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Mine Water Utilization for Geothermal Purposes in Freiberg, Germany: Determination of Hydrogeological and Thermophysical Rock Parameters

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Abstract Flooded underground mines provide an innovative opportunity to extract low-grade geothermal energy. To evaluate these geothermal systems, in situ rock sampling and the investigation of thermal (heat conduction) and hydraulic rock properties (thermal convection) is essential. This paper discusses how these geothermal parameters were determined using Freiberg grey gneiss rock samples from the Alter Tiefer Fürstenstolln gallery, where a geothermal mine water project has been successfully carried out in Spring, 2009. Unsteady autoclaving with the unsteady-state two-box method allowed us to measure the permeability of the nearly impermeable gneiss. As expected, samples drilled perpendicular to the rock foliation plane had lower permeabilities than those drilled parallel. Furthermore, it was demonstrated that the permeability varied due to the existence of fissures and the amount of the mantle pressure. The thermal conductivity was also anisotropic, and was higher in samples drilled parallel to the foliation than in those drilled perpendicular to it. Since gneiss is nearly nonporous, the effect of waterlogged pores on the thermal conductivity is minimal. The radiogenic heat production of the sampled Freiberg grey gneiss was found to lie in the lower half of the range of upper crustal metamorphic rocks.

Keywords Mine water utilization · Geothermics · Geothermal energy · Water flow · Heat transport · Geothermal parameters

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Introduction and Background of the Castle Freudenstein Geothermal Project

In Germany, the historical underground mining of ores, hard coal, and industrial minerals have left behind a multiplicity of rock voids, which now contain large volumes of water. It is possible to use such reservoirs as a source of low-grade geothermal energy (e.g. Wieber and Pohl 2008), since such water bodies usually have a near-constant temperature. Another important economic aspect is the existence of accessible shafts and galleries, which can be used for the installation of the geothermal equipment and are often located close to potential users.

Freiberg is located in the northern part of the eastern Ore Mountains in Saxony, Germany and is famous as a traditional silver mining district and an important geosciences centre of Europe. From the fourteenth to the end of the nineteenth century, the Freiberg mine drainage water flowed through the *Alter Tiefer Fürstenstolln* gallery into the Freiberger Mulde River. As a city focused on sustainable energy, Freiberg has embraced the implementation of an innovative idea: using the geothermal energy of the mine water to heat and cool the 500 year old Castle Freudenstein in Freiberg, which also houses the city's prized mineral exhibit, "Terra Mineralia". Since 2005, various committees and organizations have collaborated on developing this concept. An about 200 m long section of the gallery Alter Tiefer Fürstenstolln that lies about 60 m beneath the historic portion of Freiberg was proposed as a suitable heat reservoir for the planned geothermal system. The Castle Freudenstein Geothermal Project was successfully set into operation in Spring, 2009.

Figure 1 shows the schematic representation of the geothermal open loop system. In order to raise the water level in the $\approx$ 200 m section of the gallery (height $\approx$ 2 m, width ≈ 1 m), an obstruction weir (dam) was constructed downstream. The dammed up mine water has a nearly constant temperature of circa 10.2°C; the mean mine water flow is 3.0 L s^{-1}. The mine water has a neutral pH, an electrical conductivity of 0.9 ms cm^{-1}, and a relatively low iron and manganese content, so that it is usable without conditioning, which is not the case at many mines. A two pump loop (6 kW total, with a maximum operational mass flow rate of 6 kg s^{-1}) was installed via two ≈ 60 m deep boreholes that were drilled for the input (diameter 190 mm) and output (diameter 330 mm) delivery of the mine water from the shaft head. A 230 m long connection pipe runs from the shaft head containing the heat exchanger to the Castle Freudenstein, and transports the heat exchanging fluid to heat and cool the castle via in floor heating systems. This twofold direct use of the water for heating and cooling (total heating capacity 160–180 kW, COP ≈ 3.5; total cooling capacity 120 kW, COP ≈ 20) makes the system especially energy-efficient and less expensive than more conventional indirect systems (e.g. Watzlaf and Ackman 2006). Although the return temperature averages 5–6°C in the heating case, the flow temperature and mixing temperature of 10.2°C can almost be kept constant because only a small amount of mine water volume is removed and fed in again by the pumps, and because the bedrock acts as a temperature buffer. Furthermore, the mine water reservoir is post-heated during the cooling case (without the use of the heat pump, return temperature is 14–15°C). In order to ensure an efficient operating control (mixing temperature and water flow, especially potential stratification), temperature is being measured at five points (at the input and output and at three different water depths). The activities of the geothermal system are being monitored and regulated in a control room alongside the Castle. For more details concerning the heat pump technology, see e.g. Banks (2008).

Other examples of locations in Saxony using mine water for geothermal purposes are Ehrenfriedersdorf (a tin mine, geothermal use since 1994) and Marienberg (an uranium mine, geothermal use since 2007); nationwide examples include the Aachen coal mining area (>1,000 m depth) and the Rhenish Massif (a 600 m deep iron ore mine). For international case studies, see e.g. Wolkersdorfer (2008). Such positive experience in using flooded mines as a geothermal energy resource is significant for prospective mine-closing areas like the Saarland and the Ruhr District, where maintenance and repair of the hydraulic junctions and shafts within the mines could aid their future use for geothermal energy generation (Rosner et al. 2008).

Determination of Geothermal Parameters

Fundamentals

The key parameters that influence the geothermal energy of flooded mines are the rock type and its general heat flow characteristics, which is determined by its thermal conductivity, λ (W m^{-1} K^{-1}), specific heat capacity, c_p (J kg^{-1} K^{-1}), and radiogenic heat production, A (μW m^{-3}). These rock properties are influenced by the density, ambient temperature and pressure, and the pore fluid, which in turn depends on porosity, Φ (–), and permeability, k (m^2). Schopper (1982) differentiated between primary porosity, which originates during sedimentation or organogenesis, and secondary porosity, which can be

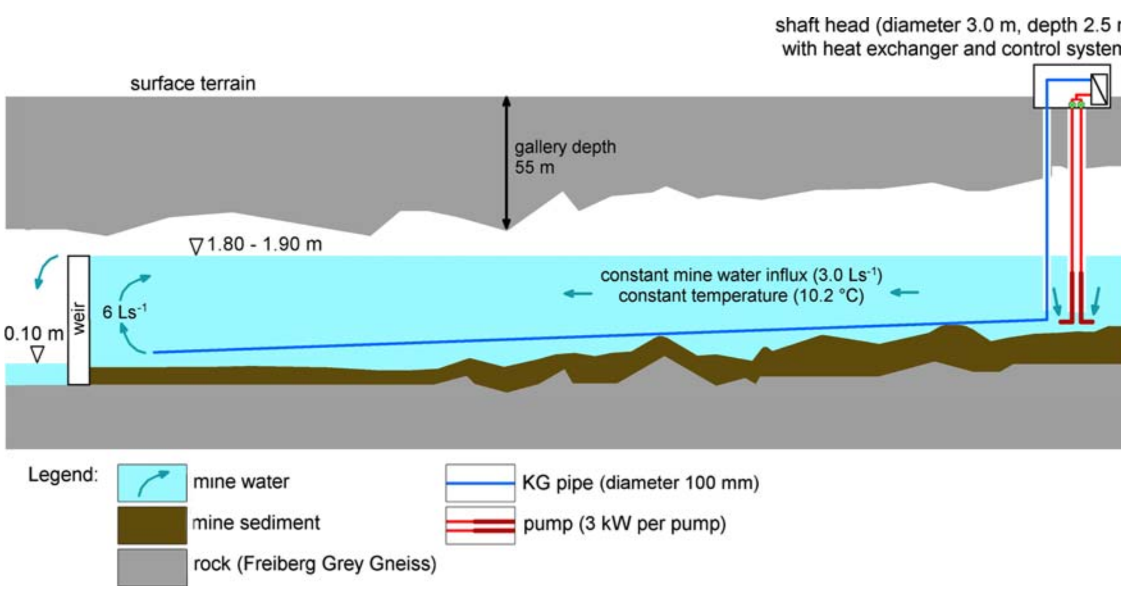

Fig. 1 Schematic representation of the geothermal open loop system "Geothermal Project Castle Freudenstein Freiberg"

ascribed to a later stage of geological development. Four types of porosity exist: (1) intergranular porosity (primary), comprising void space between grains, particles, or fragments of elastic materials (loosely packed, compacted, or cemented); (2) intragranular (inside the grain) porosity (mostly secondary); (3) fissure or fracture porosity (secondary); and (4) vugular porosity (primary or secondary), caused by organisms during genesis or by later stage chemical action.

Permeability is especially important for evaluating crossflow in deposits or underground void space. According to Wolkersdorfer (2008), the permeability is dependent on the mine's depth and the thickness of the rock disaggregation zones around the voids. Mine water monitoring should be focused on the water–rock-interaction zones, for even though water–rock-interaction in these fractured zones have little effect on the fluid flow within the voids, they do influence mine water composition. Gneiss is nearly impermeable, with a permeability of about 10^{-24} m^2 or a permeability factor of circa 10^{-17} m s^{-1}. The fissure and fracture permeability of a nearly impermeable rock is measured using a pressure transient technique. According to Buntebarth (1984) and Clauser (2006), anisotropy exists on various scales: many minerals are anisotropic, but rocks comprising anisotropic minerals can appear to be isotropic due to the random orientation of the crystals within the rock. Tectonic processes can also influence the appearance of anisotropy in the resulting rock formation. Studying samples drilled parallel and perpendicular to the foliation of the rock allows one to consider the anisotropy of the permeability.

The knowledge of the specific heat capacity, the thermal diffusivity, and the thermal conductivity is important for the characterization of a geothermal system. The heat transport in a geothermal system depends on the composition and geometry of the rock matrix, the porosity, and the pore medium (in this case, mine water). In contrast to several volcanic and plutonic rocks, the thermal conductivity of many metamorphic rocks is strongly anisotropic and influenced by the dominant mineral phase (Clauser 2006). As discussed in Börner et al. (2005), the thermal conductivity of igneous and metamorphic rocks decreases with decreasing quartz content and increasing feldspar content. Consequently, gneiss, in general, has a low thermal conductivity. Thermal conductivity decreases with increasing temperature, but the decrease for quartz-poor metamorphic rocks is rather weak compared to quartz-rich ones (Clauser 2006). Structural anisotropy (foliation) has a negative impact on thermal conductivity, as the influences of ambient pressure and ambient temperature probably cancel each other (Börner et al. 2005). Clauser (2006) recommends that thermophysical rock properties—above all, thermal conductivity—should be measured in situ, since they may differ significantly from laboratory values. Because it is best to have an average value over a larger rock volume, a second series of measurements—carried out in situ—would advance the comparability of the laboratory values presented here. However, due to the inaccessibility of the gallery, the sampling of rocks for laboratory measurements was the better choice in this case.

Pressure can also considerably affect the thermal conductivity; with increasing pressure, fractures and microcracks (e.g. caused by the sampling) begin to close, which reduces porosity. Increasing overburden pressure between 15 and 40 MPa does not have a significant impact on the thermal conductivity, but greater increases reduce the intrinsic porosity (Clauser 2006). Since pores are often filled with a low conductivity fluid, the thermal conductivity increases, though according to Clauser (2006), the thermal conductivity of the saturating fluid (in this case mine water) affects the bulk rock thermal conductivity significantly only for large porosities. In fractured rocks like gneisses, there are no bottlenecks, such as occurs between the grains in porous rocks, to provide thermal resistance; consequently, only the type of pore fluid affects the thermal conductivity (for example, the thermal conductivity of water is $\approx$ 20 times greater than the thermal conductivity of air).

According to Clauser (2006), the specific heat capacity quantifies the heat storage capacity of rocks and is affected by temperature, pressure, porosity, and degree of saturation. Hence, in situ values differ from laboratory data; the type and content of pore fluid plays a decisive role as the specific heat capacity of water is very high.

Thermal diffusivity is the petrophysical parameter that describes changing geothermal processes (e.g. the propagation of temperature changes, which also influences the mine water). Thermal diffusivity depends on thermal conductivity, specific heat capacity, and density. According to Clauser (2006), the thermal diffusivity of rocks varies even more strongly with temperature than the thermal conductivity does.

The decay of natural radionuclides produces radiogenic heat in the Earth's crust and makes up the largest internal energy source of the Earth (Clauser 2006). The only geologically significant contributions emanate from (in order of significance) the uranium decay series (decay of ^{238}U and ^{235}U into the stable isotope ^{206}Pb), the thorium decay series (decay of ^{232}Th into the stable isotope ^{208}Pb), and the decay of the potassium isotope ^{40}K (into the stable isotopes ^{40}Ca und ^{40}Ar; Čermák and Rybach 1982). The radiogenic heat production rate is a scalar unit and an isotropic petrophysical property, and is independent of in situ temperature and pressure. Generally, the U, Th, and K content of the gneiss decreases with increasing metamorphosis (Čermák and Rybach 1982).

The Ore Mountains crust is an area marked by a high surface heat flow (Hurtig and Oelsner 1979; Just 1980), which can be ascribed mainly to the occurrence of high-heat-producing granites (HHP-granites, $\lambda > 4\ \mu W\ m^{-3}$), featuring an above-average uranium content (Förster 1999; Förster and Förster 2000). The radiogenic heat production within the continental lithosphere comprises, on average, about 40% of the total surface heat flow. In the Ore Mountains granite areas, measurements as high as $6.7\ \mu W\ m^{-3}$ have been obtained (Förster and Förster 2000), which is quadruple the global average value for the upper crust ($1.8\ \mu W\ m^{-3}$). According to Förster and Förster (2000), the variability of the radiogenic heat production of the investigated granites mainly depends on the geochemical type, the intensity of alteration, and the degree of magmatic differentiation by fractional crystallisation. However, although the Freiberg grey gneiss is a meta-granite (e.g. Tichomirowa 2002), it is not a HHP-granite; its low uranium content presumably explains its comparatively low radiogenic heat production.

Determination of Hydraulic Parameters

Different laboratory methods for the measurement of porosity and permeability of rock samples have been established: while porosity is normally measured by saturation with a liquid at low or high pressure and weighting, permeability is conventionally determined by a steady-state flow test. However, we used the unsteady-state two-box method to determine both of these parameters. The advantages of determining permeability and porosity simultaneously via the unsteady-state two-box method are that it is faster to measure and it provides information regarding the pore content. Furthermore, the minimum observation limit for the permeability is lower, without significantly compromising accuracy. Thus, unsteady autoclaving allows permeability measurements of nearly impermeable material (Häfner et al. 1996).

The unsteady-state two-box method is based on the pressure dependence of permeability, which is determined on samples in an autoclave at confining gas pressures up to 4.5–8.5 bar (in this lab test), using a pressure transient technique. This laboratory method requires the installation of a triaxial cell with different possible combinations of sizes of inlet and outlet pressure boxes, pressure sensors with data communication to a PC, a vacuum pump, and equipment for generating gas and liquid pressure. In order to assure the complete saturation of the effective pores and cracks of the sample, a homogeneous gas is needed; in this case, nitrogen (N_2) was used, though water/brine can also be used. First of all, the volume of each pressure reservoir has to be quantified using the Gas Law. The experimental set-up is shown in Fig. 2. Before the cylindrical sample is

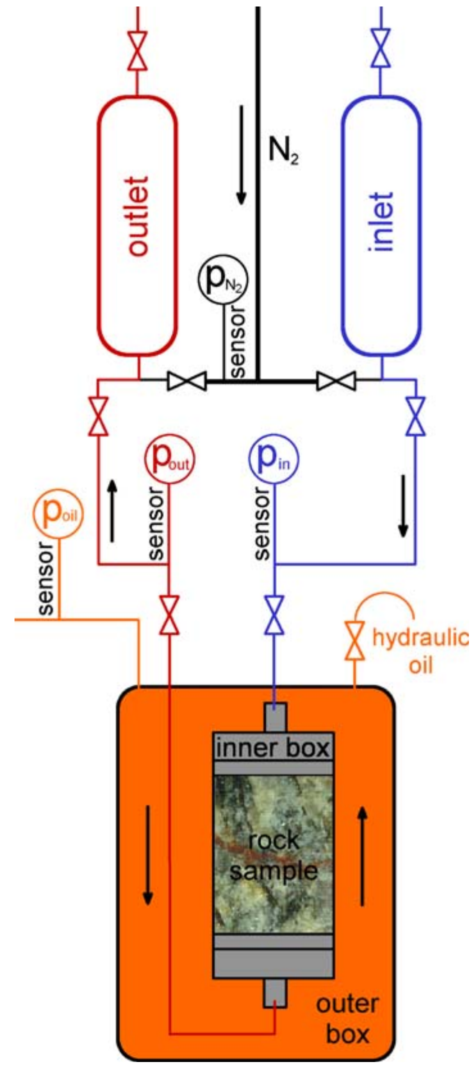

Fig. 2 The experimental set-up of the unsteady-state two-box method

housed in the pressure cell (inner box), it is sealed up with a rubber cover producing an all side mantle pressure between 14 and 25 bar. The outer box is filled with hydraulic oil, which has a set temperature of 22°C. In the inner cell, the top and the bottom of the sample are connected to one pressure reservoir, whereas the inlet, which is connected by a tube system, produces a constant gas pressure at the top and the outlet produces ambient pressure at the bottom of the sample. After opening the two pressure chambers simultaneously, two sensors detect the pressure compensation through the rock sample. A computer registers the pressure values periodically. The laboratory test is finished when inlet and outlet pressure bring each other into line (Häfner et al. 1996).

The interpretation of this unsteady-state two-box method requires a special numerical solution of the flow differential equation:

$$\frac{(\delta^2 p)}{(\delta x_D^2)} = \frac{(\delta p)}{(\delta t_D)} \text{ with } x_D = xL^{-1} \text{ and } t_D = \frac{(kt)}{(\Phi\mu\kappa L^2)} \quad (1)$$

where: L = length of the sample (m), k = permeability (m^2), p = pressure (Pa), t = time (s), t_D = dimensionless time (s), x = coordinate (m), x_D = dimensionless coordinate (m), Φ = porosity (−), μ = dynamic viscosity (Pa s), and κ = compressibility (Pa^{-1}; Häfner et al. 1992).

At the initial state, the pressure in the sample equals p_0. The integral fluid flow in and out of the chambers is used as a differential boundary condition:

$$-\frac{k}{\mu}A\int_0^t \left.\frac{(\delta p)}{(\delta x)}\right|_{x=0} d\tau = V_I\kappa\left[p_I^0 - p_I(t)\right] \text{ at the sample inlet} \quad (2)$$

$$+\frac{k}{\mu}A\int_0^t \left.\frac{(\delta p)}{(\delta x)}\right|_{x=L} d\tau = V_2\kappa\left[p_2(t) - p_2^0\right] \text{ at the sample outlet} \quad (3)$$

where: A = cross sectional area (m^2), V = volume (m^3), p_I = initial pressure (Pa), p_I^0 = initial inlet pressure (Pa), p_2 = outlet pressure (Pa), and p_2^0 = initial outlet pressure (Pa; Häfner et al. 1992).

Two algorithms were developed at the Institute of Drilling Technology and Fluid Mining of the Technische Universität Bergakademie, Freiberg: (1) a semi-analytical solution determined using Laplace and numerical inverse transformations, and (2) a numerical solution determined using the finite difference method. Although both algorithms give equivalent results for liquid flow, the numerical solution is preferred when using gas as the flow medium due to the non-linearity of the Gas Equation. Both solutions have been integrated into a programme for automatic minimization of a target function. This programme, "Parameter Identification PERMI" is connected with a finite difference model and calculates the permeability and porosity by minimizing the variation between the measured and calculated pressure sequences in the boxes via an iteration method; it starts with estimated values for k and Φ and modifies these values until measured and calculated values are about 98% identical (Häfner et al. 1996).

Determination of Thermal Parameters

The transient heat transport in rocks is primarily determined by the thermal diffusivity (10^{-6} m^2 s^{-1}), which was directly measured using the laser-flash method (using the Netzsch-Gerätebau GmbH [Selb/Bavaria] LFA 427 method). The specific heat capacity c_p (J kg^{-1} K^{-1}) was quantified using a multi-detector high-temperature calorimeter. The temperature-dependent thermal conductivity λ (W m^{-1} K^{-1}) can be calculated if the thermal diffusivity, a (10^{-6} m^2 s^{-1}), the heat capacity, c_p (J kg^{-1} K^{-1}), and the density, ρ (determined by the pyknometer method to be 10^3 kg m^{-3}), are known:

$$\lambda = a \cdot c_p \cdot \rho \quad (4)$$

The radiogenic heat production, A (μW m^{-3}), can be estimated using the concentrations of uranium ^{238}U c_U (ppm), thorium ^{232}Th c_{Th} (ppm), and potassium ^{40}K c_K (weight %), the heat production constants for each element (9.52, 2.56, and 3.48 W kg^{-1}, respectively), based on the empirical constants of Rybach (1986) (according to Oelsner (1982), these constants are not feasible for all rock types as the content of the radiogenic elements deviates strongly in each case—so it is only an approximation), and the density ρ (kg m^{-3}) of the rock:

$$A = 10^{-5}\rho(9.52c_U + 2.56c_{Th} + 3.48c_K). \quad (5)$$

These concentrations were measured by gamma-spectroscopic measurements with a germanium (HPGe; n-type) detector. Special software is used to evaluate the spectra and calculate the specific activity of particular gamma emitters in Bq kg^{-1}. These values are then converted into concentrations of potassium, uranium and thorium.

The described measuring methods are discussed in detail in several textbook articles and dissertations (e.g. Buck and Rudtsch 2007; Lotz 2004). As a result, they are neither addressed again nor are the details involved in accomplishing the actual measurements discussed.

Rock Samples from the Freiberg Grey Gneiss

The Freiberg grey gneiss is not only the most common rock type within the Freiberg region but also the oldest rock of the Ore Mountains. Three samples of the gneiss were collected from the sidewalls of the ≈ 200 m long section of the Alter Tiefer Fürstenstolln gallery that would be flooded (dammed up by using a weir) and that therefore would most influence the circulating fluids. The samples were characteristic of the rather coarse-grained Freiberg Normal Gneiss, which is often characterized by an eye-structure and basically consists of quartz (20–30%), plagioclase (20–30%), K-feldspar (15–25%), biotite (15–20%), and muscovite (0–11%). For the permeability investigation, each sample was drilled parallel and perpendicular to the foliation, resulting in a total of six cylindrical samples (Table 1).

Due to the depth of the gallery, all samples were unweathered, but some samples had small cracks or encrustations, which is a sign of fluid flow inside the rock formation. Sample 2 1 (Fig. 3) shows steeply inclined, red-brown fissures, which act as routes of transport for fluids.

Table 1 Permeability determination with the unsteady-state two-box method

Sample	Diameter, cm	Length, cm	Orientation to foliation	Weight saturated, g	Time	Pressure in/out, bar	Permeability *k* measured, m^2
1 l	4.95	4.58	Parallel	232.65	29 d, 21.4 h	5.27/5.20	0.11×10^{-18}
2 l	4.93	1.71	Parallel	80.99	1 d, 1 h	4.6/4.6	0.19×10^{-15}
3 l	4.82	5.28	Parallel	259.78	26 d, 19 h	4.62/4.60	0.16×10^{-18}
1 q	4.95	5.26	Perpendicular	267.95	19 d, 19 h	6.3/3.0	0.50×10^{-19}
2 q	4.94	2.62	Perpendicular	130.62	2 d	4.5/4.5	0.37×10^{-17}
3 q	4.86	5.25	Perpendicular	262.40	31 d, 21 h	8.57/1.71	0.19×10^{-19}

Please note that samples 2 l and 2 q are not representative for the permeability measurement, because they are too short, which could have led to formation of additional cracks and unrepresentative fissures

Small failures in the cylindrical geometry of sample 2 l, which were attributed to the drilling process, were repaired by gypsum; thus, its porosity value could not be measured.

To determine the thermophysical parameters, cylindrical samples were drilled parallel and perpendicular to the foliation (thermal diffusivity: 3.0 mm diameter and 12.6 mm length; specific heat capacity: 4.9 mm diameter and 16.0 mm length). The measurement of the thermophysical parameters was performed with samples dried at room temperature. The calculations were done at 20°C so that the measured values could be compared with literature values. The difference to in situ conditions is described in the text below.

The gneiss sample used for the measurement of the radiogenic heat production came from one of the boreholes drilled for the geothermal project: it contained about 0.8 kg drilling cuttings from the breakthrough in the Alter Tiefer Fürstenstolln gallery (40–50 m drilled), with component parts up to 1.3 cm long. These drilling cuttings were washed and dried at room temperature before being placed into the airproof Marinelli cup (sample container for the arrangement of the samples around the detector for the gamma spectroscopy).

Results

Hydraulic Parameters

The semi-logarithmical plot (Fig. 4) shows the iteration results (coloured dashed line) and the measured data (points) of sample 2 q. The upper and lower outlet pressure values align after a certain time. The pressure conditioning of the inlet and the outlet depends on the permeability and lasts, in the case of nearly tight samples, up to one month (e.g. sample 3 q).

As shown in the semi-logarithmical plot (Fig. 5), a considerable mantle pressure dependence on sample 2 l was measured, which can be attributed to the orientation of the foliation and small fractures. Expectedly, the sample had higher permeabilities associated with the pressure-caused crack closure. That reflects the significant influence

Fig. 3 The top of the sample 2 l showing a small fracture with brownish incrustation

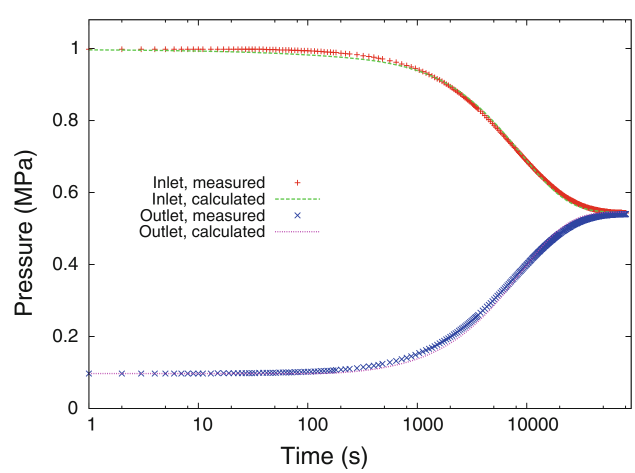

Fig. 4 Measured and calculated data of the sample 2 q with the unsteady-state two-box method

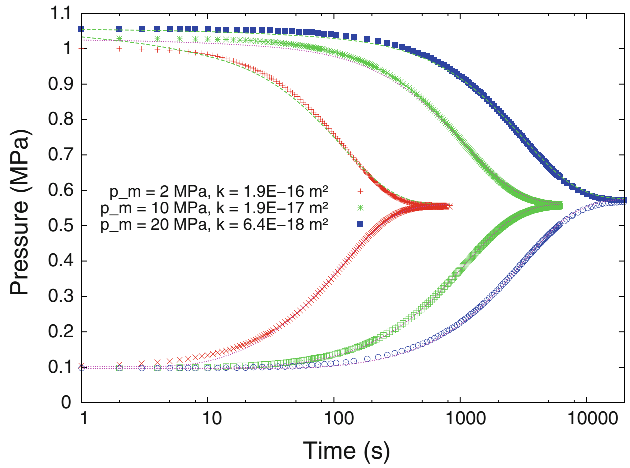

Fig. 5 The sample 2 l under different mantle pressures in the unsteady-state two-box

that the surrounding pressure had on the rock's permeability and thus, the water flow path.

The measured permeabilities of the samples are provided in Table 1. As expected, the samples drilled perpendicular to the foliation feature permeabilities an order of magnitude lower than the samples drilled parallel to the foliation. Samples 1 and 3 show similar permeabilities of 0.11×10^{-18} to 0.16×10^{-18} m^2 drilled parallel to the foliation, and 0.19×10^{-18} to 0.50×10^{-19} m^2 drilled perpendicular to the foliation. Permeability of two to three orders of magnitude higher can be recognized in samples 2 l and 2 q, which is ascribed to the fact that these samples were really too short to be appropriate for the permeability measurement.

Thermal Parameters

The density of the Freiberg grey gneiss, as determined by the pyknometer method, was 2,645 kg m^{-3}. The thermal diffusivity and specific heat capacity measurements are shown in Table 2. At the time of the measurements, all samples were waterless (see next to last column). Since gneiss is a three-component system (consisting of solid rock, pore space, and pore fluid), the fraction of porosity Φ ($\Phi \approx 0.01$) has to be included for the calculation under the assumption that all pores were totally waterlogged (see next to last column in Table 2). According to Huenges et al. (1990), the analytical results are affected by water saturation of about 10%; water saturation does not influence the anisotropy, but does affect the temperature dependence of the thermal conductivity.

As described in Table 2, the gneiss samples show anisotropic properties in thermal conductivity—the samples drilled parallel to the foliation show higher thermal conductivities than those drilled perpendicular. Anisotropy of the thermal transport properties can play a fundamental role, with anisotropy factors up to about 2 for some gneisses (Huenges et al. 1990). The anisotropy of the thermal conductivity is affected by foliation and lineation. However, De Wall (1991) established that the observed anisotropy can be ascribed basically to the orientation of micas (by contrast, quartz grains are weakly oriented and have only a small contribution to the anisotropy).

The samples that were drilled perpendicular to the rock foliation average a higher specific heat capacity (770 J kg^{-1} K^{-1}) than those drilled parallel to the foliation (700 J kg^{-1} K^{-1}). Assuming that all pores (porosity 1%) are waterlogged, the specific heat capacity increases by 60 J kg^{-1} K^{-1} (830 J kg^{-1} K^{-1} perpendicular to and 760 J kg^{-1} K^{-1} parallel to foliation). The comparison of the waterless and waterlogged specific heat capacity of the gneiss demonstrates clearly that the high heat capacity of water has a significant influence.

Table 3 Results of the measurements of the specific activity, *a*, and the calculation of the radiogenic heat production, *A* (density, $\rho = 2{,}645$ kg m^{-3})

	A, Bq kg^{-1}	*a*, ppm	*a*, weight %	Error	*A*, µW m^{-3}
^{238}U	35	2.83		0.2	1.61
^{323}Th	38	9.34		0.5	
^{40}K	880		2.91	0.02	

Table 2 Results of the measurement of thermal diffusivity and specific heat capacity

Sample	Orientation to foliation	Mean thermal diffusivity *a*, 10^{-6} m^2 s^{-1}	Mean specific heat capacity c_p for 25°C, waterless, J kg^{-1} K^{-1}	Calculated mean specific heat capacity c_p for 25°C, waterlogged, J kg^{-1} K^{-1}	Calculated thermal conductivity λ for 20°C, waterless, W m^{-1} K^{-1}
1 l	Parallel	1.82	725	794	3.63
2 l	Parallel	–	–	–	3.53
3 l	Parallel	–	–	–	3.55
1 q	Perpendicular	1.33	776	844	2.00
2 q	Perpendicular	1.01	825	892	2.00
3 q	Perpendicular	1.15	788	856	1.97

Table 4 Thermophysical properties of gneiss and especially the Freiberg grey gneiss

Thermophysical property	Gneiss	Freiberg grey gneiss
Density ρ, 10^3 kg m^{-3}	2.4–2.7[a]/2.64–2.83[c]	2.69[c]
Thermal conductivity λ, W m^{-1} K^{-1}	1.9–4.0[a]/0.94–4.86[b]/2.09–2,93[c]	2.3 ± 2%[c]
Specific heat capacity c_p, J kg^{-1} K^{-1}	667–1000[a]/754–1176[b, c]	979[c]
Thermal diffusivity a, 10^{-6} m^2 s^{-1}	0.63–1.47[c]	0.87[c]
Radiogenic heat production A, μW m^{-3}	2.4 (0.73–4.76)[d]/2.21–3.25[e]	3[f]
Dependence of the thermal conductivity λ, W m^{-1} K^{-1} on the temperature and foliation[c]		
Parallel to the foliation, at 0°C/50°C/100°C		2.16/2.09/2.02
Perpendicular to the foliation, at 0°C/50°C/100°C		3.11/2.93/2.75

[a] VDI (2000); [b] Schön (1983); [c] Schaberg (1998); [d] Rybach (1973); [e] Unpublished measurements at the Technische Universität Bergakademie Freiberg (2005); [f] Förster and Förster (2000)

The results of the measurements of the specific activity and the calculation of the radiogenic heat production are shown in Table 3. According to Förster and Förster (2000), the radiogenic heat production of upper crustal metamorphic rocks, irrespective of whether they are ortho- or parametamorphic, ranges between 1.5 and 3.5 μW m^{-3}, and the paragneiss (metagranite) features values between 1.8 (1.6) and 3.1 (2.8) μW m^{-3}. Consequently, with an estimated radiogenic heat production of 1.61 μW m^{-3}, the sampled Freiberg grey gneiss (which is, as previously mentioned, a biotite-plagioclase-gneiss and a metagranite) lies in the lower half of the range.

As uranium never was mined in Freiberg, the content of radiogenic elements in the mine water is probably lower than in other typical mine waters from the Ore Mountains. The heat production due to radioactive disintegration processes within the mine water and at the contact area of water and rock (ore veins) in the Alter Tiefer Fürstenstolln can be regarded as insignificant. Hence, the potential temperature increase of the mine water due to the disintegration of the radiogenic elements is irrelevant for the running time of the geothermal system, too.

In summary, the thermal and hydraulic properties were found to be influenced by the orientation of the gneiss foliation (anisotropy). Table 4 provides previously measured thermophysical properties of various gneisses and the Freiberg grey gneiss for comparison. However, it is important to understand that most published values comprise gneisses that are heterogeneous in mineral composition, porosity, saturation and other relevant rock properties, and that the measurements are based on different experimental conditions.

Conclusion

Due to economic as well as ecologic reasons, geothermal energy—including the use of mine water—gains in importance worldwide. In the traditional silver mining district of Freiberg/Germany, an approximately 200 m long section of the mine water bearing Alter Tiefer Fürstenstolln gallery was dammed up (using a weir) for geothermal energy generation. Because the heat transfer within the geothermal system is affected by thermal and hydraulic rock parameters, such as thermal conductivity, heat capacity, porosity and permeability, in situ rocks were sampled to allow laboratory determination of these parameters.

The laboratory measurements, which indicated high thermal conductivity and normal radiogenic heat production, are well in line with published values and verified that the Freiberg grey gneiss, with its large portion of crystalline rocks, was suitable for the proposed near-surface geothermal energy use. As anticipated, the foliated Freiberg grey gneiss was found to behave anisotropically. Hydrogeochemical analyses of the mine water and the inflows showed that the mine water was usable without conditioning. The Castle Freudenstein Geothermal Project was successfully carried out in Spring, 2009, in an open-loop system in the Alter Tiefer Fürstenstolln gallery in Freiberg, and the geothermal system is especially energy-efficient and inexpensive due to its twofold use for heating and cooling (160–180 kW heating capacity, 120 kW cooling capacity).

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