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TECHNICAL ARTICLE

Stratification Dynamics and Geothermal Potential of a Deep Shaft in the Flooded Wolf Mine, Siegerland/Germany

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Abstract

Mine water hydraulics and geothermal potential of a deep shaft of the flooded Wolf mine in the Siegerland ore district of the Rhenish Massif in Germany were investigated. The electrical conductivity (EC), temperature, pH, and E_h were logged to 580 m below water table using multi-parameter borehole tools in 2009 and 2015. Some variations were detected, which were interpreted to indicate the inflow of water with almost the same temperature from the neighbouring San Fernando mine. Borehole camera observations showed that the deeper mine levels are directly connected to the shaft and are not blocked by natural or manmade barriers. The temperature was relatively uniform throughout the underground water catchment, but variations were found in pH and E_h. The EC profile was relatively uniform in 2009, but some anomalies were seen in 2015 between the depths of 80 and 220 m, indicating changes to the mine water dynamics. Stratification at a depth of 300 m was inferred from the investigation data. The logging results and calculations suggest that the mine could be exploited to supply sustainable geothermal energy. This flooded mine could supply up to a few gigawatt hours of energy per year, and could be used as an important source of low-carbon energy for heating and cooling nearby properties.

Keywords Abandoned mine · Mine water geothermal energy · Mine water hydraulics · Mine water hydrogeochemistry

Introduction

The Siegerland-Wied mining district in the Rhenish Massif, Germany, has a long history of intensive metal ore mining dating back to the Celtic/Roman era (Gleichmann 1990), but all of the many underground mines were decommissioned before 1965 (Fenchel et al. 1985). The underground workings subsequently flooded and groundwater filled the mine shafts, some of which are more than 1 km deep, creating connections between the surface water and mineralized deep groundwater. The dynamics of the interconnected water systems is affected by the hydrogeological settings, extent of underground mine development, stress conditions created by mining in the surrounding rock, and shaft linings impeding flow between the ambient groundwater and mine water. The mine shafts provide pathways that allow heat and material that flow from deep geological strata to the surface to be exploited for thermal energy (Preene and Younger 2014; Stemke and Wohnlich 2014; Wieber and Streb 2012).

Pilot-scale systems using heat pumps to extract energy from mine water and provide heating to nearby properties were installed in the UK (Burnside et al. 2016). Plants operating for a longer period also exist in other countries, such as Germany (Ofner and Wieber 2008) and Canada (Jessop et al. 1995). Use of such ground-source heat pumps allow heat extraction with low carbon emissions, though they may be less efficient than heat pumps using electricity from the grid (Bailey et al. 2016).

The long-term sustainability of a post-mining heat extraction system depends on a thorough understanding of the heat and material flow pathways in the mine workings. Distinct stratification boundaries between water bodies with different mineral contents and temperatures have often been observed in collieries at various locations (e.g. Melchers et al. 2015; Wolkersdorfer 1996, 2008). The main cause of this stratification are density differences, e.g. thermal and chemical stratification (FH-DGGV 2017). Stratification boundaries

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can limit the exchange of heat between stagnant mineralized water bodies because mixing does not occur and stable disconnected convection cells form (Melchers et al. 2015). Stratification boundaries can also cause changes in pumped water quality and limit the exploitation of a heat reservoir if they are not considered when planning a mine-water treatment system (Nuttall and Younger 2004). An understanding of the development and locations of stratification boundaries and convection cells in abandoned mine shafts may therefore be key for managing post-mining heat extraction systems.

Wieber et al. (2016) and Wolkersdorfer (1996) showed that the location of stratification boundaries are hard to predict because of their spatial variability and dynamic nature. This is particularly true for the Rhenish Massif area because the rock permeability varies widely on a small spatial scale, meaning that groundwater hydraulics may also vary widely. Groundwater hydraulics are affected by: Darcy flow, laminar and turbulence-free potential-driven flow, laminar and turbulent density-driven, or temperature-convection-driven flow, and molecular diffusion. There are more than 500 abandoned mines in the Siegerland-Wied district, and they have considerably altered the large scale hydrogeological properties of the subsurface in this area (Fenchel et al. 1985). The widespread Devonian silt and sandstones in the area unaffected by mining typically have low permeability (Wieber et al. 2011). In contrast, the backfilled mine workings have increased hydraulic conductivities. Mine water in neighbouring shafts is often connected by laterally extended underground developments. However, this does not mean that the water tables in the shafts show the same elevation. Interconnected mine shafts can contain water of different densities, causing the water tables in the shafts to differ by up to several meters, depending on the density of the water (Wolkersdorfer 2008). The equilibration of the water table in connected mine workings may cause distinct stratification dynamics, depending on the transmissivity of the flooded, collapsed workings, which are laterally widespread and extend to depths of up to 1 km. Heat circulation is likely in these mines, and heat conduction across the large rock–water interfaces in the mine workings is expected to replenish heat rapidly after exploitation. These 'mine aquifers' (Singh 1986) therefore merit further study and monitoring.

Mixing and stratification dynamics were studied in a shaft of the Wolf Mine, one of several deep underground mines in the Siegerland-Wied district. Our hypothesis was that the inundated mine could potentially be exploited to supply sustainable geothermal energy. The water in the shaft was investigated during two campaigns, in 2009 and 2015. During these campaigns, continuous vertical measurements of physico-chemical parameters were made in the water column of the main shaft to a depth of 580 m below the water table (m b.w.t.). At the time of the campaigns, the water table was at 80 m below the shaft collar. The total shaft volume was estimated at 6700 m^3. Investigating of stratification in such mine settings using physico-chemical parameters requires instruments with a high degree of sensitivity and data analysis methods that can enhance small changes in parameter values with depth. The data of the 2015 campaign are presented and discussed in this paper. However, to highlight the differences, data collected in 2009 are also presented.

Geological Setting of the Siegerland-Wied Mining District

The fold-and-thrust belt of the Rhenish Massif is part of the Rhenohercynian Zone of the Variscan mountain range of central Europe. Ore deposits were formed when highly mineralized water ascended along fractures through very low grade metamorphic Paleozoic siliciclastic sediments (Devonian schists). Renewed post-Variscan subsidence reactivated pre-existing fault systems, causing intensification of the fluid flow and the upward migration of hot sodium-calcium brines. These brines, mixed with cooler and more dilute fluids at shallower crustal levels, caused precipitation of ore minerals in voids and fissures. The contributions of the different fluid types and local fluid fluxes determined the ultimate hydrothermal vein mineralogy (Kirnbauer et al. 2012).

There has been mining in the Rhenish Massif for more than 2500 years. There are more than 500 abandoned iron and non-iron ore mines in the Siegerland-Wied district (Fenchel et al. 1985). The investigated mine is located in the Siegerland-Wied district near Herdorf (Fig. 1). The amalgamated mine originally consisted of five initially separate iron ore pits, namely Wolf, San Fernando, Friedrich Wilhelm, Füsseberg, and Glaskopf. The pits were later connected by deep drifts or crosscuts (Fig. 2). Mining in the Siegerland-Wied district mostly followed the ore veins hosted by the Devonian sedimentary rocks. The ore were excavated by stope mining, and the remaining caverns were backfilled with waste rock. In the Wolf Mine, the 'Mahlscheid Verschiebung' fault zone was worked downwards along the north–south axis to exploit an up to 7 m thick sub-vertical iron ore vein. With increasing depth, the ore vein splits into several sub-veins. Another vein, the Bernhard vein, was also mineable below the 250 m level. The minerals in the steeply inclined veins are dominated by siderite ($FeCO_3$).

Wolf and San Fernando Mine Developments

The Wolf Mine includes the main shaft studied here, a blind shaft, an old shaft (not shown in Fig. 2), and developments on 16 levels below the lowest mine adit, the "Tiefer Stollen" (Fig. 2). Above the dewatering adit there is another open adit ("Hochbausohle"). The neighbouring San Fernando

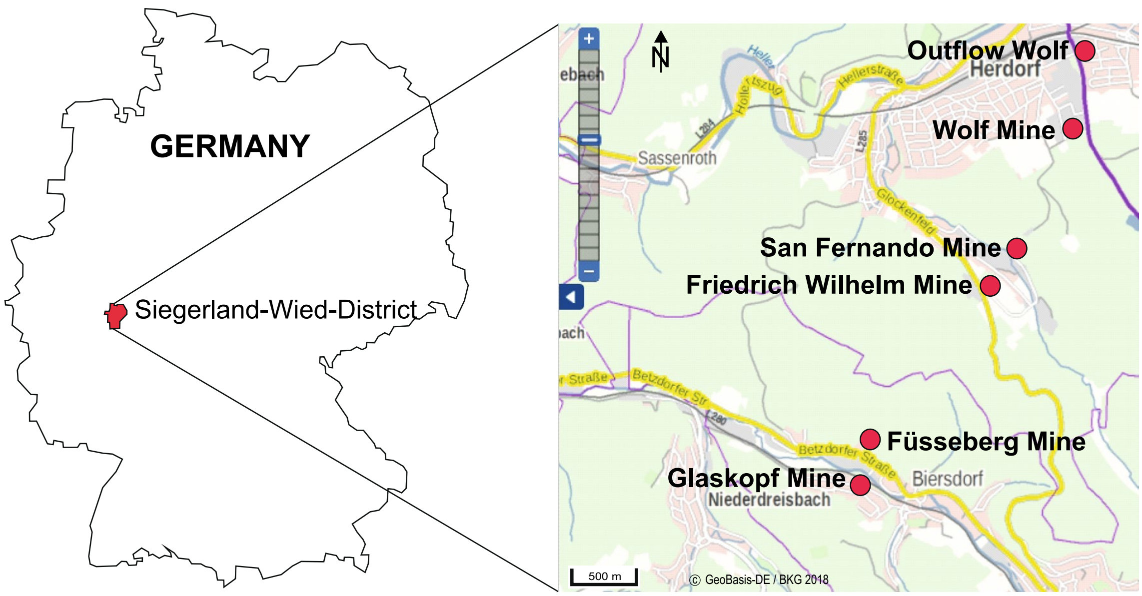


Fig. 1 Location of the mine (background map: ©GeoBasis-DE/BKG 2018)

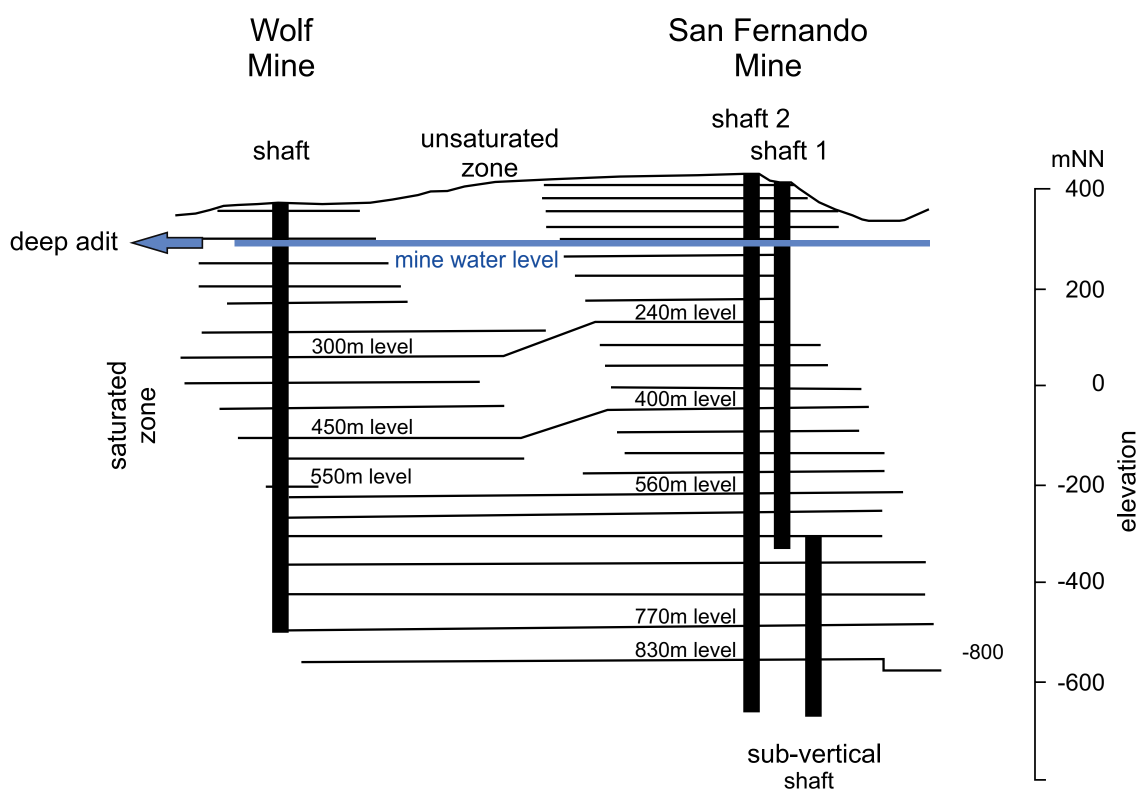


Fig. 2 Schematic diagram of the Wolf and the neighbouring San Fernando mine developments (Streb 2012)

Mine has two main shafts to depths of 675 and 1002 m, and a 340 m deep blind shaft connecting the five lower mine levels. The San Fernando Mine has another four open adits ("Hochbausohlen") above the dewatering adit. Both mines are connected by the 560–770 m levels. The 240 m level developments of the San Fernando Mine are connected by a decline to the 300 m level workings of the Wolf Mine. Another decline exists between the 450 m level of the Wolf Mine and the 400 m level of the San Fernando Mine. Other connections between the two mines are through galleries below 550 m, from which there is a hydraulic gradient towards the Wolf Mine shaft (Fig. 2). Mineshafts #1 and #2 of the San Fernando Mine (Fig. 2) are plugged with stowing material from the surface to the "Tiefer Stollen". Streb (2012) estimated the total volume of the Wolf Mine shaft at 6700 m^3, while the total volume of the San Fernando Mine shafts is approximately 26,500 m^3. The shaft volumes of the Friedrich Wilhelm, Einigkeit, Füsseberg, and Glaskopf mines account for about 70,000 m^3 in total.

Groundwater Hydrology of the Wolf and San Fernando Mines

The mean precipitation (2000–2015) in the Siegerland-Wied district is 1056 mm/a, and the annual average temperature is 8 °C (Deutscher Wetterdienst climate station Bad Marienberg). Drainage is dominated by surface runoff due to the many steep slopes in the area and argillaceous Devonian schist, which typically has low permeability. Groundwater recharge rates are typically low, ranging between 25 and 50 mm/a (LUWG 2005).

After mine closure in the 1960s, pumping was discontinued. Subsequently, the groundwater level rebounded to the level of the Tiefer Stollen, which is connected to the surface and gravity drains the upper levels of the Wolf Mine. Flooding of the mines led to the formation of an aquifer below the Tiefer Stollen level with both, pore porosity (interstitial pore space of the waste rock backfill) and fracture porosity (Devonian rock joints). The interconnected shafts and other flooded mine developments are comparable to a network of communicating water pipelines. The flooded volume of the Wolf Mine is almost 139,000 m^3 (Streb 2012). Wieber and Streb (2011) estimated the volume of water stored within the backfilled workings at 523,000 m^3, assuming a porosity of 0.35 for the backfill. Estimates of 822,000 m^3 reported by Younger et al. (2000) were based on a porosity of 0.55.

Logging, Sampling, and Measurements

Physico-chemical parameter measurements in the flooded main shaft of the Wolf Mine were carried out to a depth of 580 m using multi-parameter borehole tools. During the December 2015 field campaign, an Ocean Seven 303 Plus CTD probe (IDRONAUT, Brugherio, Italy) was used for recording the electrical conductivity (EC, compensated to 25 °C), temperature, hydrostatic pressure/depth, pH, and redox potential. The measured redox values (Ag/AgCl; KCl saturated) were corrected to the potential of the standard redox electrode.

These measurements were supplemented with video logging performed using a BK100-LWL borehole camera (Gullyver, Bremen, Germany). A CTD48M sensor (Sea & Sun Technology, Trappenkamp, Germany) was used by Streb (2012) for a preliminary investigation in March 2009. During this investigation, pressure, temperature, and EC were measured in the shaft to below 500 m.

Results and Discussion

Video records taken down the Wolf Mine shaft in December 2015 showed good hydraulic connections between the shaft and crosscuts at all levels, i.e. there were no rock obstructions or engineered barriers apart from the gates (Fig. 3).

In 2011, the hydraulic connection from the Friedrich Wilhelm Mine to the San Fernando Mine (shaft 2) and the Wolf Mine (Tiefer Stollen) was demonstrated by an uranin-based tracer test. The shaft of the Friedrich Wilhelm Mine was used to inject the tracer while shaft 2 of the San Fernando Mine was pumped. The measured maximum flow velocities determined by this tracer test were 2.9 mm/s to the San Fernando Mine shaft and 3.6 mm/s to the Wolf Mine (Streb 2012).

The temperature logs showed only small temperature changes with depth and no distinct temperature stratification in the Wolf Mine shaft (Fig. 4a) was apparent. In addition, the temperature profile did not follow the geothermal gradient of 3 K/100 m typical for the Rhenish Massif. Instead, the data records predominantly showed a trend of 0.02 K/100 m with temperature slightly increasing from 17.50 to 17.65 °C

Fig. 3 Gate at the 200 m Level in a video record of the flooded Wolf Mine shaft. The still image was taken at a camera depth of 201.47 m below shaft collar or 121.5 m b.w.t

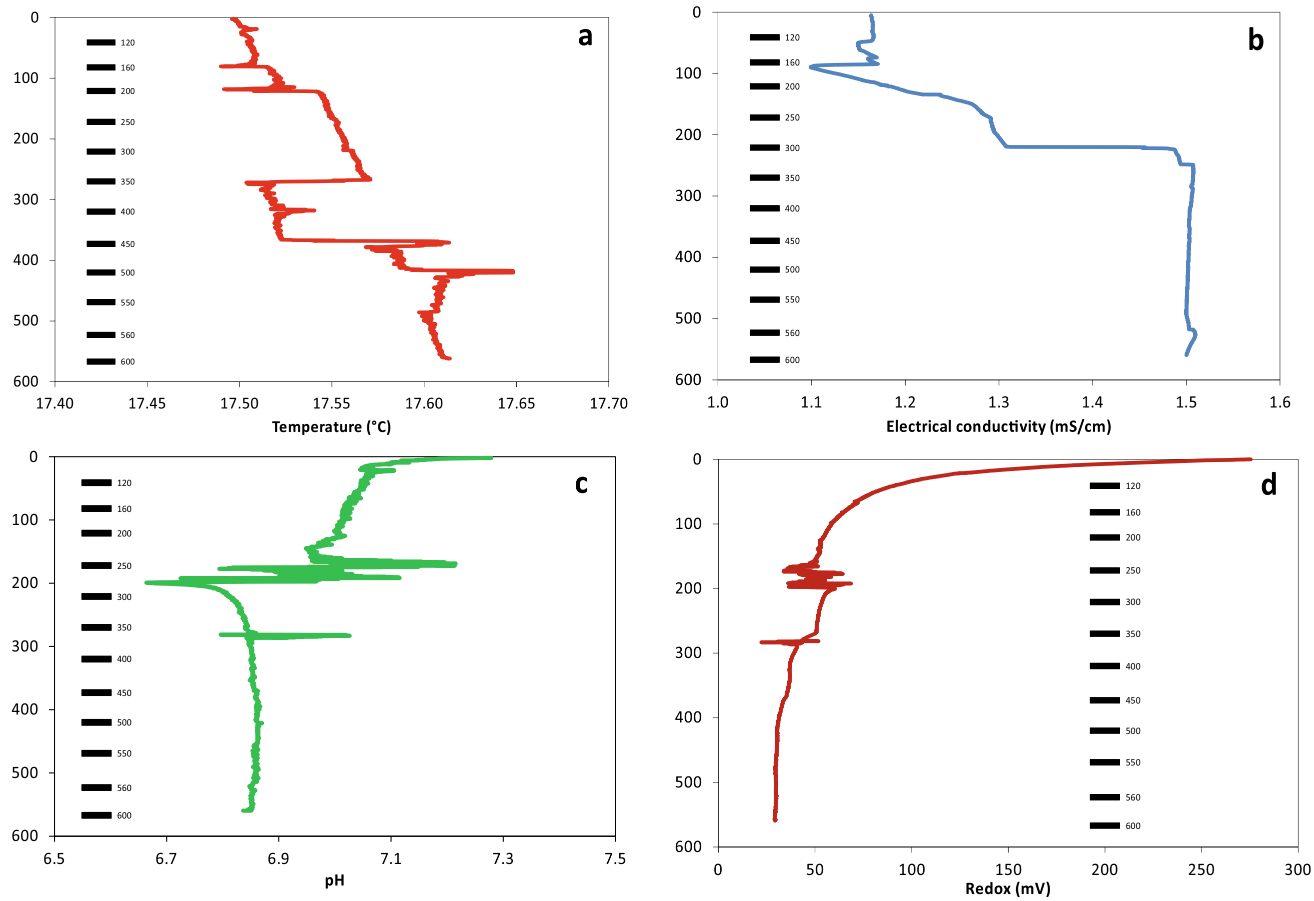


Fig. 4 Graphs showing stratification in various parameters in the flooded Wolf Mine shaft measured in December 2015. The depth on the y-axis is in metres below the water table. **a** temperature (°C), **b** electrical conductivity, **c** pH, **d** redox. The black lines in the graphs indicate levels of flooded mine developments

between 0 and 580 m b.w.t. Some temperature fluctuations of up to 0.1 K were recorded at depth and are noticeable in the data records presented in Fig. 4a. Five temperature zones were distinguished. From the water table to 121 m b.w.t., the temperature increased linearly by approximately 0.02 K. The first interval with major temperature fluctuations (± 0.05 K) was recorded at 121 m b.w.t., followed by an interval with a temperature increasing by ≈ 0.025 K. Another temperature change occurred at 270 m b.w.t, where the temperature decreased by 0.05 K, followed by an interval with temperature rising linearly. At 373 m b.w.t., another sudden increase of 0.1 K was recorded. Below this depth, the recorded temperature values varied randomly by up to 0.05 K (Fig. 4a).

In general, mine water tends to become more mineralised with depth. Wolkersdorfer (2008) explained this trend by the increased duration of the water–rock interactions with depth and the inflow of water from elsewhere at greater depths. The EC data for the Wolf Mine shaft show that although the water became more saline with depth (Fig. 4b), the salinity did not increase gradually with depth. The EC remained relatively constant at ≈ 1.16 mS/cm for the first 90 m b.w.t., and then increased to ≈ 1.3 mS/cm between 90 and 220 m b.w.t. At 220 m b.w.t., records show a sudden rise in EC to ≈ 1.5 mS/cm, and remained constant again between 220 and 580 m b.w.t. (Fig. 4b).

The pH decreased from 7.3 near the water table to 6.95 at 160 m b.w.t. There was a 40 m deep interval between 160 and 200 m b.w.t., in which the pH varied between 6.65 and 7.20 (Fig. 4c). Between 200 and 280 m b.w.t., the pH rose with depth from 6.65 to 6.80. At 280 m b.w.t., the pH fluctuated between 6.80 and 7.05. The pH was relatively uniform at 6.85 in the more saline water between 280 and 580 m b.w.t. The main ore in the mine is siderite rather than di-sulphides and therefore, the mine water was not markedly acidified.

The redox potential (E_h) decreased from around + 275 mV to + 52 mV between the water table down to 160 m b.w.t. (Fig. 4d). Between 160 and 200 m b.w.t., the E_h fluctuated between + 72 and + 32 mV and then decreased slightly to + 45 mV at 280 m b.w.t. In a short interval below 280 m b.w.t., the E_h fluctuated between + 27 and + 52 mV, below which the E_h was relatively constant at + 38 mV. The redox potential was relatively constant at + 35 ± 5 mV in the more mineralized zone between 280 and 580 m b.w.t.

To investigate the changes in the logged physico-chemical parameters, the differential temperature, differential EC, differential pH, and differential E_h were calculated by taking the differences between the parameter values p_i and the mean of the logged values in a range of 20 cm below to 20 cm above the parameter value p_i using the following equation:

$$\Delta p_i = p_i - \ mean(p_{i-2},\ p_{i-1}, p_i, p_{i+1}, p_{i+2}). \tag{1}$$

The differences were calculated from four adjacent single values and the original value. The distance of depth between the individual values is 10 cm. The differential parameters Δp_i were plotted against the depths z_i (Fig. 5). If there is no significant change in adjacent values, the value for function (1) is close to zero for the hypothetical layer at the differential depth, i.e. $f_i \approx 0$. Deviations from zero can easily be identified, and exact locations of even slight variations in parameter values with depth can be easily detected.

Spikes in the temperature data can be seen in Fig. 5a at the water table and at ≈ 80, 120, 270, 320, 375, and 420 m b.w.t. The most important feature was the change in EC at 221 m b.w.t. (Fig. 5b), which matches the 300 m level, the most upper level of the Wolf Mine connected to the San Fernando Mine. Less pronounced spikes were found at ≈ 80, 120, 140, 245, and 520 m b.w.t., some of which again matched the depths of the galleries. Based on Fenchel et al. (1985), there are no known galleries between 140 and 250 m b.w.t. Therefore, the EC variations identified at these depths were not related to galleries.

The differential pH and E_h values (Fig. 5c, d) showed similar patterns but somewhat different from the differential temperature and EC values (Fig. 5a, b). The differential pH and E_h plots in Fig. 5c, d, respectively, show two very prominent features. A broad zone of fluctuations is noticeable between ≈ 160 and 200 m b.w.t., and there is a spike at 280 m b.w.t. These variations are probably caused by water–rock interactions that do not markedly affect the temperature. The differential pH values increased slightly to circumneutral between ≈ 160 and 200 m b.w.t (Fig. 5c). The E_h decreased from about + 72 to + 32 mV, indicating that the conditions became slightly more reducing, and the EC decreased slightly from 1.25 to 1.10 mS/cm with increasing depth (Fig. 5d). These variations suggest that reactions may

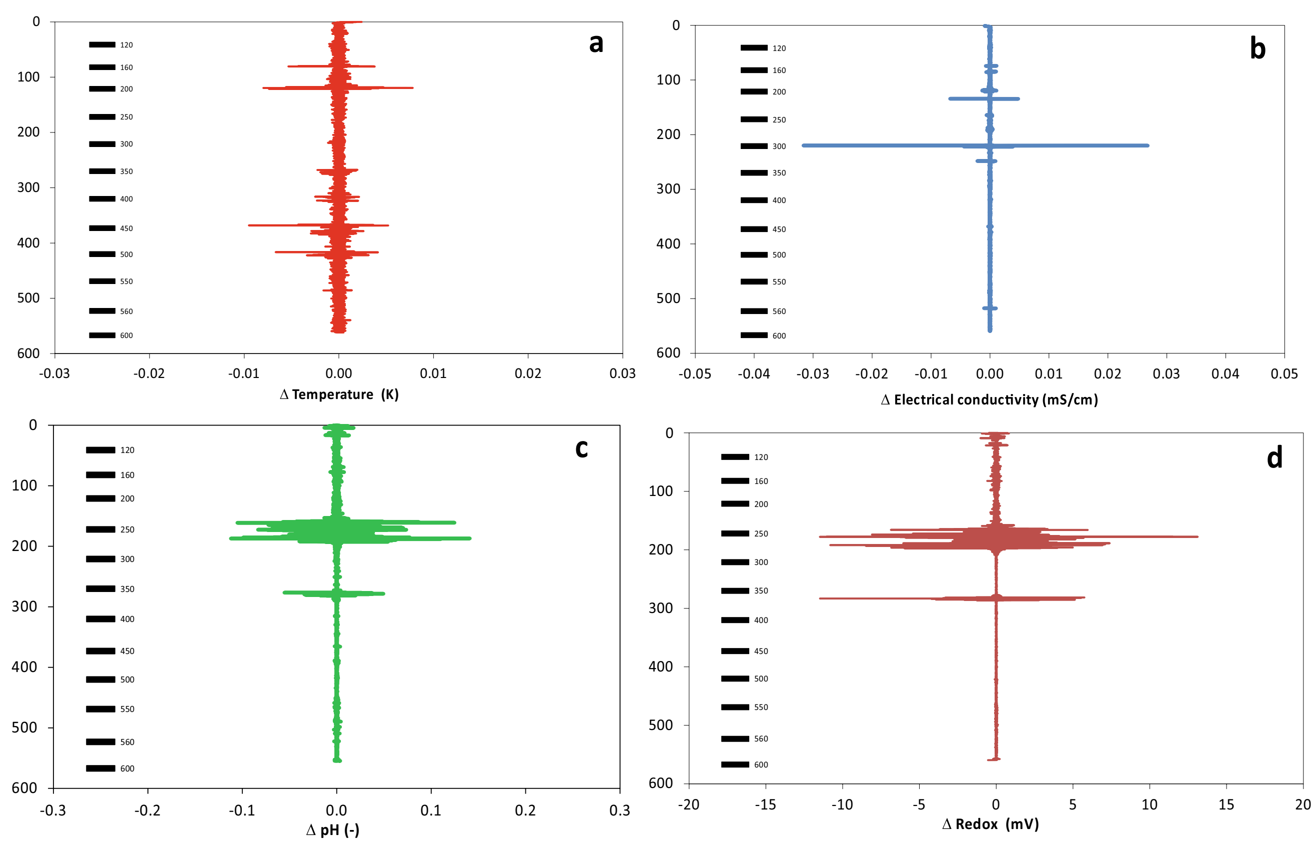


Fig. 5 Differential data for **a** temperature, **b** electrical conductivity, **c** pH and **d** redox potential. The depth on the y-axis is in metres below the water table

have occurred between water circulating within the shaft and water ingressing from open adits. The reactions could have caused the precipitation of minerals and concomitant decreases in water EC and pH buffering. Unfortunately, no turbidity data are available, but the video logs show that the water is slightly more turbid in some parts of the water column than in others.

The most important feature was the change in EC at 221 m b.w.t (Fig. 5b), which matched the 300 m level, the most upper level connecting the Wolf Mine to the San Fernando Mine. It may therefore be concluded that water entering the Wolf shaft at the 300 m level is less mineralised than the water below the 300 m level.

The December 2015 logs (Table 1) were compared with the parameters logged in March 2009 (Streb 2012). These parameter logs were, in general, similar; however, some parameter variations with water column depth were found. The temperature at the water table in the earlier logs was 17.53 °C, increasing to 17.63 °C at 480 m b.w.t., almost the same as in 2015, despite different measurement methods. This suggests a high quality and reproducibility of the data in the different measurement campaigns. Random variations of up to 0.1 K were also found in the earlier logs, particularly from 80 to 120 m, 260 to 360 m, and 360 to 410 m b.w.t. (Fig. 6). The EC was relatively constant, at around 1.08 mS/cm, with some minor changes of ± 10 µS/cm above 360 m b.w.t. The EC was higher below 360 m b.w.t (in March 2009), but not at 1.5 mS/cm between 220 m and 580 m b.w.t., as it was in December 2015. The differences between the EC logs of the two measurement campaigns indicate a change in flow direction. The 2009 data did not show any stratification. This means that either only similar water flows through the shaft or that an upwelling took place. In contrast, the data from 2015 showed stratification, which suggests a main inflow through the 300 m level.

The less mineralized water was clearly related to local groundwater recharge, and the more mineralized water represents mine water exchange during strong recharge events through only the deeper levels. The annual average mine water discharge was 10 L/s, but may exceed 30 L/s after snow melting or intensive rainfall (Streb 2012).

Geothermal Use

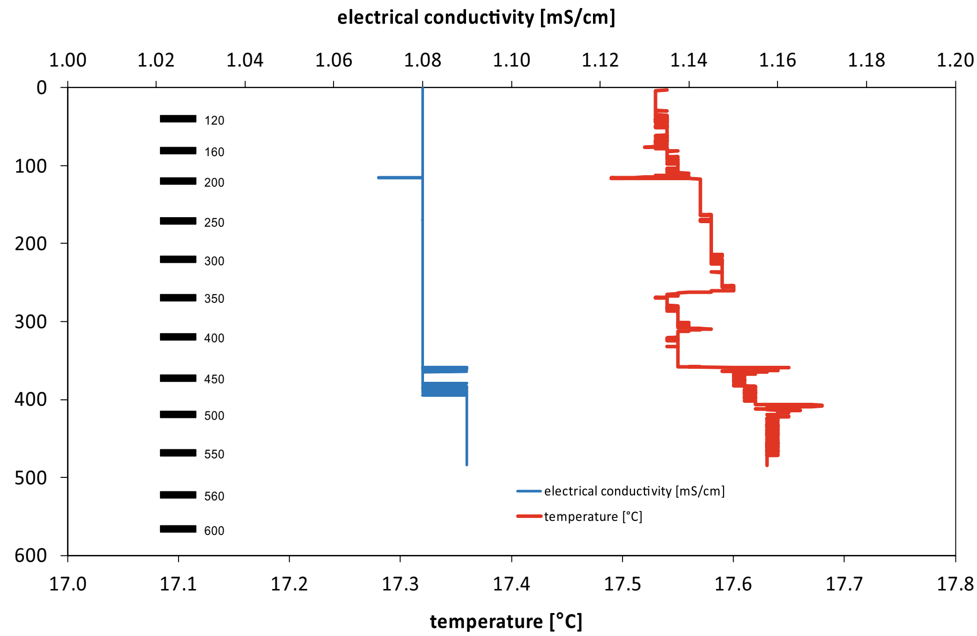
Intriguingly, both the water in the Wolf Mine shaft and the water ingressing from the neighbouring San Fernando Mine were nearly at the same temperature. In their summary of

Table 1 Interpretations of the physico-chemical parameter variations in the water column data for the Wolf Mine shaft, as measured in December 2015

Depth below water table (m)	Gallery	Hydrogeochemical characteristics
0	Water table	System open to the atmosphere, steep gradients in the temperature and CO_2 volatilization and therefore increasing pH and oxic milieu
8	First winze floor	
41	120 m level	
82	160 m level	Ingress of small amounts of cooler and more mineralized water (local anomaly)
121	200 m level	Ingress of cooler water (temperature of shaft water decreased by 0.025 K)
140		Slight change in conductivity curve
172	250 m level	Slight change in conductivity curve, relevant changes in redox potential and pH, strong ingress of more anoxic water with higher pH values
200		
221	300 m level	Significant decrease in conductivity (≈ 200 µS/cm), strong ingress of less-mineralized water
270	350 m level	Ingress of warmer water (temperature increased by 0.05 K) and slight variation in redox potential (E_h increased by 10 mV)
280		Local anomalies in pH and E_h
320	400 m level	
373	450 m level	Ingress of cooler waters (temperature decreased by ≈ 0.08 K)
420	500 m level	Ingress of cooler waters (temperature decreased by ≈ 0.015 K)
469	550 m level	
523	560 m[a] level	Ingress of warmer water
567	600 m[a] level	

[a]Change in reference (from 0 to less than 523 m reference point for level measuring is the Wolfe Mine shaft collar, deeper than 523 m the San Fernando Mine shaft collar)

Fig. 6 Graphs showing measured parameters in the flooded Wolf Mine shaft in March 2009



density stratification theory, Melchers et al. (2015) stated that the temperature reaches equilibrium about 100 times faster than salinity. Thermal conduction is therefore a more efficient transport process than material diffusion in mine water. The mine workings in the study area are tens of kilometres long and act as heat exchangers with volumetric heat capacities of 1.73–5.02 MJ/m^3 for backfill and 1.31–3.52 MJ/m^3 for Devonian sedimentary rock (Wieber et al. 2012; Streb and Wieber 2011).

A geothermal use of the Wolfs Mine water depends on the amount of heat that can be obtained under the conditions determined. The temperature in the flooded shaft was relatively stable, at 17.6 ± 0.5 °C, between 2009 and 2015. The temperature would not have changed markedly even at a maximum outflow from the composite underground mine system of 0.03 m^3/s. At this outflow, the sustainable geothermal potential P_c on the cool side would be (Ochsner 2008):

$$P_c = \Delta T \times F \times C_T \times \rho \approx 0.63 \times 10^6\,\mathrm{J/s} = 0.628\,\mathrm{MW}, \quad (2)$$

where ΔT is the temperature difference for the mine water at the evaporator (usually 5 K for common heat pumps), F is the pumped flow rate (0.03 m^3/s), C_T is the specific heat capacity of water (4187 J/kg/K), and ρ is the density of water (≈ 1000 kg/m^3).

The coefficient of performance (COP) indicates the amount of heat delivered in relation to the power required to drive the pumps (Ochsner 2008). In a case similar to the Wolf Mine, producing water at 35 °C required a COP of 6 (Ordonez et al. 2012), although a lower COP may be achieved in reality. The thermal potential of the warm side would be:

$$P_w = \frac{P_c \times COP}{COP - 1} \approx 0.754\,\mathrm{MW}. \quad (3)$$

The work attributed to the heat pump compressor would be:

$$W_C = P_w - P_c = \frac{P_w}{COP} \approx 0.126\,\mathrm{MW}. \quad (4)$$

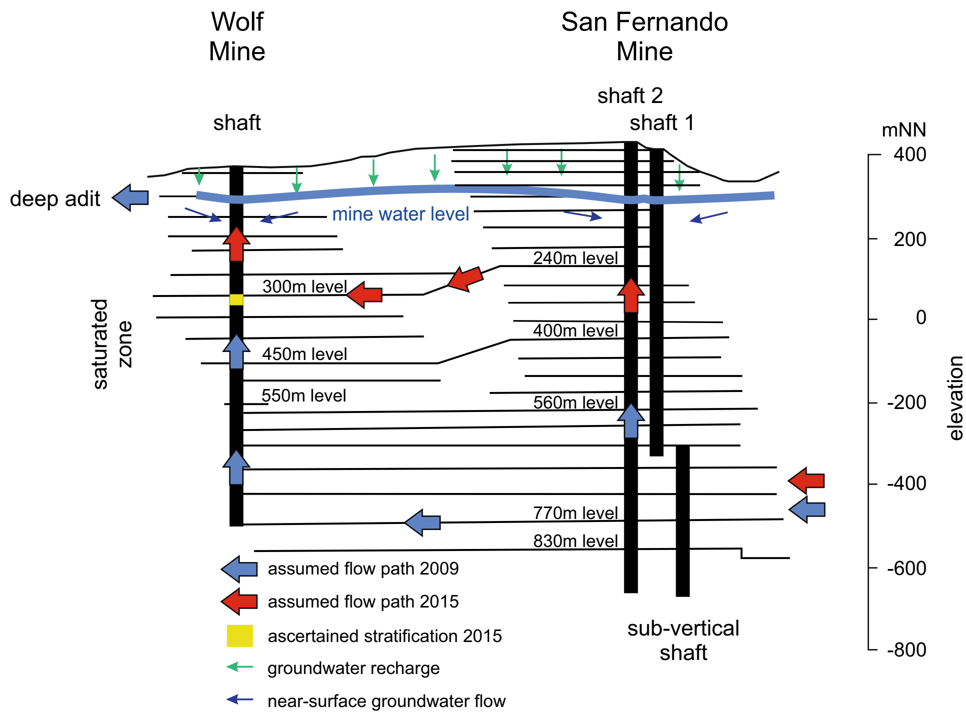
A typical heat pump used for 1700 h/a (Ochsner 2008) would produce 1.3 GWh of geothermal energy using an electric pump consuming 0.2 GWh. Better results would be obtained by connecting two or more heat exchangers in series. This would markedly increase the amount of geothermal energy produced, as an average temperature increase of 10 or 15 K would thus increase the amount of energy generated to 2.6 or 3.8 GWh, respectively.

Summary and Conclusion

Using high-precision logging of physico-chemical parameters, slight differences in parameter values with depth were found in moderately mineralized water (less than 1.5 mS/cm) of the flooded Wolf Mine shaft that is more than 900 m deep. Exact locations and extents of mine water stratification were determined taking the differences between the parameter values and the mean of the logged values.

The Wolfs and San Fernando mines together constitute a complex and extensive underground catchment that drains tens of cubic kilometres of rock and resembles a karst-type ‘anthropogenic aquifer’, with large volumes of water available for geothermal use. The groundwater dynamic of the

Fig. 7 Schematic diagram of the Wolf Mine and the neighbouring San Fernando Mine (Streb 2012) illustrating inferred flow paths and stratification



system is characterized by potentiometric flow between mines several kilometres apart but connected through dozens of flooded mine levels. The main flow passes through shafts and a few flooded levels. This led in the long term to equilibration of physico-chemical parameters of the water in the shaft and to a relatively constant water temperature of 17 to 18 °C from surface to maximum depths measured.

Data obtained during the 2009 investigation campaign suggest that the flow paths at that time were mainly above the gallery below the 560 m level (Fig. 7, blue arrows), which could be proved by tracer tests. In contrast, the data from the 2015 investigation campaign suggest that water entering the Wolf Mine shaft above the 300 m level is less mineralised than the water below this level. Stratification has developed at a depth of 300 m, indicating a change in the flow paths from the deeper levels now to the 300 m level (Fig. 7, red arrows).

The data were used to assess the geothermal potential of the Wolf Mine water. A maximum of 4 GWh of geothermal energy was estimated, assuming an electric pump consuming less than 1 GWh would be used for pumping the water from the shaft. This geothermal energy source has a high potential for supplying heat to local housing, considering that 10 MWh is used in average to heat a typical family house at present climate conditions in Germany. The Wolf Mine system could therefore become an important low-carbon source of energy for heating nearby properties, particularly if locally produced wind power could be used to drive the heat pump(s). This preliminary estimate has not yet been validated by on-site pumping tests. Further investigations are required to test different application scenarios to assess more specifically how the nearly uniform 3D temperature field will react to different heat extraction schemes. The challenge will be to determine the optimum amount of energy that can be extracted sustainably to supply as many properties as possible. An alternative option that should also be evaluated for a sustainable steady-state system would be to use the flooded mine as a geothermal heat storage system. For this purpose, a hydraulically isolated, adjacent mine can be used.

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References

Bailey MT, Gandy CJ, Watson IA, Wyatt LM, Jarvis AP (2016) Heat recovery potential of mine water treatment systems in Great Britain. Int J Coal Geol 164:77–84

Burnside NM, Banks D, Boyce AJ (2016) Sustainability of thermal energy production at the flooded mine workings of the former Caphouse Colliery, Yorkshire, United Kingdom. Int J Coal Geol 164:85–91

Fenchel W, Gies H, Gleichmann HD, Hellmund W, Hentschel H, Heyl KE, Hüttenhain H, Langenbach U, Lippert H-J, Lusznat M, Meyer W, Pahl A, Rao MS, Reichenbach R, Stadler G, Vogler H, Walther H (1985) Sammelwerk Deutsche Eisenerzlagerstätten, I. Eisenerze im Grundgebirge (Varistikum), 1. Die Sideritergänge im Siegerland-Wied-Distrikt. Geol Jb D77 **(in German)**

FH-DGGV (Fachsektion Hydrogeologie der Deutschen Geologischen Gesellschaft e.V.) (2017) Glossar Bergmännische Wasserwirtschaft. 1. Auflage. Neustadt/Wstr **(in German)**

Gleichmann HD (1990) Bergbaumuseum des Kreises Altenkirchen—184 S. Speyer (**in German**)

Jessop AM, MacDonald JK, Spence H (1995) Clean energy from abandoned mines at Springhill, Nova Scotia. Energy Sources 17:93–106

Kirnbauer T, Wagner T, Taubald H, Bode M (2012) Post-Variscan hydrothermal mineralization, Taunus, Rhenish Massif (Germany): constraints from stable and radiogenic isotope data. Ore Geol Rev 48:239–257

LUWG (2005) Hydrologischer Atlas Rheinland-Pfalz, Landesamt für Umwelt, Wasserwirtschaft und Gewerbeaufsicht, Rheinland-Pfalz. http://213.139.159.59/Service/Downloads/Wasserwirtschaft/Hydrologischer-Atlas/. Accessed 21 Aug 2017 **(in German)**

Melchers C, Goerke-Mallet P, Henkel L, Coldewey WG, Wesche D (2015) Density stratification in mine water bodies as a contribution to better long-term water management. Min Rep 151:503–510

Nuttall CA, Younger P (2004) Hydrochemical stratification in flooded underground mines: an overlooked pitfall. J Contam Hydrol 69:101–114

Ochsner K (2008) Geothermal heat pumps: a guide to planning and installing. Earthscan, London

Ofner C, Wieber G (2008) Geothermische Nutzungsmöglichkeiten gefluteter Bergwerke. Fachmagazin für Brunnen- und Leitungsbau, 12/2008, Bonn **(in German)**

Ordóñez A, Jardón S, Álvarez R, Andrés C, Pendás F (2012) Hydrogeological definition and applicability of abandoned coal mines as water reservoirs. J Environ Monit 14:2127–2136

Preene M, Younger PL (2014) Can you take the heat? Geothermal energy in mining. Min Technol 123(2):107–118

Singh RN (1986) Mine inundations. Int J Mine Water 5(2):1–27

Stemke M, Wohnlich S (2014) Stillgelegte Erzbergwerke: Geothermisches Potential am Beispiel Grube Ameise, Siegen. Geotherm Energie 78(1):8–11 **(in German)**

Streb C (2012) Hydrochemische und hydraulische Untersuchungen eines gefluteten Bergwerkes—Thermodynamische Modellierung zur geothermischen Nutzung des Grubenwasserpotentials. Ph.D. Thesis, Univ Mainz **(in German)**

Streb C, Wieber G (2011) Geothermal energy from a flooded mine: a hydraulic model. In: Proceedings of the 11th international mine water association (IMWA) symposium, Aachen, pp 189–193

Wieber G, Streb C (2011) Hydrochemistry and mine water of flooded mines: case studies from the Rhenish Massif, Germany. In: Proceedings of the 11th IMWA symposium, Aachen, pp 633–637

Wieber G, Landschreiber K, Pohl S, Streb C (2011) Geflutete Grubenbaue als Wärmespeicher. Fachmagazin für Brunnen- Leitungsbau 5/2011:34–40, Bonn **(in German)**

Wieber G, Enzmann F, Kersten M (2012) Heat storage potential of a flooded mine in the Siegerland-Wied District, Germany. In: Proceedings of the 12th IMWA symposium, Bunbury/Perth (Australia), pp 459–463

Wieber G, Enzmann F, Kersten M (2016) Entwicklung und Veränderung der Dichteschichtung in Schächten gefluteter Erzbergwerke. Mainzer Geowiss Mitt 44:205–226 **(in German)**

Wolkersdorfer Ch (1996) Hydrogeochemische Verhältnisse im Flutungswasser eines Uranbergwerks—Die Lagerstätte Niederschlema/Alberoda. Clausthaler Geowissenschaftliche Diss 50:1–216 Clausthal (**in German**)

Wolkersdorfer Ch (2008) Water management at abandoned flooded underground mines. Springer, Berlin

Younger PL, Lapierre AB (2000) 'Uisge Mèinne': mine water hydrogeology in the Celtic lands, from Kernow (Cornwall, UK) to Ceap Breattain (Cape Breton, Canada), In: Robins NS, Misstear BDR (eds), Groundwater in the celtic regions: studies in hard rock and quarternary hydrogeology, geological society, London, special publications, vol 182, pp 35–52