Geothermal multiple use of mine water from the Wolf–San Fernando–Friedrich Wilhelm composite mine, Rhenish Massif, Germany

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Abstract

In the German low mountain ranges, ore was mined down to depths of over 1000 m in some cases. Mining substantially changed the hydrogeological conditions and created large water reservoirs. There was large scale siderite ore mining in the Siegerland until the 1960s. Some of the mines were connected via mining tunnels to form composite mines. A geothermal multiple use was investigated and installed in a combined mine in Herdorf/Sieg. On the one hand, industrial use is planned on a large scale. Mine water is pumped into a mine via a downstream shaft and infiltrated back upstream into the composite pit after use. With a flow path of 2250 m in the flooded mine systems, the geothermal potential is completely regenerated. The composite pit is drained further downstream of the industrial use. A residential area is being built directly next to the drainage tunnel, which is to be heated entirely using geothermal energy.

Introduction

Looking on climate change I think, everyone should do his bit to reduce carbon dioxide emissions. In addition to major tasks such as the conversion of iron and steel production to hydrogen or the supply of electricity-intensive production with wind energy, many small and mostly decentralized energy uses can make a relevant contribution to the carbon-free supply of society.

A simple way to do this is to use existing thermal energy instead of generating heat by burning carbon-containing materials. Geothermal energy, for example, is extracted from the depths by lifting mine water and feeding it into the surface waters. However, the use of this uplifted or – in the case of flooded mines – free-flowing water does not have to be limited to the extraction of rare elements, as the energy content also represents a “valuable material”.

The focus here is on regions with mines whose mining-hydrogeological situation, in conjunction with the regional water balance, suggests a usable percolation system. Ore districts in the low mountain ranges of the temperate zones can be regarded as suitable regions in this respect. One such region is the Rhenish Slate Mountains, in which the Siegen ore district can be examined more closely (Fig. 1).

Geological conditions

The Rhenish Slate Mountains consist mainly of sedimentary rocks that were deposited in the Variscan Ocean during the Devonian period. In addition to the predominant claystones, siltstones and sandstones, the synorogenic volcanites (keratophyres) and magmatites (diabase) were also pushed together and folded during the Variscan mountain formation. Parallel to and following the folding, hydrothermal solutions penetrated the interface structure of the mountains and thus formed the siderite veins of the Siegerland ore district. Various ores were mined here for centuries.

The Rhenish Slate Mountains, which extend from Belgium far into Hesse, form a moderately developed weather divide between southern and northern Germany. Due to the altitude of the mountain ridges at over 800 m above sea level, this mountain region is characterized by higher rainfall, which leads to a clearly positive water balance.

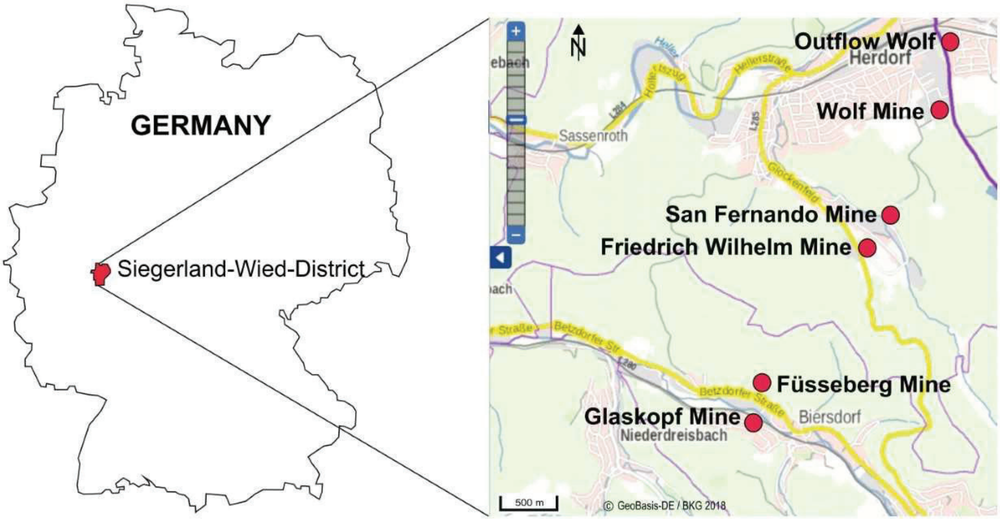

Figure 1 *Germany – Rhenish Slate Mountains (from Wieber* et al. *2019)*

Weathering and erosion of the rock with the formation of a flat, essentially horizontal hull surface result in a high retention of precipitation in the terrain and thus, depending on the rock permeability, also lead to relatively high groundwater recharge of generally 175 mm.

The beginnings of mining in the Siegerland region (Fig. 1) go back around 2500 years into the past. There was a total of over 5000 mines that were focused on various ores. Mining was mainly focused on iron and manganese ores, but copper, lead, zinc, cobalt and nickel compounds were also mined. Rarely, antimony and silver ores were also extracted (Fenchel et al. 1985).

The oxidative transformation of siderite into limonite ($\mathrm{FeOOH \cdot nH2O}$) by oxygen and water ingress results in the formation of an oxidation zone above ground, the so-called iron cap. This loosens the ore above ground and allows water to penetrate underground along veins, faults and fissures. The depth and range of this oxidation zone varies from mine to mine, for example, the iron cap of the San Fernando-Wolf mine extends to a depth of 400 m on the main vein and the Bernhard vein (Fenchel et al. 1985). In contrast, the oxidation zone of the Füsseberg–Friedrich Wilhelm mine was only found to a depth of about 20 to 40 m (Fenchel et al. 1985, Hoffmann, 1964). The deep weathering is achieved in particular where loosening zones caused by faults and fracturing allow the access of day water to greater depths (Hoffmann 1964).

Mine hydrogeology

After ore mining was completed, dewatering was generally abandoned and the groundwater or mine water rose in the mine workings to the level of the deepest adits/shafts, which had a direct connection to the surface. As a rule, these deep tunnels in the Rhenish Slate Mountains were at valley level (Wieber 1999). From the deep adit, they usually drained in free-fall channels to the natural receiving waters. However, the groundwater level does not return to the original level before mining began, as the mine workings continue to lower the groundwater to the deep gallery level. In hydraulic terms, they correspond to deep drainage extending over several kilometers, depending on the extent of mining (Wieber 1999).

Mining was sometimes associated with very complex dewatering measures, with mining extending over the deep levels (below groundwater level) to depths of over 1300 m. After mining ceased, the mine workings were largely flooded, or dewatering was discontinued. As a result, the mine water carried via tunnels and flumes comes to the surface at tunnel mouth holes and is fed to a receiving watercourse in gravity flow.

Wolf–San Fernando–Friedrich-Wilhelm–Einigkeit–Füsseberg–Glaskopf composite mine

The mines were initially operated as independent mines. As a result, there is no connection between the mines at the upper levels. It was only in the last few years of operation that optimizations were made with joint processing plants. This led to connections between the mines via shared underground levels, which created the current hydraulic system.

One of the peculiarities of the Herdorf mine field is the fact that the mine workings form a network in which the mine water circulates or is fed into a deep percolation system (Fig. 2). The drainage of the entire interconnected pit (Fig. 2) takes place from the Glaskopf pit via the Füsseberg–Einigkeit–Friedrich-Wilhelm–San Fernando pits to the so-called conveyor tunnel of the Wolf pit (Wieber et al. 2019). The mine workings of the Zufällig Glück pit are not connected to the interconnected system, as there is no connection via underground levels in the water-saturated zone.

The underground mining facilities with their tunnels and shafts have created a system of "communicating pipes" in which the mine water is collected and drained off after flooding at high flow rates. The original groundwater level is no longer reached after flooding; instead, an oversized subsidence funnel is formed in which deeper groundwater rises and groundwater close to the surface flows in from the side. Approx. 4 million m³ of groundwater or mine water is dammed up in the flooded compound mine (Streb 2012).

Geothermal use

Both the circulating and the outflowing water can be used to generate energy.

The discharge from the Wolf mine's tunnel mouth fluctuates seasonally between > 5 (hydrological summer half-year) and < 10 L/s (hydrological winter half-year). The water here shows a relatively constant temperature of approx. 17 °C, which is only slightly seasonally influenced.

Geothermal uses are planned in an industrial area, which is in a stream valley between the Friedrich Wilhelm and San Fernando mines and a new development area currently under construction at the outlet of the Wolf mine's winding tunnel.

Industrial area

A trial operation for geothermal use is currently taking place here on a small scale. Mine water is extracted from shaft II of

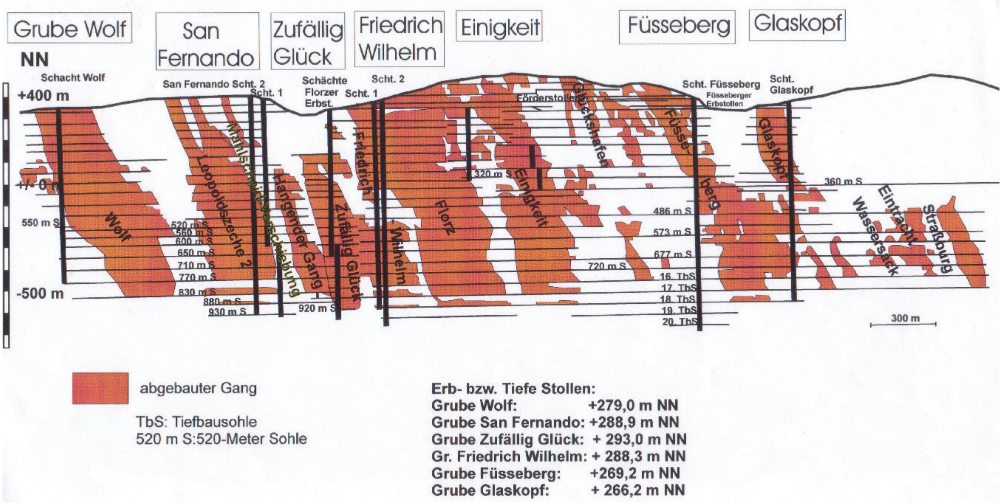

Figure 2 *Cross-section of the Wolf - San Fernando - Friedrich Wilhelm - Einigkeit - Füsseberg - Glaskopf composite mine (modified after Heyl, 1985) Missing: Elevation data for the winding tunnel as the deepest tunnel of the Wolf mine*

the San Fernando mine. After geothermal use, infiltration takes place in a shaft of the Friedrich mine. The infiltrated water flows via the shaft to a depth of 800 m, from there 650 m over the 800 m deep construction level to the San Fernando shaft, where it rises another 800 m. On this flow path of approx. 2250 m, the geothermal potential is completely regenerated even with intensive use (Streb 2012), as the tunnels and shafts here transfer the rock heat to the mine water. They therefore act as heat exchangers. Plans are currently being drawn up for an industrial plant that envisages very intensive cooling for the operation. The town of Herdorf is considering not infiltrating this heated mine water directly but using it for geothermal purposes to heat municipal buildings (e.g. schools, kindergarten, retirement home) and then either using the cooled water for industrial cooling purposes or infiltrating it into the shaft of the Friedrich Wilhelm mine.

Hydraulic investigations (Wieber et al. 2019) show that the flow paths change depending on whether is operated with or without a pump (Fig. 3). During pumping operation in Shaft II of the San Fernando mine, the water flowing over the 800 m deep mine floor rises almost completely (red arrows in Fig. 3). The mine water that is not pumped out again then flows over the 250 m San Fernando level via the 300 m Wolf level to the Wolf shaft, where it exits via the winding tunnel. Stratification occurs in the shaft below the 300 m Wolf level (Fig. 3). If there is no mining in San Fernando, mine water flows directly to the Wolf shaft via underground levels and rises there. Stratification does not occur due to the flow forces (Wieber et al. 2019).

Residential area

The composite pit is drained via the Wolf shaft and drains in a free fall in the "conveyor tunnel" to the tunnel mouth (Fig. 3). The underground tunnel length from the Wolf shaft to the tunnel mouth is approx. 600 m. The mine water flows a few tens of meters from the adit mouth into an open ditch

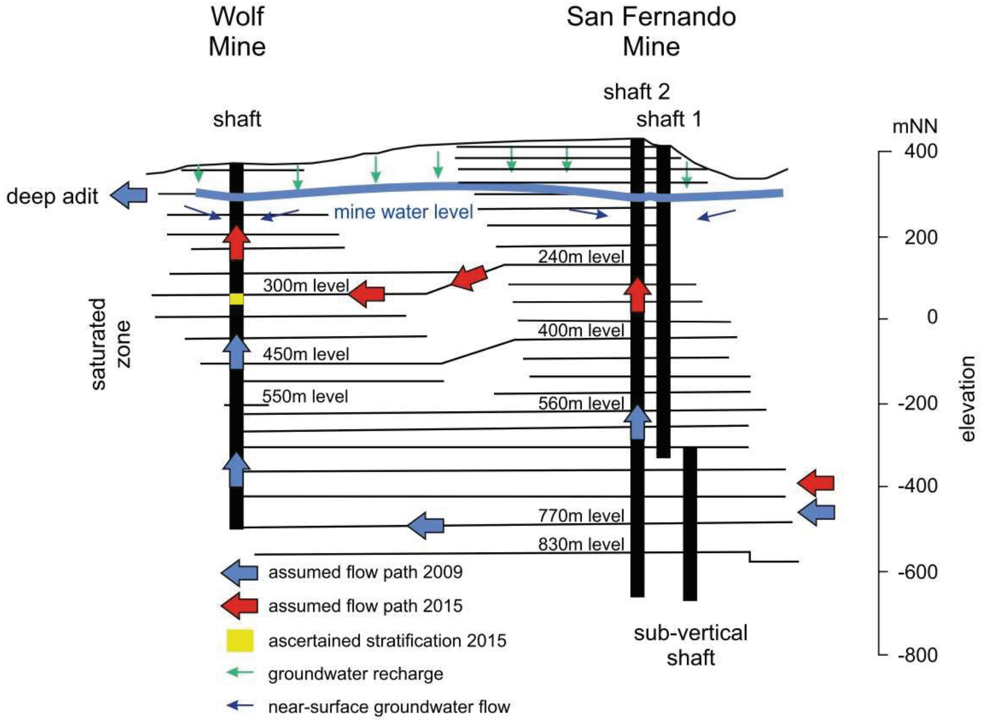

Figure 3 Hydraulic model of the mine water from the Wolf and San Fernando pits with and without pumping in shaft II of the San Fernando pit (from Wieber et al. *2019)*

(surface water) and flows into the surface drainage system of the town of Herdorf, which in turn is discharged into the Heller to the north. The percolation flow is maintained by the hydraulic conditions within the mine network. The highest mine water level is in the mine workings of the Friedrich Wilhelm pit, while the lowest mine water level is at the outlet level of the Wolf pit. There, a hydraulic gradient defined by groundwater recharge and the depth of the outlet ensures constant water movement.

A residential area directly adjacent to the tunnel mouth to the west has been approved in a development plan. Construction is due to start shortly. The residential area is to be heated using mine water geothermal energy. Pipe heat exchangers are planned for this purpose. These are already to be laid underground in the "drainage tunnel"; if necessary, an extension to the surface (open trench) is planned.

With a discharge of 10 L/s and a cooling by 15 K, this corresponds to a potential of 600 KW. If necessary, optimization is possible through water retention in times of non-use or supplementary pumping operation. The residential area has a total living space of 21000 m^2. Heat extraction is planned via tube bundle heat exchangers in the tunnel. The subsequent provision of cold local heating via heat pumps is planned. According to the current state of knowledge, the amount of water flowing freely is sufficient to supply the entire residential area with heat.

Outlook

In the Siegerland region, there was large scale ore mining in flooded underground mines of the siderite mine. Mining reached depths of over 1000 m below ground level. In some cases, the mines at greater depths were connected over several kilometers by underground workings. This led to the formation of large water reservoirs in the otherwise groundwater-poor slate mountains. Connections were created via the shafts and tunnels, enabling high flow velocities (Wieber 1999; Wolkersdorfer 1996; Melchers et al. 2019). The example presented of Herdorf an der Sieg shows that there is a high regeneration potential in these composite mines and that multiple uses are possible. The flooded underground mine floors act as oversized heat exchangers.

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