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Geothermal Baseline Study for District Heating in the Metropolitan Area of Dresden (Germany)

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ABSTRACT

This paper addresses important aspects of a baseline study aimed at deciphering the subsurface geology and thermal conditions fundamental for the development of a geothermal project targeted at the use of geothermal resources in the metropolitan area of Dresden, Germany. The geological target is a low-permeable diorite−monzonite−granite igneous complex that needs to be developed as an EGS/HDR reservoir. The baseline study comprised (I) the generation of a conceptual geological model to drillable depth, (II) the modeling of the subsurface thermal conditions based upon surface heat flow and a large number of measured thermal rock properties (thermal conductivity, density, and U, Th and K bulk-rock concentrations to calculate radiogenic heat production), and (III) an assessment of the chemical reservoir integrity by evaluating the possible consequences of fluid−rock interactions that may occur during deploying the geothermal reservoir at depth.

1. INTRODUCTION

The growing interest in the provision of alternative energy as one carbon-dioxide reduction option attracted research into geothermal resources worldwide. In Germany, federal organizations as well as communities and local energy providers share these view and become interested in the development of projects targeted at the use of the Earth heat as part of a future energy mix. One perspective option is the use of geothermal energy for district heating systems in urban areas. The city of Dresden (pop. 525,000) in southeastern Germany is a community owing such a large district-heating system for which the base-load use of geothermal heat on the order of 11-12 MW_t is an economically viable option. In contrast to the hydrothermal use of geothermal energy, which has reached a stage of technology readily deployable under favorable conditions (mostly in sedimentary systems), the geothermal potential of sites that need to be developed as Enhanced Geothermal System (EGS) or Hot Dry Rock System (HDR) is nearly untapped due to the immature stage of science and technology for those low-permeability rocks. If geothermal heat should be an option for the city of Dresden, an EGS/HDR concept would be indispensable, based on an engineered heat exchanger developed in crystalline rocks at greater depth.

An integral component of all geothermal plays, regardless whether sedimentary or crystalline rocks are involved, is the geological site exploration (sometimes comprising several phases and including different disciplines of geosciences) to tailor drilling and reservoir engineering concepts. The baseline study presented here is seen as a first measure in the exploration of the Dresden area that needs to be succeeded by further in-depth studies, which should comprise a surface seismic survey and the drilling of an exploration borehole, for improved assessment of the geological system and the target depth at which temperatures (T) of 100 – 120°C occur.

2. GEOLOGY AND ANALYSIS OF THERMAL ROCK PROPERTIES

The Dresden geothermal site is situated in the Elbe Zone, which is a tectonic zone of 25 – 30 km width, bordered by several regional, NW – SE trending fracture zones of different age. The most prominent tectonic feature is a major thrust fault, the Lausitzer Überschiebung (Fig. 1). The Elbe Zone is located between the Cadomian Lausitz Granodiorite Massif (granodiorite, granite) in the northeast and the Variscan Erzgebirge gneisses and the Paleozoic Elbtalschiefergebirge (schists) in the southwest. The Meissen Massif (an intrusive complex of mostly diorite, monzonite, and granite) forms the central part of the zone. The central and southeastern parts of the study area are covered by sedimentary rocks of Cretaceous and Permo-Carboniferous age.

The temperature prognosis could not take advantage of T data measured in boreholes, so that the T assessment is entirely based on modeling. The lack of T data also prevented the determination of a surface heat-flow value. Thus the *conceptual geological model* for the thermal model was set up to a depth of 20 km (Fig. 2), to apply thermal boundary conditions derived from regional terrestrial heat flow at Moho depth. In the central part, the model comprises the presumably 8-km-thick assemblage of igneous rocks of the Meissen Massif. It is assumed that the upper part of the massif down to a depth of about 5 km is mainly composed of monzonites/syenites replaced by gabbros/diorites in the lower part. To the west of the massif are the slates of the Elbtalschiefergebirge, to the east the Osterzgebirge gneisses, respectively. In the depth range of 8 – 15 km, the crust is composed of igneous plus para- and orthometamorphic rocks. Amphibolites and gneisses form the crust at depths of 15 – 20 km. This model configuration benefitted from seismic data (Behr et al., 1994), a crustal thermal balancing (Förster and Förster, 2000), gravimetric and magnetic surveys, as well as from data of the mining industry and from tunnel excavations (Krentz and Koch, 2010, and references therein).

An extensive program of laboratory measurements formed the basis to determine t*hermal conductivity* (TC) of all volumetrically important igneous and metamorphic rocks. Measurements were performed by using the optical scanning method (Popov et al., 1999), termed Thermal Conductivity Scanning (TCS). The technique is described in detail e.g. by Fuchs et al. (2013). Samples were measured under ambient temperature and pressure conditions in a dry state. Due to the low porosity of the crystalline rocks, a correction of TC for water saturation was not necessary. For the TC of the thin Cretaceous sediments in the central parts of the modeled profile (Fig. 1, Fig. 2) a value of 4.0 $Wm^{-1}K^{-1}$ was used. The error in T prediction caused by the uncertainty of this adopted value is negligible as the sedimentary unit above the metamorphic and igneous rocks is thin.

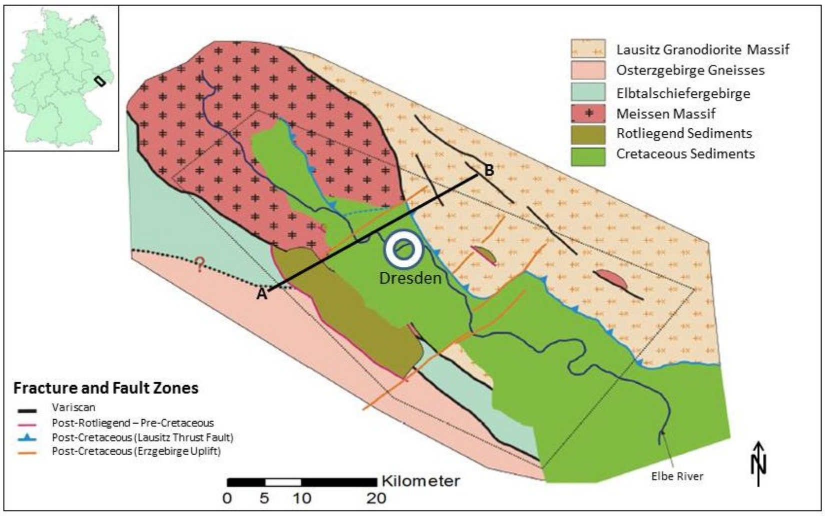

Figure 1: Surface geology of the study area (rectangle) in the Elbe Zone near Dresden (Stanek, 2010). A – B denotes the location of the cross section shown in Figure 2. Inset map delineates the location of the study area in Germany.

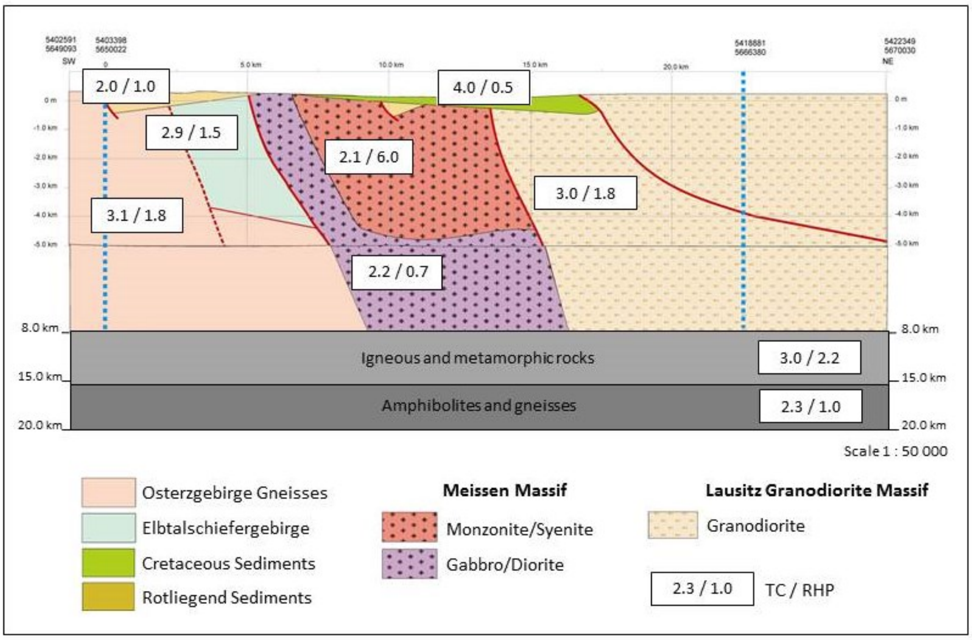

Figure 2: Simplified geology along a SW – NE cross section A – B (for trace see Fig. 1) (modified after Stanek, 2010) with major rock types and their thermal rock properties (after Förster and Förster, 2010). TC is thermal conductivity, RHP is radiogenic heat production. Vertical axis is out of scale.

The gneisses of the Osterzgebirge show a consistent TC with an average value of 3.1 ± 0.3 $Wm^{-1}K^{-1}$ (Fig. 2). More diverse is the TC of the metamorphic rocks in the Elbtalschiefergebirge unit with values between 2 $Wm^{-1}K^{-1}$ (mafic tuffs) and 6.6 $Wm^{-1}K^{-1}$ (silicic slates). The most common rock type in the unit is argillaceous slate with TCs between 2.0 and 4.8 $Wm^{-1}K^{-1}$. However, the weighted average TC (2.9 ± 1.0 $Wm^{-1}K^{-1}$) of the Elbtalschiefergebirge is quasi-identical to the TC of the westerly gneisses. Intermediate to mafic rocks of the Meissen Massif have a consistently lower TC. The monzonites expose an average TC of 2.1 ± 0.3 $Wm^{-1}K^{-1}$, which is similar to the gabbro/diorite value of 2.2 $Wm^{-1}K^{-1}$. A TC of 3.0 $Wm^{-1}K^{-1}$ typifies the granodiorites of the Lausitz Granodiorite Massif. TC for the Permian was assumed to 2.0 $Wm^{-1}K^{-1}$ and for the Cretaceous sediments to 4 $Wm^{-1}K^{-1}$, respectively.

Radiogenic heat production (RHP) was calculated according to the equation of Rybach (1976) using measured rock-density values and the whole-rock concentrations of U, Th and K measured either by XRF and ICP-MS. Rocks abnormally rich in heat-producing elements are the monzonites/syenites of the Meissen Massif. If samples showing effects of mineral alteration are discarded, the average RHP is 6 µWm^{-3} (Förster and Förster, 2010). This high average is well substantiated (32 samples) by low standard deviation. Compared to the monzonites/syenites, all other rocks in the study area show normal RHP. The lowest values are observed for the gabbro/diorite unit (0.7 – 1.2 µWm^{-3}; Förster et al., 2010). The RHP of the Osterzgebirge gneisses display an average value of 1.8 (n = 25), which is identical with the value for the granodiorites of the Lausitz massif (Förster and Förster, 2010, and references therein). The metamorphic rocks of the Elbtalschiefergebirge display the largest range in values (0.6 – 2.3 µWm^{-3}, determined by gamma spectrometry), with a weighted average of 1.5 µWm^{-3} considered in thermal modeling. RHP of sediments assigned to the thermal models was taken from literature values for the respective rock types.

3. TEMPERATURE MODELS

Thermal models are generated using the equation for 2-D steady-state heat conduction and different contributions of RHP. The TC used in the models reflects isotropic rocks and are treated as a temperature-dependent parameter. The heat equation is solved by a numerical finite-element approach using the PDE toolbox of the commercial software MATLAB6.5. For calculation of the T-dependence of thermal conductivity, the experimental results obtained by Seipold (2001) for different rock types are considered. To exclude side effects on the modeling results, the conceptual model was enlarged on each side by 5 km. A constant surface temperature of 8°C is applied as upper thermal boundary. At the side boundaries, horizontal heat transfer was set zero. The lower model boundary (at 20 km) is defined by a heat-flow value. Two different scenarios are eligible for this value owing to varying results on the Moho (mantle) heat flow at 30 km: (I) 25 mWm^{-2} (Förster and Förster, 2000) and (II) 30 mWm^{-2} (Norden et al., 2008). Interestingly, both regions of different Moho heat flow display the same depth of the thermal asthenosphere (Heuer et al., 2007) so that the difference can entirely be attributed to the thermal balancing using a known surface heat flow. In turn, the lower boundary heat flow at 20 km then will be (I) 30 mWm^{-2} resp. (II) 35 mWm^{-2} considering the heat budget of a 10-km-thick lowermost crustal unit (mafic amphibolites/felsic gneisses/metabasites/mafic granulites, RHP between 1.0 and 0.3 µWm^{-3}) to be 5 mWm^{-2}.

The thermal models (Fig. 3) delineate isotherm patterns that differ slightly with respect to location on the cross section and the depth of observation. In the shallow part of the section (< 2 km), T in the west (Elbtalschiefergebirge and Osterzgebirge) is slightly higher than in the east (Lausitz Granodiorite Massif). The higher T is due to the comparatively lower TC of the Rotliegend sediments. At ≥ 2 km depth, the warmest subarea along the cross section is the Meissen Massif, which results from a combined effect of low TC and high RHP in the monzonite/syenite unit. Temperatures between 3 and 7 km are consistently higher by 15 – 20°C than in the adjoining areas. Thus, temperature-wise, the most favourable subarea for a geothermal development is the Meissen Massif.

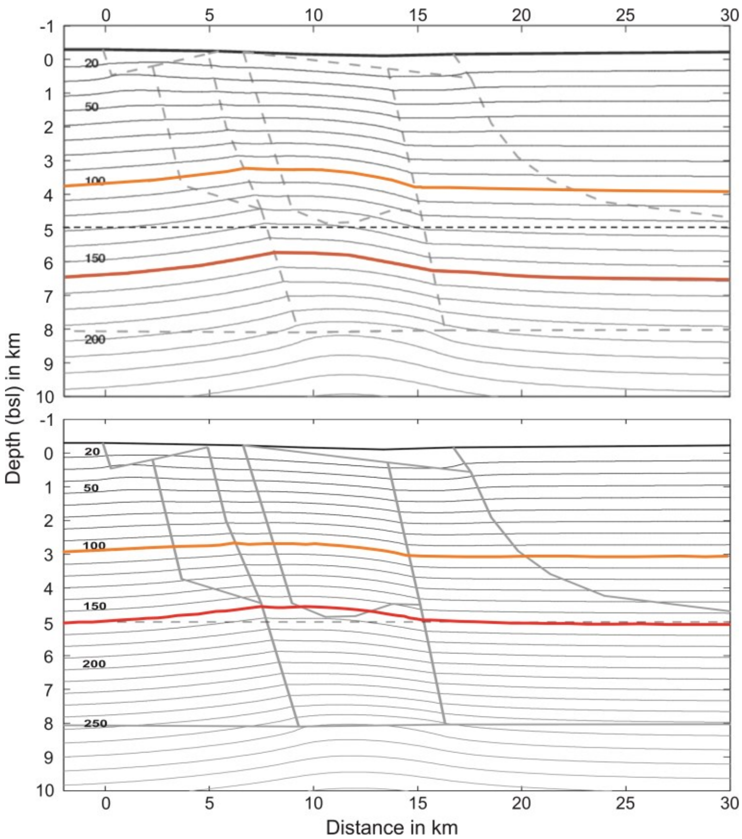

Figure 3: 2-D temperature models along profile A – B. Geology is provided as background. For better orientation, the 5-km depth (below sea level) is shown as stippled line and the 100°C (yellow) and 160°C isotherms (red) are marked in color. Upper: isotherms according to a lower-boundary heat flow of 30 mWm–2 [heat flow scenario (I)] and thermal rock properties according to Figure 2 (Förster and Förster, 2010); Lower: isotherms according to variations in thermal rock parameters (see text) combined with a higher lower-boundary heat flow of 35 mWm–2 [heat flow scenario (II)].

The upper diagram in Figure 3 delineates T of 100 – 160°C between 3.5 and 6 km depth (heat-flow-(I) scenario) for the massif. At 5 km, the model predicts T of ~ 140°C. In the heat-flow-(II) scenario, respective temperatures are slightly higher (by about 15°C). Changes in the geological model by substituting gabbro/diorite by monzonite/syenite also would raise T by 10°C. The resulting values of the surface heat flow in both boundary heat-flow scenarios are on the order of 65 – 70 mWm^{-2}. To estimate maximum possible T, a geologically reasonable variation of the input thermal properties was made for an economically most optimistic scenario. The parameter variation pertains to a lower TC value for the Osterzgebirge gneisses (2.7 $Wm^{-1}K^{-1}$), the rocks of the Elbtalschiefergebirge (2.5 $Wm^{-1}K^{-1}$) and the granodiorite of the Lausitz Massif (2.6 $Wm^{-1}K^{-1}$). All these values are at the lower end of range measured for these units and could be applicable if a higher percentage of the particular subspecies of rocks of lower TC are dominant. Simultaneously, the RHP for the gabbros/diorites was set higher (1.2 μWm^{-3}) according to Förster et al. (2010). For the Meissen Massif, this parameter variation yields at 5 km depth T on the order of ~ 150°C (heat-flow-(I) scenario) and of ~ 170°C (heat-flow-(II) scenario) (lower diagram in Fig. 3), which is consistent with an T increase 15 – 20°C compared to results shown in the upper diagram of Figure 3.

4. MOBILITY OF RADIOACTIVE ELEMENTS DURING WATER-ROCK INTERACTIONS

Monzonites/syenites constitute the envisioned reservoir of the Dresden deep geothermal project. In these rocks, Th (55%) and U (40%) account for almost all radioactive heat generation. To examine potential risk of contamination of the geothermal fluid by radioactive elements during operation of the plant, the main mineralogical hosts of Th and U were studied by electron microprobe and LA-ICP-MS (Förster et al., 2010). These studies identified thorite (Fig. 4a) as the main repository of both Th (75% of the whole-rock budget) and U (40%). It is followed by zircon (Fig. 4b), which account for ~ 10% of the Th and 20% of the U budgets. Another minor host of U is fluorapatite (~ 20%). Other Th–U-bearing accessory minerals [allanite-(Ce), titanite] contribute insignificantly to the rock radioactivity. All these species are comparatively stable at the T–p conditions anticipated for the operation of the geothermal system. Consequently, the risk that significant amounts of radioactive elements get mobilized during water-rock interaction in the reservoir is assessed minor.

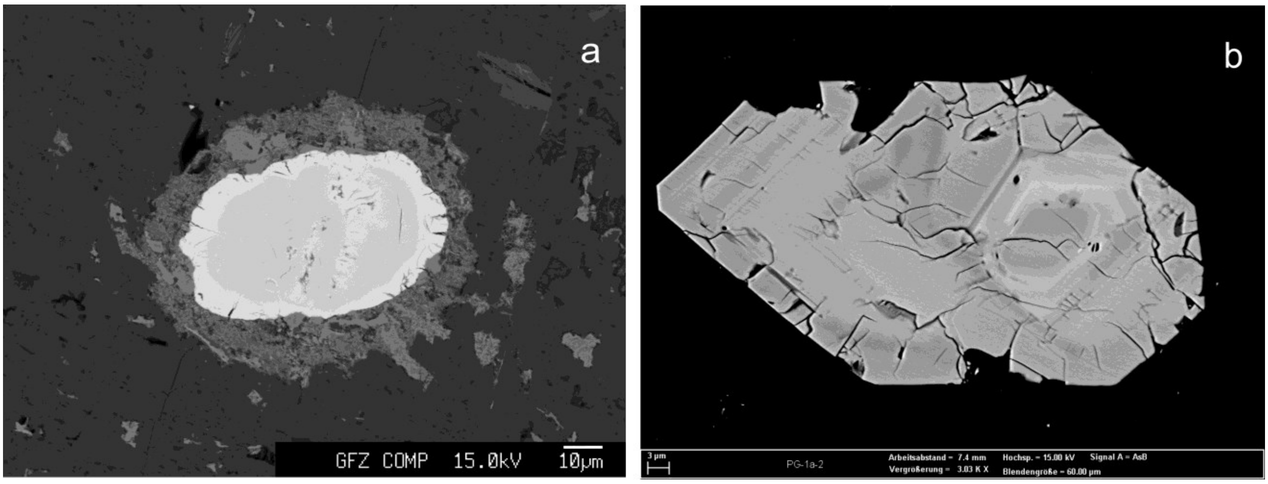

Figure 4: (a) Anhedral grain of thorite (ideally ThSiO4) that has caused radioactive damage in the enclosing feldspar. (b) Subhedral zircon grain showing a weak oscillatory zonation pattern und a plethora of tiny cracks.

5. CONCLUSION

The results of thermal modeling clearly demonstrate the tremendous effect that a conceptual geological model and its parameterization have on the final temperature prognosis and, thus, on the projected depth of drilling to the desired geothermal target. They also highlight the uncertainties that a project developer has to face in the early stage of geothermal projects if both, geology, thermal rock properties and surface heat flow are imperfectly known.

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