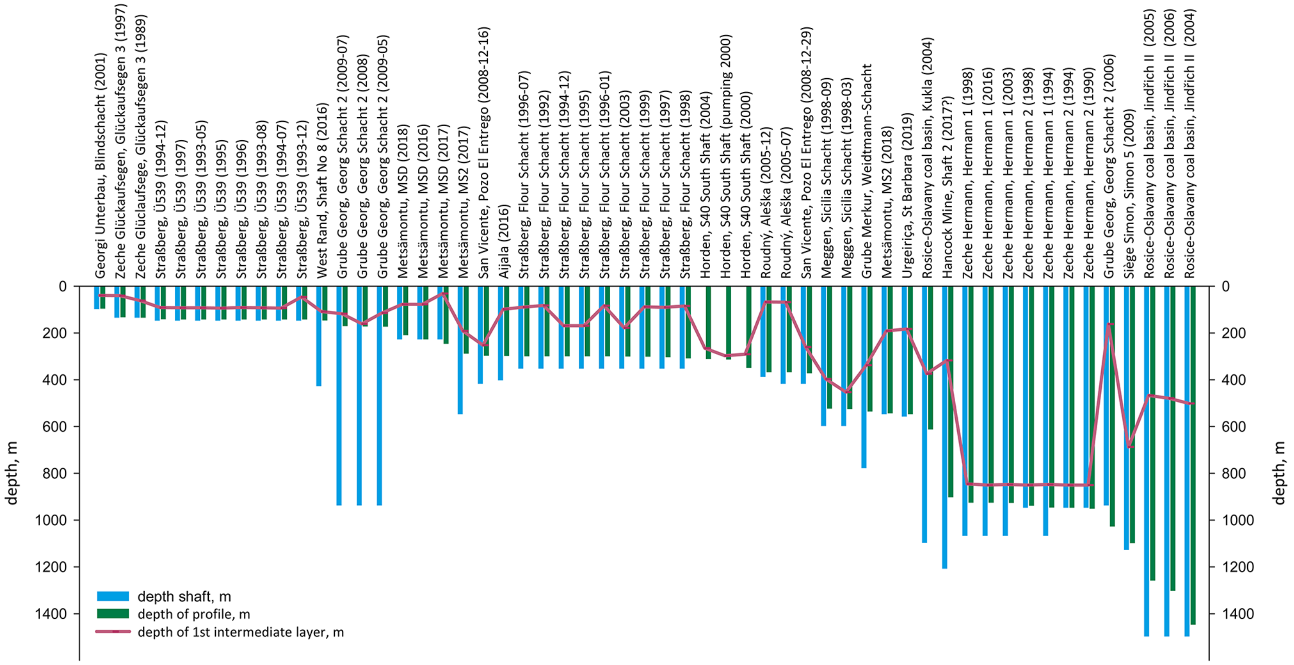

Fig. 6. Depths of shafts and temperature as well as electrical conductivity profiles (profiles with two or three water bodies). Grube Georg, Georg Schacht 2 with a probably incorrect depth of the depth profile from 2006. Horden, S40 Shaft depth of the shaft unknown. Black line represents the location of the topmost (first) intermediate layer.

In some cases, aquifers are located in the vicinity of the flooded mine. Based on the extensive literature study conducted for the present study and communication with colleagues, contamination of the aquifer by mine water is unlikely, but cannot be fully excluded. As far as the authors are aware, the only case of this occurred in county Durham (UK), where an aquifer was contaminated by mine water, causing sulfate concentrations increasing in the aquifer[52]. To protect the aquifer, consideration should be given to sealing the uppermost connected level, so that the intermediate layer between the CF and WM water bodies can be shifted to the next lower connected level. This will increase the width of the CF water body with better quality and thus keep away higher contaminated mine water from the aquifer (Fig. 9). To the authors´ knowledge, this has not yet been deliberately done in the field, but there are scenarios in which hermetisation could be useful.

Some shafts have no natural discharge, but instead the water is pumped from the shaft. It has been shown, that operating pumps in flooded underground mines degrade the water quality in the upper part of the mine and consequently at the point if discharge, which is caused by stratification breakdown. This deterioration of water quality due to pumping indicates that stratification in a flooded mine must always be considered before pumps are used. However, it is necessary to distinguish the different application of pumps. Firstly, pumps are used for dewatering. As an example, authorities require that the water level in the Witwatersrand Gold Fields around Johannesburg, South Africa be kept at the Environmental Critical Level (for example 1150 m a.b.s.l. in the East Rand) by pumping[53]. Therefore, the shaft may not be completely flooded at any given time. Many other examples can be found around the world where no natural discharge occurs, but the water level is maintained by pumping. If pumping cannot be avoided, it might be possible to prevent breakdown of stratification by lowering the pump rate and by ensuring a sufficient distance between the pump and the intermediate layer. As stratification normally occurs at the first or second uppermost connected level, a sufficient distance between the pump and the intermediate layer may not be guaranteed and stratification may be destroyed. To increase the distance between the pump and the stratification, and thus avoid the breakdown of the stratification by pumping, the width of the CF water body can be extended by sealing the topmost connected mine level (Fig. 8).

Furthermore, pumping for geothermal exploitation of mine water can result in stratification breakdown (Fig. 8). If the warm mine water shall be used in heat exchangers, an evaluation for stratification is essential as well. If stratification is destroyed by pumping for geothermal use, negative consequences arise for the water temperature of the withdrawn water. After breakdown of stratification, the mixed water is colder than water just from the WM water body. Additionally, the water quality of the near surface, possibly discharged mine water will deteriorate as well. Therefore, maintaining stable stratification should always be the main goal for a flooded underground mine.

Conclusions, recommendations and outlook

Understanding density stratification in flooded underground mines is essential for successful mine water management. Based on the present study, new insights into density stratification in flooded underground mines could be gained. This was possible by a comparative approach and findings that apply to a large set of mines

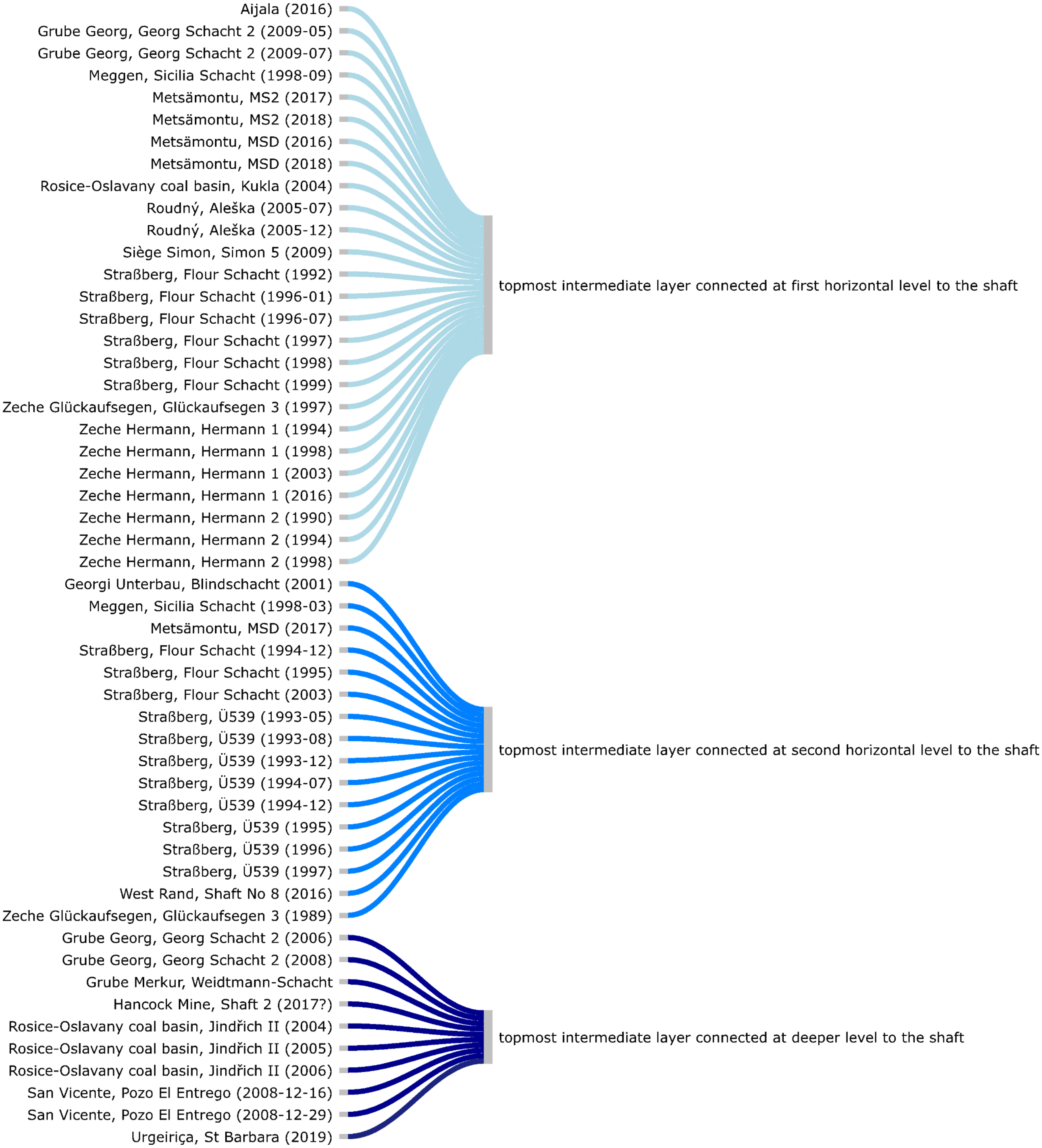

Fig. 7. Sankey diagram to illustrate location of the topmost intermediate layer.

and not just for individual examples. It could be shown that stratification is not an exception, but it occurs in almost all flooded underground mines and is responsible for the formation of water bodies with different physico-chemical properties. Usually, the cold freshwater (CF) water body is located above one or several warm mineralised (WM) water bodies. In almost all cases, the CF water body has a lower water temperature and a lower electrical conductivity with a relatively better water quality, compared to the underlying WM water body or bodies with a comparably worse water quality due to a higher mineralisation. In the majority of flooded shafts, only two (CF and WM) or three (CF, upper WM, lower WM) water bodies exist, whereby some cases show a staircase profile, especially in the deeper shaft section. The range of temperatures and electrical conductivities is large in the individual water bodies themselves. Between the CF and WM water bodies, as well as between different WM water bodies, usually an intermediate layer exists, which can be identified as a "jump" between the water bodies. However, this intermediate layer can have small but also very large temperature and electrical

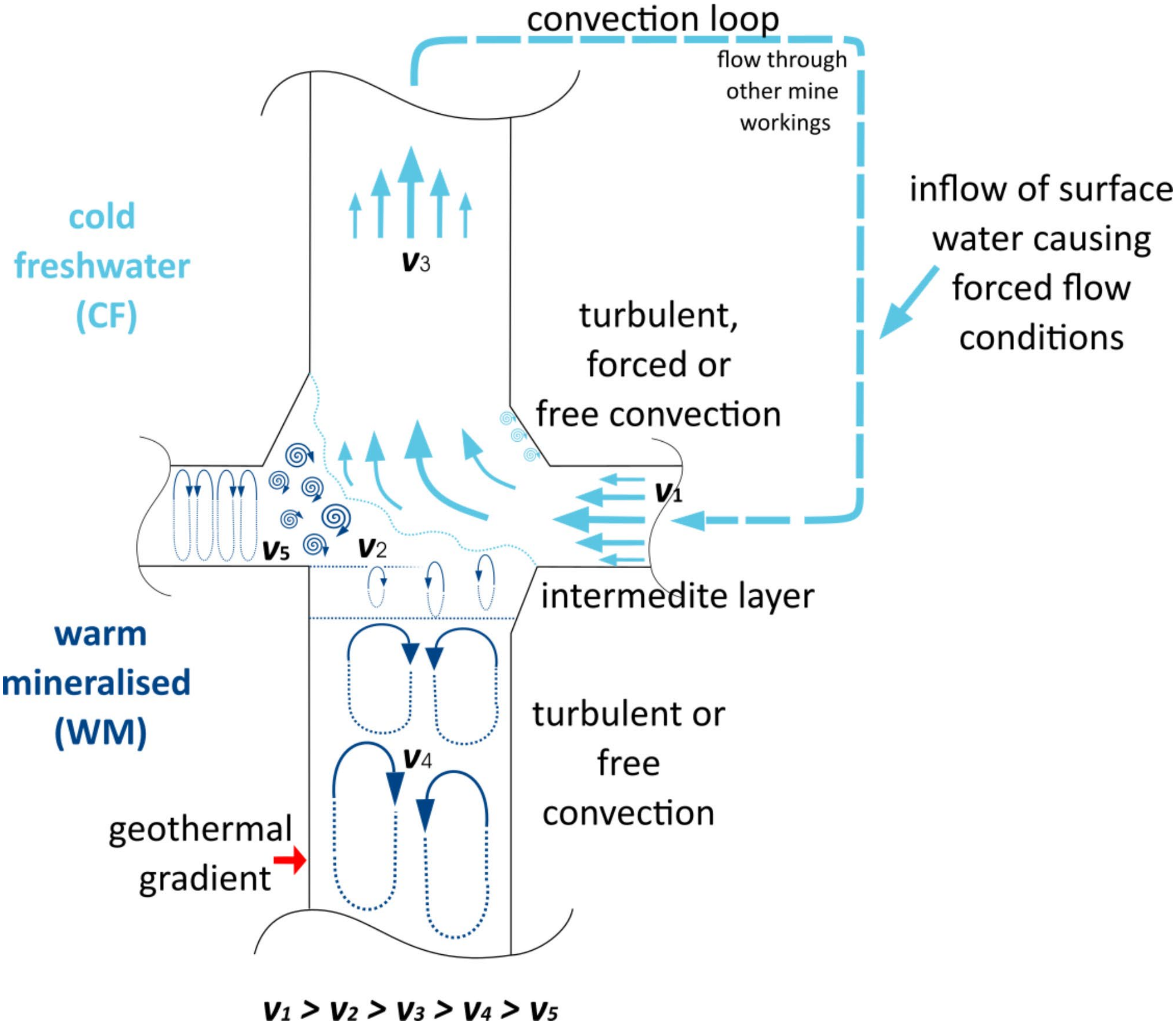

Fig. 8. Overview of possible stratification scenarios. Location of intermediate layer (boundary between CF and WM water body) is a simplification, as camera measurements and tracer test show, that the intermediate layer can be located either closer to the roof or bottom of the level. For simplification purposes, water reinjection during geothermal exploitation was not taken into account.

conductivity differences. The topmost intermediate layer is mostly located in the upper part of the mine, at the first or second connected level to the flooded shaft. One explanation for this observation is that the infiltration water, which is less mineralised and therefore has a lower density, mainly flows towards the uppermost mine water body, feeds this CF water body and overlays the higher mineralised WM water body. Tracer test have shown that these intermediate layers reliably prevent the fast exchange of water between individual water bodies.

Although density stratification is stable in most cases, pumping activities can disturb and collapse the stratification, causing a deterioration of the mine water quality in the upper part of the mine. If pumping activities are necessary for maintaining a certain water level or for geothermal exploration of mine water, the flooded shaft should always be examined by depth profile measurements for density stratification. Additional water samples above and below the stratification help to characterise the mine water body further. When installing pumps, the distance to the intermediate layer should be as far as possible and the pumping rate as low as possible in order to avoid a collapse of the stratification. If pumps, for example for geothermal exploitation, are installed in the WM water body, stratification breakdown is likely, despite a sufficient distance to the intermediate layer. Whether pumped water, which is used for heat exchangers and later re-injected at a different, deeper location in the mine, can prevent a collapse of the stratification cannot yet be determined. Frequent switching on and off the pumps should be avoided as well, as this causes a change in the mine water beach, where renewed oxygen supply restarts oxidation processes with further acid generation and deterioration of the mine water quality.

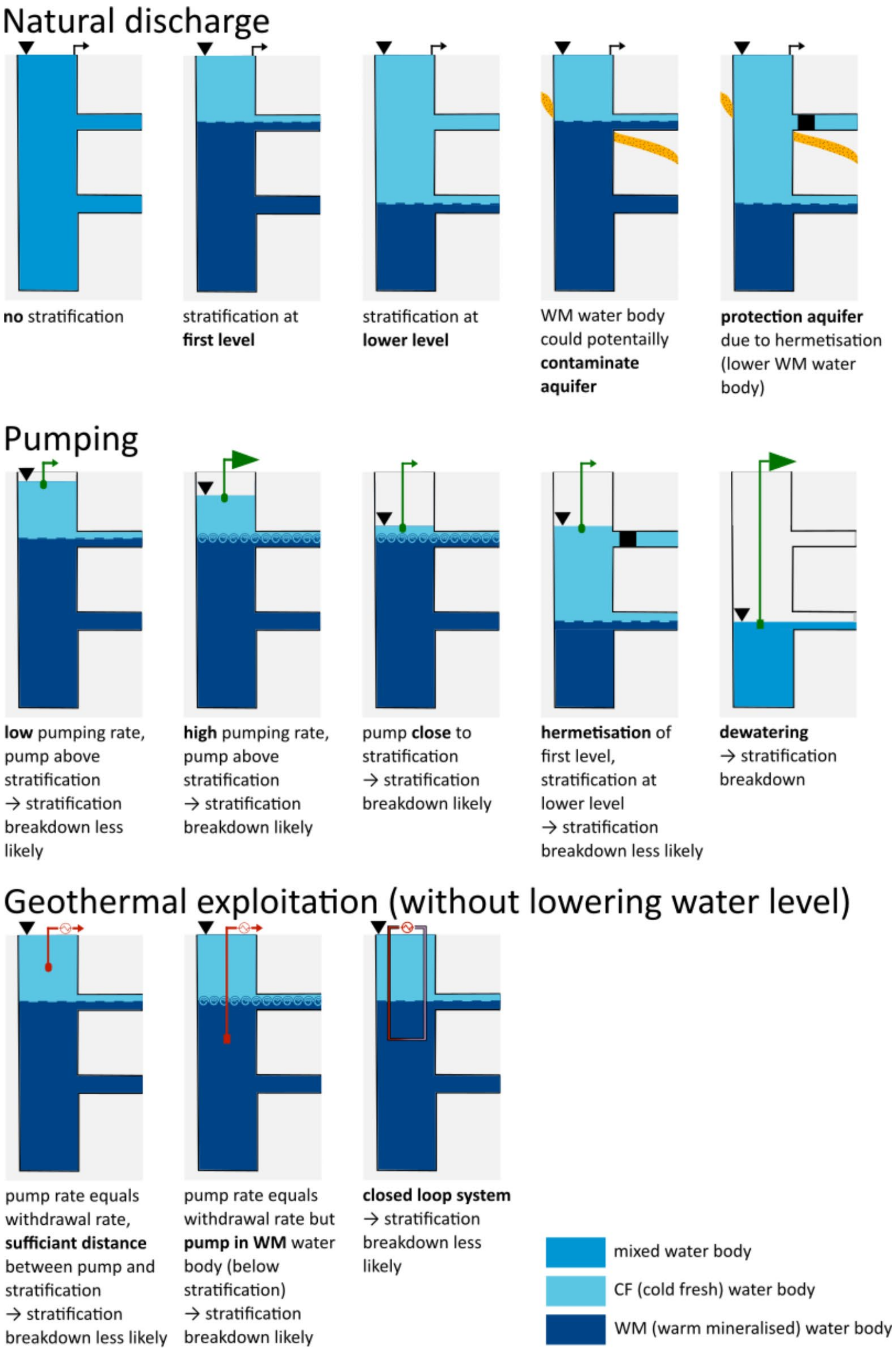

Fig. 9. Scheme of possible hydrodynamic processes in a flooded shaft.

Whether it is actually possible to influence or change the depth of stratification through hermetisation cannot be definitively answered. This approach would be most sensible if a sufficient distance between the stratification and the pump needs to be maintained.

In order to validate the new findings about stratification, in particular the option of artificial hermetisation, as well as the breakdown of stratification through pumping activity, laboratory experiments are planned at the Agricola Model Mine (AMM) analogue model at the Tshwane University of Technology in Pretoria, South Africa. In addition, shaft cameras may be used to gain a better understanding of stratification and are a valuable addition to the usual dipper measurements. Furthermore, further tracer tests can help to investigate stratification. The authors recommend keeping shafts open for measurements, both during flooding and after flooding has been completed.

Understanding and considering stratification is crucial for successful mine water management and has direct effects on the discharged mine water quality. When stratification develops and remains undisturbed, it considerably reduces the effort required for mine water treatment – as the case of the Urgeiriça or Metsämonttu mines exemplify. In both cases, a low mineralized CF water body overlays a highly mineralized WM one. For most mines, water from the upper CF water body with a typically better quality, requires minimal treatment (Urgeiriça case) or could be discharged untreated (Metsämonttu case). In contrast, the results of this study show that water from the WM water body should remain unaffected. It is highly recommended to maintain stratification for efficient mine water management. Preserving stratification can then greatly reduce the resource consumption involved in mine water management and treatment processes.

Data availability

All data generated or analysed during this study are included in this published article and its supplementary information files.

Received: 8 May 2024; Accepted: 4 December 2024

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Acknowledgements

The authors thank their respective research institutions for providing support in conducting this research. The German foundation "Forum Bergbau und Wasser" made travel funds available, and the NRF SARChI chair for Mine Water Management, Department of Environmental, Water and Earth Sciences, Tshwane University of Technology under Grant № 86948 supported this research. Thanks to our colleagues who made site visits possible and provided us with their research results. We also thank various colleagues for intensive discussions about mine water stratification and continuous shaft measurements, some of them provided under the conditions of the Chatham House Rules.

Author contributions

E.M. : Investigation, Writing – original draft. C.W.: Funding acquisition, Supervision, Writing – review & editing. All authors reviewed the manuscript.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1038/s41598-024-82293-y.

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