Pycnocline Dynamics in an Abandoned and Flooded Mine

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Abstract

Data from our time-lapse sampling and measurement campaign on an abandoned mine in Germany revealed an unstable stratification. Significant but reversible dynamics in pycnocline depths were found to be due to changes in physico-chemical characteristics of the upper water layer above a stagnant water body with high mineralization and density. We observed at times the collapse of the stratification. The dynamics of the layering was caused by an increase in temperature, mineralization, and thickness of the upper layer, hence decreasing the density difference until reestablishing of the upper layer by groundwater recharge of low density.

Key words: Mine water, abandoned mine, pycnocline dynamics

Introduction

This study was performed on one of the many abandoned and flooded mines in the Siegerland-Wied-District of the Rhenish Massif, a Variscan mountain range in the central part of Germany mainly consisting of Devonian schists. Within the area, there are a large number of historical iron and non-iron ore deposits. Mining continued over a period of more than 2000 years but ultimately ceased in 1965. Because of subvertical oriented ore veins, the underground mining reached depths of more than 1000 m. Our aim was to investigate the mine "Grube Georg" for their hydrothermal reservoir and storage potential [1]. The water body in flooded mines is often stratified. However, unlike the case with open waters, data on dynamics of this stratification are scarce.

Geology of the mine "Grube Georg"

The abandoned mine "Grube Georg" is situated in the Wied Ore District in the middle of the Rhenish Massif near the town Willroth directly beside the national highway A3. The dominating Devonian schists are hydrogeologically characterized as joint aquifers with low rock permeability. Interbedding layers of greywacke and sandstone have higher permeability. Fractured quartz and ore veins may also store groundwater. In particular, the mined and backfilled ore veins have high water capacities of ±50%. The ore veins are intensively divided by geological fault zones.

The mine was opened up by two transport shafts, one ventilation shaft, and 23 deep mining tunnels (Fig. 1). The two main shafts were worked down to 967 m and 907 m depth below surface. The mineralization within the steeply inclined veins is dominated by siderite ($FeCO_3$). The ore veins covered an area of up to 860 m² on the 100 m floor, 4790 m² on the 600 m adit, and 2060 m² on the 800 m floor.

During mining activities, the veins were excavated completely and the caverns refilled by excavation material. The volume of mined veins can be estimated at nearly two Mio. m³. The stagnant water within the drained shafts, adits, and fillings has still a volume of about one Mio. m³ (Wieber et al., 2011). While the hydraulics can be described simply as a communicating pipe system controlled by the open shafts and adits, there are also high permeability zones of mined veins and other voids with stope fillings. Both laminar and/or turbulent flow is to be expected in such complex hydraulic systems (Wolkersdorfer, 2006).

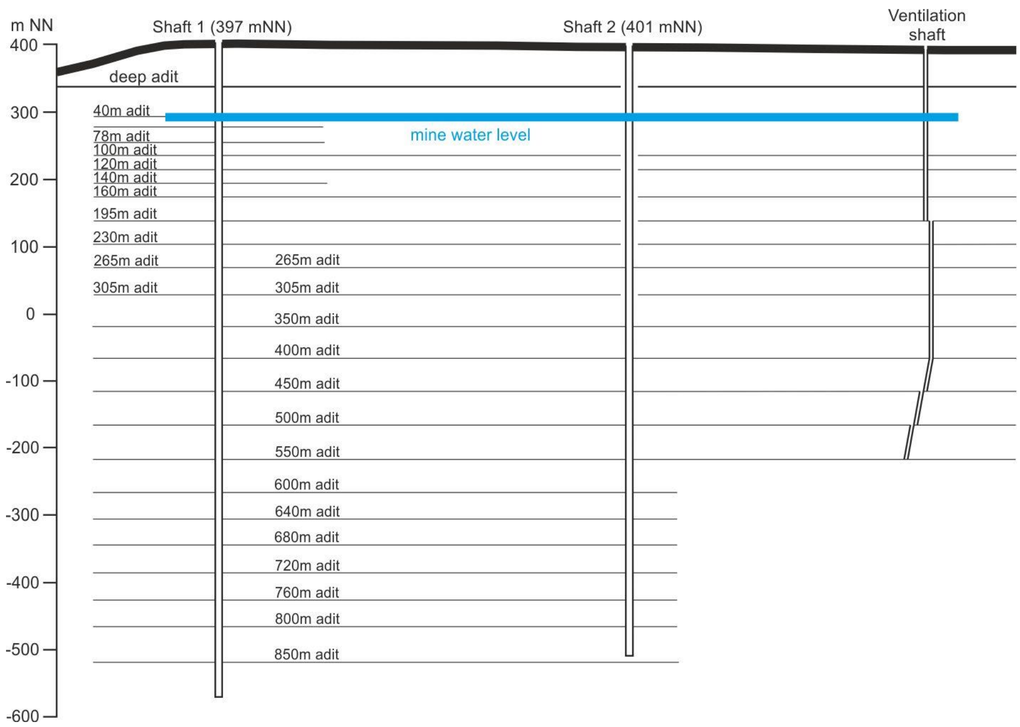

***Figure 1**: **C**ross profile of the mine "Grube Georg", Rhenish Massif (Germany)*

Hydrochemistry of the mine water

The mine water level was detected at a depth of about 100 m. Groundwater of the saturated zone is actually accessible by shaft #2 only [4] . Water was sampled and analyzed at times over a couple of years (Tab. 1). A debris barrier within shaft #2 hampered measurements below a depth of 65 m.

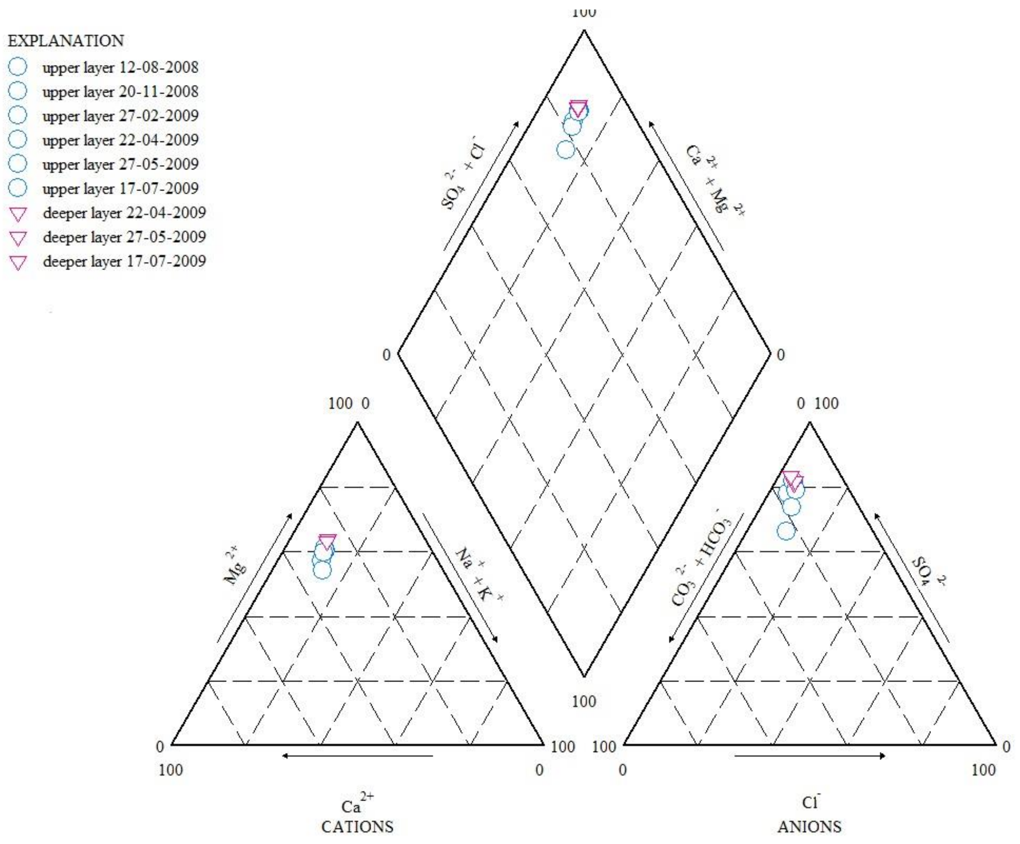

***Figure 2** Piper diagram of mine water*

***Table 1** Composition of mine water samples.*

	Upper layer	Deep layer
Sampling dates	12.08.2008; 20.11.2008; 27.02.2009; 22.04.2009; 27.05.2009;17.07.2009	20.11.2008; 22.04.2009; 27.05.2009; 17.07.2009
Depth below groundwater surface [m]	7 bis 30 m	50 bis 65
Temperature [°C], in situ sensor	15.4 bis 17.8	19.6
pH	7.48 bis7.90	7.39 - 7.45
$eH_{cor.}$ [mV]	278 bis 482	104 - 162
Conductivity [µS/cm]	920 - 2060	2810 - 2840
O_2 [mg/L]	3.1 - 6.3	0.4 - 0.8
Na [mg/L]	36.9 - 78.8	86.5 - 86.8
K [mg/L]	15.5 - 23.6	23.4 - 24.1
Ca [mg/L]	98.0 - 211	229 - 232
Mg [mg/L]	99.0 - 278	328 - 342
Cl [mg/L]	56.4 - 83.8	51.1 - 82.0
SO_4 [mg/L]	480 - 1470	1720 - 1770
HCO_3 [mg/L]	214 - 317	351 - 369
Fe [µg/L]	<25 - 1260	4330 - 4500
Mn [µg/L]	40 - 1930	4160 - 4730
Zn [µg/L	<3 - 120	<3 - 85
Pb [µg/L]	<15 - 60	<43
As [µg/L]	<30	40 - 80

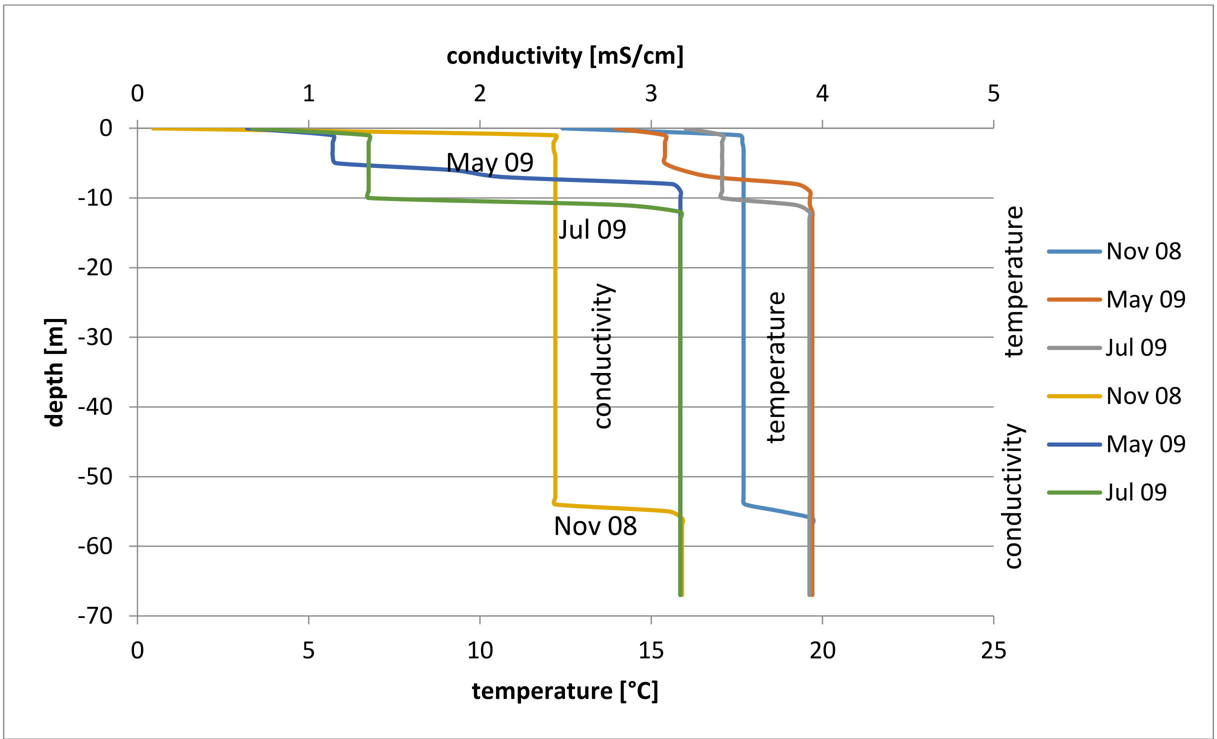

***Figure 3**: CTD profiles and depth of the boundary layer measured in 2008 and 2009*

Electric conductivity and temperature (CTD) logs revealed a strong stratification in the years 2008 to 2009, with a quite steep pycnocline at 55 ± 0.4 m depth in November 2008 (Wieber et al., 2011). The upper layer was characterized by temperatures of 15.4 – 17.8 °C (CTD) and electrical conductivities of 0.920 - 2.06 m. The hydrochemical composition of the deep stratum with higher temperature and mineralization did not change during the period of investigations. Sulfate and alkaline earth metals (Fig. 2) dominate the water chemistry. The concentrations of total dissolved (0.45 µm membrane filtered) Fe and Mn were increased, whereas other trace elements (Zn, Pb, As) were detected at low levels only (Tab.1).

Surprisingly, end of May 2009 a change in pycnocline depth has been found (Fig. 3). The upper water stratum was found now at a depth of only 7.2 ± 1.2 m, with a significantly lower temperature of 15.4 °C and conductivity of just 0.92 mS/cm and, hence, a much steeper pycnocline with density difference of 1.3 kg/m³ (Tab. 2). Already two month later, the density has been found to slowly increase again to 1.14 mS/cm, and the pycnocline was found 4.6 m lower in depth. No any significant change was found in physicochemical characteristics of the lower stratum.

Thermodynamic calculations using the PHREEQC v.3 code with the minteq.v4 database (Parkhurst et al., 2013) indicated that the upper water body was undersaturated while the deep water was at equilibrium (SI = 0 ± 0.5) with gypsum, calcite/aragonite, magnesite, rhodochrosite, siderite, and Na-jarosite. Geochemical equilibration with such minerals typical for the oxidation zone suggests that there was a very minor deep recharge of groundwater, i.e., the groundwater is stagnant.

***Table 2**: Mine water saturation conditions*

	Mineral phases	Saturation index (SI) upper layer	Saturation index (SI) deeper layer
n	number of analyses	6	3
Carbonates	Aragonite $CaCO_3$	-0.10 bis 0.52	0.16 bis 0.25
	Calcite $CaCO_3$	0.10 bis 0.73	0.36 bis 0.44
	Magnesite $MgCO_3$	-0.47 bis 0.26	-0.16 bis -0.08
	Rhodochroisite $MnCO_3$	(-1.38) 0.05 bis 0.37	0.53 bis 0.68
	Siderite $FeCO_3$	-6.10 bis -2.03	0.11 bis 0.22
Sulfates	Anhydrit $CaSO_4$	-1.30 bis -0.79	-0.73 bis -0.71
	Epsomit (Bittersalz) $Mg(SO_4) * 7H_2O$	-3.21 bis -2.53	-2.47 bis – 2.50
	Gypsum $CaSO_4 * 2 H_2O$	-1.02 bis -0.48	-0.44 bis -0.45
	Na-Jarosite $NaFe_3(SO_4)_2(OH)_6$	-0.30 bis 2.58	0.26 bis 0.52
Fe mineral phases	Na-Jarosite $NaFe_3(SO_4)_2(OH)_6$	-0.30 bis 2.58	0.26 bis 0.52
	Siderite $FeCO_3$	-6.10 bis -2.03	0.11 bis 0.22
	Ferrihydrite $Fe(OH)_3$	2.87 bis 3.73	2.84 bis 2.97
Mn mineral phases	Rhodochrosite $MnCO_3$	(-1.38) 0.05 bis 0.37	0.53 bis 0.68

Model of stratification dynamics

The hypothesis of a stagnant water body is corroborated by the fact that there were relatively low water volumes to drain out of the system during active mining, e.g. on the 680 m floor the drainage was only 0.015 m³/s (Fenchel et al., 1985). Although the mining area is located on a water divide without inflow of upstream groundwater and characterized by a mean surface precipitation of up to 1000 mm/a, because of the low Devonian sedimentary host rock permeability, the drainage regime is dominated by surface runoff.

A key to understand this anomalous pycnocline dynamics lies in the decline of the density difference. In between August 2008 to November 2008, it decreased from 0.47 kg/m^3 to 0.35 kg/m^3. This was due to increasing mineralization of the upper stratum as indicated by a rise in conductivity and decreasing undersaturation with respect to above mentioned minerals. This increasing mineralization has led to a break-up of the stratification in between 11/2008 and 5/2009. For reestablishing of the fresh water stratum, and a rise in depth of the pycnocline by 2 m/month, a groundwater drainage of 40 m^3/month is necessary.

***Table 3**: Mine water densities*

Sampling dates	Density of the upper layer (kg/m^3)	Density of the deep layer (kg/m^3)	Difference (kg/m^3)
12.08.2008	1000.61	1001.08	0.47
20.11.2008	1000.73	1001.08	0.35
17.07.2009	999.77	1001.08	1.31

Main implications of the knowledge about the dynamics in physicochemical water characteristics are for the potential use of the mine water body as a geothermal reservoir and storage system (Wieber et al., 2011). This may become severely hampered by a less stable temperature regime. Therefore, the pycnocline dynamics has to be monitored to understand the extent and key factors driving this dynamics.

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