Hydrochemistry and mine water hydraulics of flooded mines: Case studies from the Rhenish Massif, Germany

Georg H.E. Wieber, Christiane Streb

Johannes Gutenberg Universität, Angewandte Geologie, Becherweg 21, D-55099 Mainz, Germany, wieber@uni-mainz.de; Institut für geothermisches Ressourcenmanagement igem, Berlinstraße 107a, D-55411 Bingen, Germany, wieber@igem-energie.de; streb@igem-energie.de

Abstract The Rhenish Massif with its Cenozoic volcanism was a historically important ore mining district with pits reaching local depths of more than 1,000 m. In the now flooded mines, the mine water hydraulics of the saturated zone are characterized by high differences in rock permeability. Mineral water springs are often found in deeper levels of the mines. The hydraulics can be described as a system of communicating pipes dominated by shafts and galleries. Degassing triggers a gas lift and a multi-component turbulent flow. This results in minor differences in the physical-chemical composition of the groundwater within these shafts. Measured temperature and electrical conductivity values are constant for a more than 500 m long vertical profile. Flow velocities between 2 and 40 mm/s were detected.

Key Words mine water, gas lift, turbulent flow, Rhenish Massif

Introduction

The Rhenish Massif is a variscan mountain range in the central part of Germany. It consists mainly of the Devonian rocks of the Westerwald (with the Siegerland-Wied-District) and the Taunus mountains in the east and the Eifel and the Hunsrück in the west. Eifel and Westerwald are regions of Cenozoic volcanism. Foliation produced preferred pathways for mineral/thermal water and carbonic acid gas. Highly mineralized water ascended along fractures and ore minerals precipitated within the voids. The mineralizations are dominated by siderite ($FeCO_3$), galenite (PbS), sphalerite (ZnS) and copper sulfides.

Within the area, there is a large number of historical iron and non iron ore deposits. The ore veins are hosted by Devonian sedimentary rocks. Mining continued over a period of more than 2,500 years and ceased in 1965. The underground mining reached depths of more than 1000 m. In the last period of activities the pits were connected over distances of several kilometers by deep underground adits ending at large scale plants.

Extensive investigations were carried out to explore the hydrothermal potentials of selected flooded mines. In central Europe temperatures increase about 3 °C/100 m with depth. Already during times of active mining, Bornhardt (1912) described mine water temperatures >20 °C at depths of >500 m below surface in the Siegerland-Wied-District (Rhenish Massif). Fenchel *et al.* (1985) locally detected temperatures up to >30 °C (1000 m adit of Grube Vereinigung, 700 m adit of Grube Wingardshardt). After mine closure the water level rose and the hydrochemical composition of mine water changed.

Generally, it is possible to use the geothermal

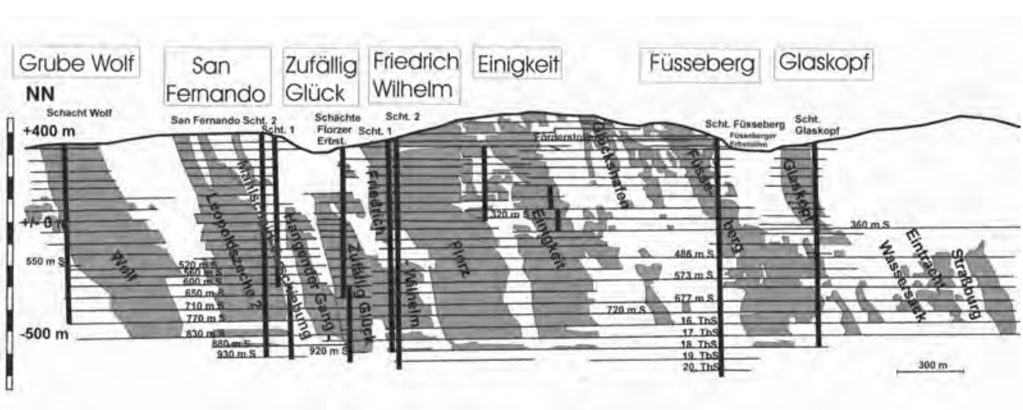

Figure 1 *Cross section of the Wolf – San Fernando – Zufällig Glück – Friedrich Wilhelm – Einigkeit – Füsseberg – Glaskopf mine,Germany*

energy of a) the water drainage or b) the large water reservoir within the flooded mine. For this reason we investigated quality and quantitiy of both the discharged water and the mine water within the shafts for its energy potential. Depth profiles of temperature and electrical conductivity were measured continously up to depths of >500 m.

Mine water hydrogeology

It is a matter fact that underground mining influences groundwater hydraulics. During active mining the groundwater table is lowered by pumping. Additionally, mineral water springs are often found within the mines. Heyl (1954) and Wieber (1999) investigated mine-/groundwater chemistry in the Siegerland-Wied-District and other regions of the Rhenish Massif. Heyl (1954) observed that the hydrochemical composition altered with depths. Different chemical types of groundwater can be distinguished:

- acid predominant sulphate earth alkaline water caused by oxidation of the sulfides;
- nearly neutral, highly mineralized, predominantly bicarbonate earth-alkaline and alkaline water caused by influent of mineral water with carbonic acid;
- deep part of the mine: nearly neutrally, predominantly chlorine alkaline water caused by deep NaCl groundwater in the underground.

In abondoned mines the groundwater table rises and a homogeneous water body can be generated within the shafts and adits. In the Rhenish Massif flooded underground pits are commonly drained by deep adits. The hydraulics can be described as a system of communicating pipes defined by the shafts and tunnels. Additionally, there are high permeable zones as a result of the mined veins and other voids with stope fillings. In contrast, the Devonian sedimentary rocks are characterized by predominant low rock permeability. Several types of laminar and/or turbulent flow can occur in this complex hydraulic system (Wolkersdorfer 2008): Darcy flow, non-Darcy flow such as Poiseuille flow, convective flow or diffusion (no flow). Due to degassing, multi-component flow develops with gas lift and turbulent flow. The dewatering of the important underground mines is characterised by a large discharge of „warm“ water. A description of the hydrogeology of two important mines of the Rhenish Massif follows:

The Wolf – San Fernando – Zufällig Glück - Friedrich Wilhelm – Füsseberg – Glaskopf mine, Germany

This important mine complex comprises the mines Wolf, San Fernando, Zufällig Glück, Friedrich Wilhelm, Füsseberg, Glaskopf (fig. 1). At first, each mine was exploited as a separate pit. In the last period of activity, the pits were connected to each other via deep underground adits over distances of nearly 5 kilometers ending at large scale plants.

After its closure in 1965, the complete pit was flooded. Now the groundwater of the whole underground workings dewaters by the deep adit of the mine Wolf at a level of about +256 m NN (fig. 2). The groundwater of the flooded shafts of the mines Wolf, San Fernando and Füsseberg were analysed. Temperature and electrical conductivity along a vertical profile (fig. 3) of > 500 m (shaft Wolf) and along ≈ 100 m (shaft San Fernando) were continuously monitored.

The chemical composition of the groundwater within the shaft is nearly neutral with an electrical conductivity of around 1mS/cm. The temperature is constantly around 17 °C with only small, seasonal variations (fig 2). The oxygen content is < 1 mg/L and pe values of 6 to 8 were detected.

The groundwater within the shafts can be classified as predominantly earth alkaline bicarbon-

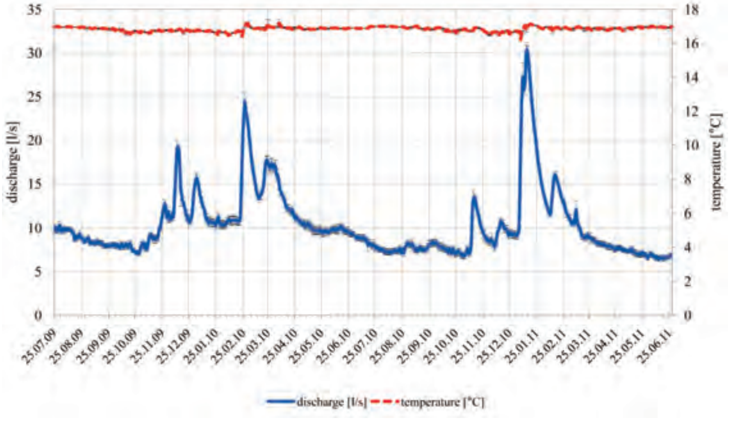

Figure 2 *Discharge hydrograph Mine Wolf, Herdorf, Germany*

ate water. The sum of ions adds up to 26 mmol(eq)/L. Fe and Mn analysis showed concentrations of only a few mg/L. Other trace elements such as As, Al, Cd, Cu, Pb, Zn were either identified with only some µg/L or could not be detected at all.

Locally, as in the shaft of San Fernando, intensive degassing with turbulent flow occurs (fig. 5). In other shafts these phenomena either do not occur at all (e.g. main shaft mine Wolf) or only with low intensity. The base flow is 7 - 10 L/s. The discharge hydrograph (fig. 2) shows that there are several kinds of water. The other discharge water is infiltration water from long periods of rain or snowmelt. This young water contingent can add up to 20 L/s, for instance, in January 2011 after snowmelt. There is a small temperature decrease detected before the discharge increases. This can be explained by the colder infiltration water which circulates in the upper adits. Subsequently, temperature increases slightly. This phenomenon results from the fact that groundwater with higher temperatures is pressed out from the deeper tunnels of the pit.

The temperature and conductivity profile does not show any great variation over a depth of 500 m (fig. 3). The connections to the neighbouring San Fernando mine by the -300 m and the - 500 m deep tunnel are not indicated by variations in temperatures or electric conductivities.

The particle velocity in the groundwater within the main shaft was recorded half a meter below the surface with values between 4 mm/s to 11 mm/s. Assuming that the velocity is similar over the whole shaft section, average interstitial velocities between 0.8 mm/s [7 L/s] and 3.6 mm/s [32 L/s] can be calculated. This method simplifies real groundwater flow because it ignores adit collapses, roughness of rocks and other inhomogenities of the mines. It only indicates the dimension.

The Merkur mine, Bad Ems, Germany

This non-ferrous base metal vein was one of the most important deposits of the Rhenish Massif. Already the Romans mined and smelted lead ore in Bad Ems. The deposit consists of four districts (fig. 4). The most important ones were the "Neuhoffnungsgang" and the "Pfingstwieser Gänge". The thickness of the "Neuhoffnungsgang" added up to 30 meters and the maximal mined length of the vein was 380 meters. Mining reached depths of 800 m below surface. The metal deposits of Pfingstwiese comprise more than 10 individual veins with a thickness of < 2.0 m. The veins are intensively fragmented by geological faults.

Thermal water discharge was observed all over the Emser Gangzug, but the quantity and depth of the inflow changed. The highest water in-leakage occurred in the Neuhoffnung mine below the 8th deep floor level (≈ -220 m NN) and in the Pfingstwiese mine below the 14th deep floor level (≈ -300 m NN). Thermal water flowing into the shafts from the surrounding rocks reached temperatures of up to 48 °C. During active mining, the water pumpage for the whole connected mine (-700 m NN) amounted to 10,100,000 m^3/a (tab.1). Currently, the flooded mine dewaters continuously at 35 L/s (tab. 1) via the Neuhoffnungsstollen (fig. 4).

Mine water from Schacht II, the Weidtman Schacht (Neuhoffnung) and the Hillschacht (Pfingstwiese) was sampled and analyzed. The chemical composition of the groundwater within the flooded shafts is characterised by slightly acid pH values, high carbonic acid contents (fig. 5) and a temperature of 25 °C. The water is highly mineralized (sum of ions: ≈50 mmol(eq)/L with an electrical conductivity >2,100 µS/cm). Hydrogeochemically, the mine water can be classified as predominantly bicarbonate alkaline. High contents

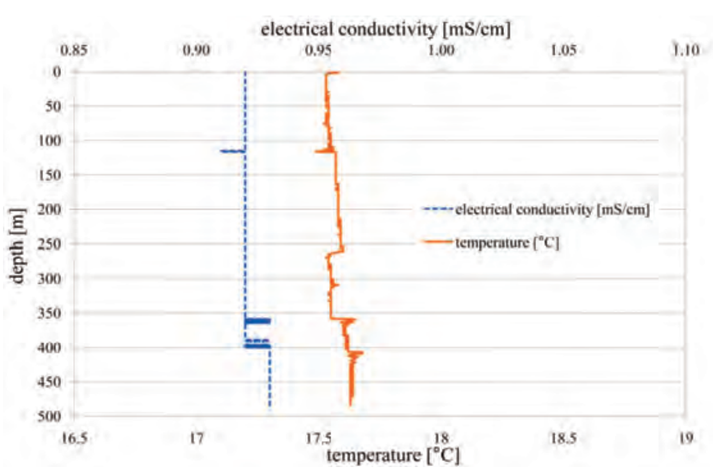

Figure 3 *Depth profile of temperature and electrical conductivity, shaft Mine Wolf, Herdorf, Germany*

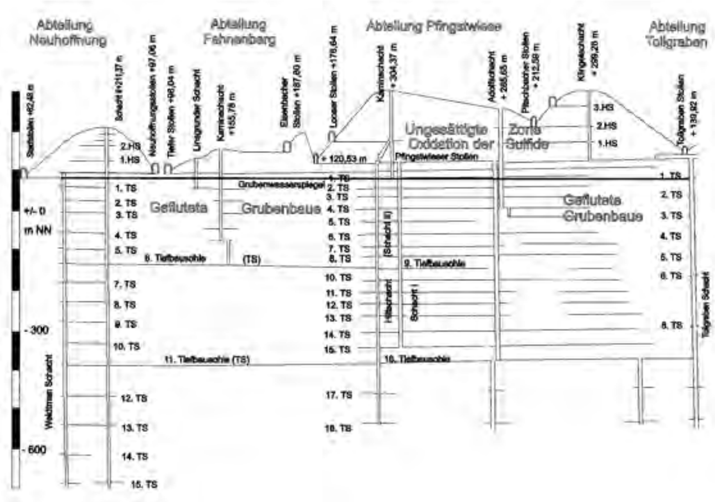

Figure 4 Cross-section of the Merkur mine at Bad Ems, Germany

Table 1 Water pumpage rate and volume of dewatering of the mine Merkur, Germany (Herbst & Müller 1964)

Level of dewatering	Topographic height [m NN]	Volume of dewatering	
Acitive phase:		m^3/a	L/s
Neuhoffnungsstolln level	+97	518,000	16.4
- 5. Tiefbausohle/-5. deep adit without Pfingstwiese	-95	1,080,000	34.2
- 11. Tiefbausohle/-11. deep adit without Pfingstwiese	-385	4,400,000	140
- 11 Tiefbausohle/-11. deep adit with Pfingstwiese	-385	9,600,000	304
- 15 Tiefbausohle/-15. deep adit	-684	10,100,000	320
Flooded Mine:			
Stadtstollen	+82	1,100,000	35

Figure 5 Weidtman Schacht Merkur mine: degassing of carbonic acid

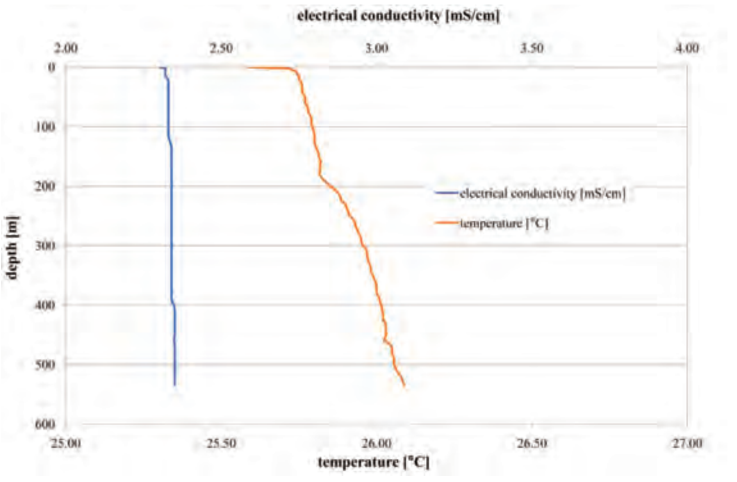

Figure 6 *Depth profile of temperature and conductivity of the Weidtman Shaft Mine Merkur (17.07.2008)*

of iron (< 15 mg/L), manganese (≈1.5 mg/L), nickel (0.7 mg/L) and zinc (1.2 mg/L) were detected.

Profiles of temperature and conductivity were taken at depths of 550 m in the Weidtman Schacht (fig. 6) and the Schacht II. There is a small temperature anomaly at a depth of ≈ 200 m below the minewater surface, which could be caused by the 6th deep adit, which dewaters the Pfingstwiese mine into Neuhoffnung (fig. 4). Below the 6th deep tunnel the temperature increases slowly. Above the 6th deep adit the temperature is nearly constant up to the water surface. This could be an indicator that more thermal water flows to the Neuhoffnung - District than to the other sections (Pfingstwiese) of the mine.

The groundwater flow in the shafts is turbulent. The groundwater flow velocity in the Weidtman Schacht, for instance, reaches values of ≈40 mm/s half a meter below surface.

Other types of mine water hydraulics

Layers of groundwater with different densities can develop in hydraulically isolated pits with "no" groundwater flow and no gas lift. The boundaries between these layers are very thin and the thickness of such layers can vary with time. The water in the deeper layer can even equilibrate to minerals like gypsum (saturation index 0). However, due to convection, the composition of water within each layer does not change (Wieber *et al.* 2011).

Conclusions

In the Rhenish Massif there are a lot of important historical mines with depths of more than 1,000 meters. Springs of thermal water with carbonic acid can be found in the mines. Within the shafts, gas lift and turbulent groundwater flow prevail. There are only minor differences in physical and chemical water characteristics along depth profiles of several hundreds of meters.

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