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Petrothermal Energy Generation in Crystalline Rocks (Germany)

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ABSTRACT

Petrothermal power stations (EGS, Enhanced Geothermal Systems) will be established in massive rocks. Initially two boreholes will be sunk at depths which correspond to specified temperatures. The way to construct such a heat exchanger has not yet been satisfactorily resolved. Given the large potential attributed to the EGS technology in general, the Free-State of Saxony in Germany has started an initiative to set up a research and development campaign to determine the most effective means of utilizing its' deep geothermal EGS potential. This project will be carried out in crystalline rocks comparable to other projects conducted in the world, so that cross correlations are to be expected. Here, we report first results from the exploration including thermal rock parameters, thermal models, the modern stress field, and geo-mechanical parameters. In this first stage, the Free State of Saxony plans, in close cooperation with research institutions within the research network of "Tiefengeothermie Sachsen", to sink an exploration well with the intention of establishing a deep-petrothermal project. The principle idea of this enterprise is to utilize one or more faults or fault zones as a natural heat exchanger.

1. INTRODUCTION

The growing interest in the provision of geothermal energy as part of an energy mix has required the German government to provide larger subsidies for the development of heat-mining projects. Although the EGS technology has advanced in the last decade and many projects have shown the feasibility of EGS is technically feasible, there is still uncertainty about the chance of success for such projects and their economy, as well as concerns about safety aspects. Geological diversity of EGS sites makes a generalization of the technology difficult. There is still tremendous lack of knowledge concerning the appropriate stimulation techniques, the choice of production and injection regime, geochemical impacts, and the avoidance of induced seismicity above undesired levels. In 2009, the Federal State of Saxony (eastern Germany) has started an initiative to set up conditions for utilizing its deep geothermal EGS potential by exploring the geological and geothermal conditions. All target areas for this exploration are in crystalline rocks. A roadmap for this ambitious goal is developed by a consortium of partners –"Tiefengeothermie Sachsen Research Network-, comprising several Federal research institutions, such as the Technical University Bergakademie Freiberg, the GFZ German Research Centre for Geosciences (Potsdam), the Federal Institute for Geosciences and Natural Resources (Hannover), the Leibniz Institute for Applied Geophysics (Hannover) and the Saxon State Office for Environment, Agriculture and Geology (Freiberg). The ongoing first baseline exploration for this project is financially supported by the Saxon State Ministry and it is expected that the project will be successful in the application for R&D grants from the German Federal Ministry. The first goal is the drilling of a deep borehole "Schneeberg 1" (Figure1) in one of the selected target areas, the western part of the Saxothuringian Unit "Ore Mountains" in an old uranium mining area. The research well should provide comprehensive and fundamental information in order to address the many technical and technological issues that are presently relevant for the implementation of deep geothermal systems in the Federal Republic of Germany.

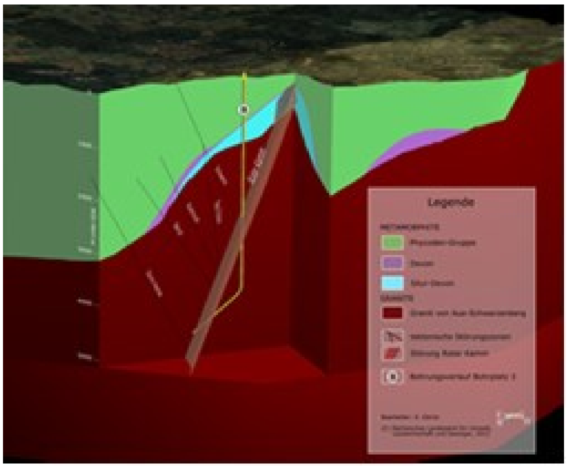
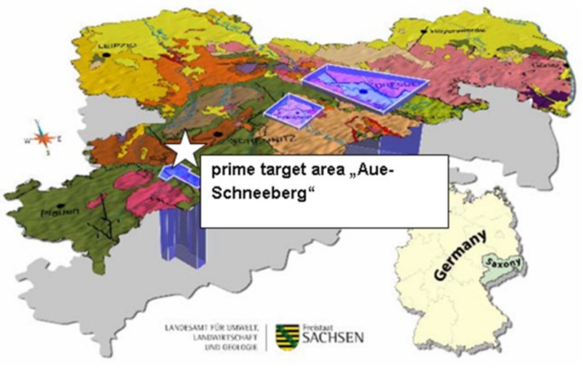


Figure 1: A sample of a 3D model of target petrothermal area with the well path (NW-view) of the possible research well (Research Network, 2012).

2. EXPLORATION STRATEGY

A guideline in form of a feasibility study was elaborated to select and quantify sites best suitable for geothermal use and, hence, for baseline exploration. The site screening process resulted in three prime target areas, being close to energy consumers (Figure 2). Areas in Saxony exhibiting elevated natural seismicity with earthquake magnitudes Mw > 2.5 were excluded in the site selection, to minimize the risk for induced seismicity during reservoir stimulation and production/injection.



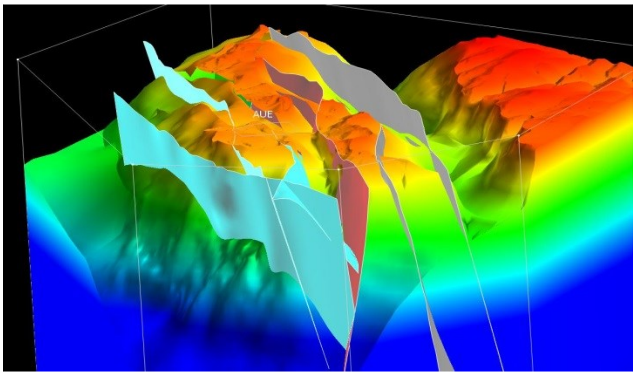


Figure 2 (left): The Area of the Freestate of Saxony in the Eastern Part of Germany, with the location of the prime target areas for geothermal exploration. Red colors – granitic rocks (magmatite), orange colors – gneiss and granulite (high metamorphic rocks), green colors – phyllite (metamorphic rocks), [Source: Scientific report, SMUL, 2010 and Felix et al., 2011].

Figure 3 (right): 3D-model of the granitic surface with the tectonic elements in the area of "Aue-Schneeberg" (Scientific report, SMUL, 2010).

The baseline exploration for geothermal use is targeted to 5 km depth and involves: (1) Generation of 2D-geologic/tectonic cross sections and 3D-geologic/tectonic models, using data from deep seismic sounding, boreholes, and underground mining. (2) Laboratory measurement of thermal properties (k- thermal conductivity and radiogenic heat production) for representative rock types and calculation of average values for thermally relevant rock complexes / stratigraphic units. (3) Generation of conductive temperature−depth models (2D, 3D), to identify areas, in which sufficiently high temperatures are to expected at accessible, moderate depths. (4) Study of the in-situ stress field conditions at the surface and at depth, to predict the local stress field, and to optimize the fracture layout and, finally, the design of the underground heat exchanger. (5) Generation of geomechanical models for the three areas for the tailoring of stimulation techniques (Felix et al. 2011). Figure 4 shows a geological cross section in granite for which a conductive temperature-depth model was generated in the well location area. The section shows two distinct HHP-granite plutons (red colors) intrusive into low-grade metamorphic rocks (light green and blue). Numbers in the white boxes indicate the averages of k and A, respectively. Vertical variations in both parameters within the granite intrusions consider within-pluton variation in rock type and the operation of alteration processes. Thermal modeling suggest for this area of voluminous HHP rocks temperatures on the order of 180°–200°C at depths between 5 and 6 km. At this depth there is furthermore a geological fault zone called the "Rote Kamm" (Figures 3, 4), which is well known, because it has already been mined and explored to a depth of 2000m.

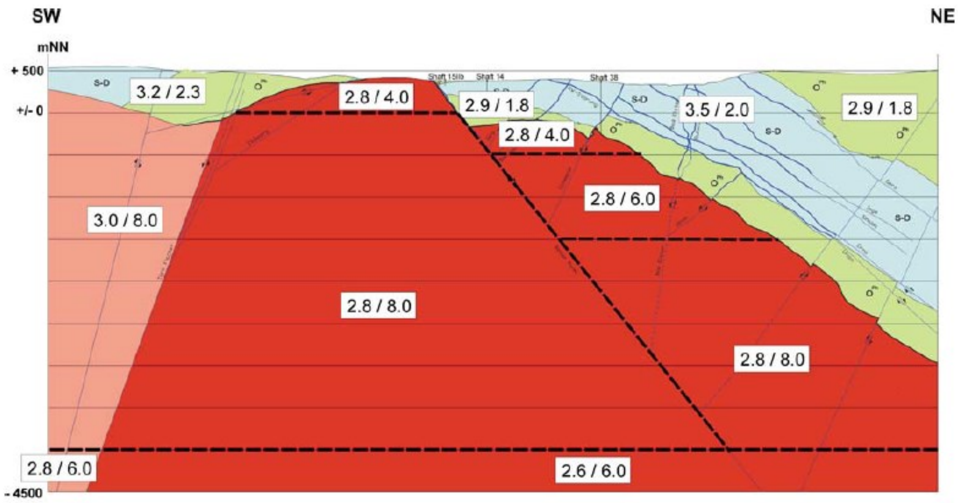


Figure.4: Thermal conductivity k (W/m/K, first number) versus radiogenic heat production A (µW/m³, second number) for the granite intrusion and its country rock in the area of "Aue-Schneeberg" region as part of the 2D temperature-depth cross section (Scientific report, SMUL, 2010, Felix et al. 2011).

2.1 Seismic Measurements

New 3D-seismic measurements are executed in 2012/13 by the LIAG Hannover in preparation of the deep drilling project "Schneeberg1". They should confirm the elongation of the fracture zone "Roter Kamm" for greater depth (> 5000m) and we got additional information about the target area of the borehole as well as about the unknown structure of the granitic rock formation around the target area. Therefore the seismic measurements were the first milestone in our project (Figure 5).

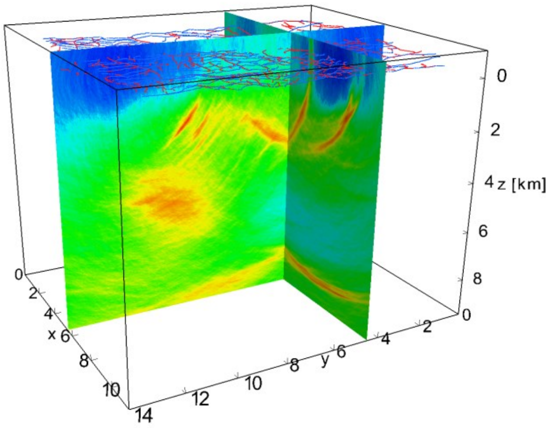


Figure 5: Geothermal Reservoir Characterization in Crystalline Rock using 3D Seismics (Schneeberg, Germany) HLOUSEK, F., HELLWIG, O., BUSKE, S., TU Bergakademie Freiberg, 2014)

2.2 Drilling Program

The "Schneeberg1" borehole will be aligned with the granite pluton, which was pre-cut by the "Roter Kamm", and is planned to approximately 5000m TVD and reach the target area after approximately 5250m MD. The lower third will have an inclination of 60 °, (Figure 6). The research project consists of geological information of the granite plutons in the Aue-Schneeberg region for the purpose of assessing the possible geothermal use of the existing system of fractures of the "Rote Kamm" subsequent to hydraulic stimulation treatment. The project includes drilling a highly inclined and large-caliber research well in the fault regions of the granite body, with a two-time drilling through the "Rote Kamm", each associated with about 60m of core recovery, as well as a comprehensive scientific support program for the purpose of petrographic characterization and assessment of the technical and economic feasibility of petrothermal deposits in granite formations in Saxony.

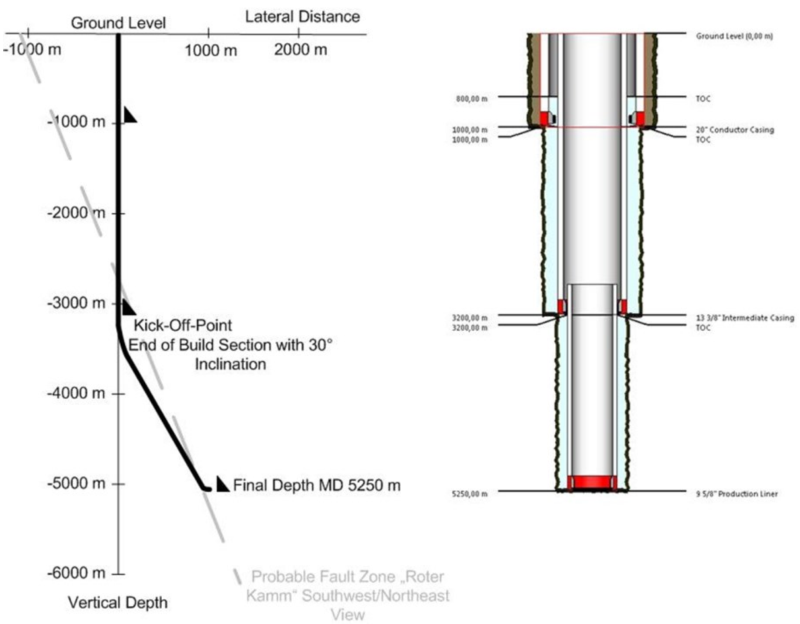


Figure 6: Borehole profile of the research well "Schneeberg 1" (Prevedel, B. & T. Hoffmann, 2012, Research Network)

2.3 Drilling associated Research

Drilling hard rock at depths of 5000 to 10000 m, despite careful planning and execution, is time-consuming und thus associated with a high financial risk. That applies especially to the drill bit and directional drilling technology required for crystalline hard rock. The proposed drilling project provides an excellent opportunity to put new methods of hard-rock drilling to the test, as well as new measuring techniques to locate fractures and faults, and the critical evaluation of results so that future geothermal projects under similar geological conditions can be achieved considerably more cost-effective and with diminished risk. The necessary program for drilling the research and exploration well includes the following topics for the scientific support of the drilling operations:

- Evaluation and development of conventional and alternative drilling systems
- Underbalanced drilling in hard rock
- Core recovery in granite and the fault zones ("Roter Kamm")

One of the main tasks of a scientific drilling operation in granite is to extract core material of the highest quality from the largest possible diameter that is characterized with minimal loss of core, as well as with the least infiltration of drilling mud so that geomechanical, geohydrological, geothermal-physical, geochemical, mineralogical-geological, as well as seismic base data of the relevant rock formations and fault zones can be acquired. The gentle wire-line drilling technique will be selected for core quality and cost-effective reasons and a minimum core distance at final depth is planned for the "Roter Kamm fault".

- Utilization of super-hard materials to minimize wear and dullness of drill bits and drill-string components

- Drill-bit seismology and seismic prediction while drilling in order to explore ahead of the drill bit.

In particular regard to determining thin or steeply dipping fault elements in hard-rock formations, look-ahead exploration methods in which seismic sources and/or seismic receivers are integrated within the BHA has advantages over classical 3D reflection seismology. Drill-bit seismology (DBS) is a method in which the cutting noise of the drill bit itself serves as a seismic source signal. Seismic Prediction While Drilling (SPWD), however, provides an even higher resolution of seismic structure. Directed and focused wave-radiation is enabled via an integrated borehole logging system (source and receiver in the BHA) so that obstacles or objects in the space in front of the drill bit can be detected. Both mechanisms for forward-looking exploration and optimal definition of core sections in hard-rock formations for this proposed pilot implementation of the Schneeberg1 borehole until the first penetration of the "Roter Kamm" will be tested and evaluated.

- Technical and geological/geophysical borehole measurements
- Autoclave tests on core material (T > 130°C, 150 MPa)

Geophysical-borehole measurements yield in situ physical properties of the penetrated rock and enable the recognition of rock-formation structures, differentiation of radiogenic heat production of granite and the depth of the uranium leach-zone in the granite, which up till now is unknown. Furthermore, hydraulically important parameters, inflow regions and possible outcomes of stimulation measures will be identified. The technical logging is not only important for monitoring the drilling process, but also to determine the preconditions for the correct cementation procedure for casings, which is particularly important in geothermal wells in order to sustain undisturbed future production-operation. The diameter for geothermal wells is larger than that which is used for hydrocarbon wells, which results in increased efforts required for interpretation and processing.

3. PETROPHYSICAL RESERVOIR PROPERTIES: THERMAL, HYDRAULIC AND MECHANICAL

The characterization of the petrochemical reservoir within such a project, based on the temperature and the pressure conditions at depth, involves the determination of, conductivity of heat, heat capacity, radiogenic heat production, porosity, permeability, as well as the mechanical properties of reservoir rock formation from the recovered core material and the acquired laboratory and logging data. This laboratory work is closely correlated with the autoclave tests of the core material and is important in the determination of preconditions for the planning of borehole construction, as well as future production of water from the underground heat exchanger. The fissure and fracture permeability of a nearly impermeable rock (granite, gneiss) is measured using a pressure transient technique.

3.1 Temperature and Pressure Conditions

Although Saxony exposes a stabilized crust, the conductive surface heat flow is variable, showing moderate to high values (65−110 mW/m²; Förster, H.-J. and A. Förster, 2000). Large-scale variations in surface heat flow can be almost entirely attributed to upper crustal heterogeneity in terms of radiogenic heat production. High surface heat flows (>80 mW/m²) refer to regions of high-heat-production (HHP) magmatites and, because of heat refraction effects, also to areas in their immediate vicinity. These positive anomalies are not related to phenomena of fluid convection or to sub-recent magmatism, which is devoid in the area (Felix et al. 2011). Geological and gravity data imply that these granite plutons are widely distributed, forming a connected area of the size of several 10,000 km², with granite thicknesses of up to 8 km. During the baseline exploration for an in-depth study of the range in radiogenic heat production, an extensive laboratory program was set up to determine the U, Th, and K concentrations in igneous and metamorphic rocks. The resulting comprehensive database of thermal properties now contains 250 thermal-conductivity (k) values and about 150 values of radiogenic heat production (A). The bulk of metamorphic rocks displays A values between (1.5) 2 and 3 (3.5) µW/m³. Granites and monzonites are typified by A values of >4 – (12) µW/m³. The k values are lowest (2 ± 0.2 W/m/K) for diorite, gabbro, monzonite, and quartz-poor phyllite, and highest (<4 – 6 (8) W/m/K) for sandstone, quartz-rich phyllite, and quartzite. Granites and the majority of metamorphic rocks display values of 3 ± 0.5 W/m/K. The diversity of both thermal parameters has a large impact on the specific temperature −depth distributions modeled for the target areas (Felix et al. 2011), (Figure 7).

3.2 Recent Stress Conditions and geo-mechanical Parameters

An important task for the later design of the stimulation work (to establish the underground heat exchanger, as well as the directional drilling orientation of the follow-up drilling operations), is to obtain the measurements acquired from core material and logs as well as the numerical stress field simulation for the target area and to continually compare the results to update and calibrate the model for the primary stress field. Based on field measurements from the former mining activities up to a depth of 2000m the following stress field model could be developed: principle vertical stress δ1 = 105 – 130 MPa (80 – 140 MPa measured),
maximum principle horizontal stress δ2 = 50 – 60 MPa (45 – 60 MPa measured), minimum principle horizontal stress δ3 = 35 – 45 MPa (20 – 40 MPa measured). The extrapolation into a depth of 5 km resulted in: δ1 = 185 – 190 MPa, δ2 = 140 – 145 MPa, δ3 = 95 – 100 MPa. The principle vertical component of the stress field is approximately equal to the lithostatic pressure. Therefore we expect a 180°C temperature- and a 190 MPa pressure- region in our target horizon for the geothermal reservoir.

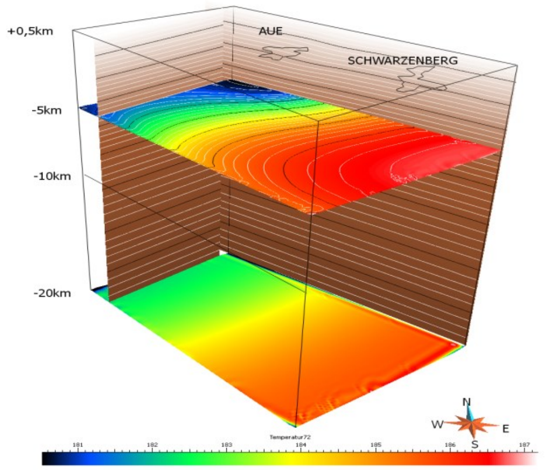
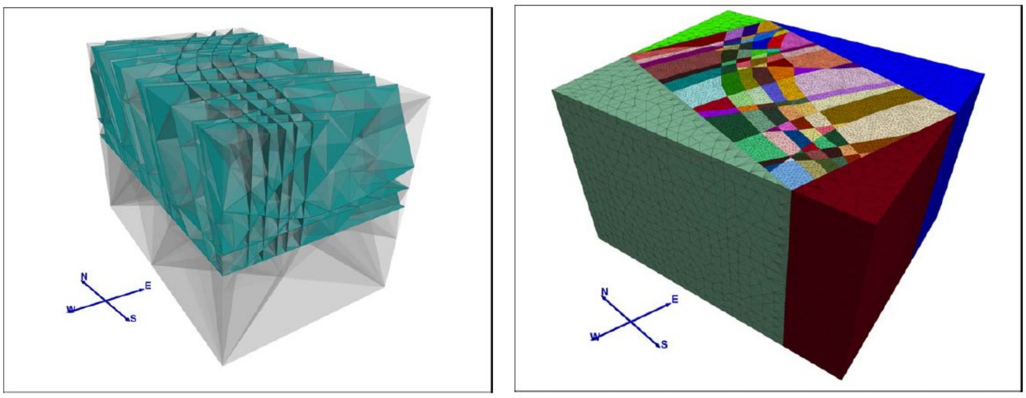


Figure 7: Model of temperature-depth distribution at Aue-Schneeberg region, in Scientific report, SMUL, 2010).

The stress field models are based on detailed geological maps and corresponding 3D-GIS models generated from geophysical surface data, borehole data, and geological interpretations (Figs. 8a + 8b). At the current stage of the project, numerical 3D-scoping calculations are performed to get a first understanding about the potential stress field at depth. As part of a parameter study, the far field stresses according to these data will be applied at the outer boundaries of the numerical model. Also rock mass parameters and especially the parameters of fractures and joints will be varied. This allows the investigation of the sensitivity and the general characteristics of the stress field at depth for selected positions. In addition, complete stress profiles can be obtained, for example along the planned borehole path (Felix et al. 2011). At the current stage of limited knowledge, relatively simple elasto-plastic constitutive laws on the Mohr-Coulomb basis are applied. The models have a vertical extension of 10 km and horizontal extensions between 10 and 25 km. Figures 8a and 8b provide examples of those models. Based on in-situ stress data, measured to a depth of 2 km, and geophysical investigations (fault plane solutions) performed at several sites inside the region, the following general trend can be deduced (Scientific report, SMUL, 2010): The dominant stress regime is strike-slip. The maximum principle horizontal stress (δ2) has NNW−SSE to NW−SE orientation. The magnitude of δ1 is about twice the other two components. From the primary stress field simulations we get a fracturing pressure of 100 to 120 MPa at depth of 5 km. If we consider a pore-pressure (poro-elastic constitutive law) in the granitic rock then the fracturing-pressure decreases to 50 until 63 MPa.



Figures 8a +8b: 3D-GIS model and numerical model for stress field simulations, in Scientific report, SMUL, 2010).

3.3 Reservoir Engineering: Hydraulics, Stimulation and Testing

Different laboratory methods for the measurement of porosity and permeability of rock samples have been established. 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. The interpretation of this unsteady-state two-box method requires a special numerical solution of the flow differential equation (Amro et al. 2010), Figure 9. The semi-logarithmical plot shows the iteration results (colored dashed line) and the measured data (points) of gneiss sample. 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. As shown in the semi-logarithmical plot (Figure 10), a considerable mantle pressure dependence on the sample was measured, which can be attributed to the orientation of the foliation and small fractures. Expectedly, the sample had higher permeability associated with the pressure-caused crack closure. That reflects the significant influence that the surrounding pressure had on the rock's permeability and thus, the water flow path. The nature of the petrothermal deposit, such as for example the presence of faults with or without water flow or the existence of dry and undisturbed granite can only be determined after completion of the drilling operation when all measurements can be conclusively evaluated. A scenario for the completion of the project should also be established in the case where the stimulation of the existing fault zones, e.g. in the "Rote Kamm - fault zone", would be unsatisfactory. This planning will already commence during the beginning of the drilling operation, and will be considerable during the hydraulic test phase. The exploration well "Schneeberg 1" will be drilled to its final depth with a diameter of at least 12 ¼ inches to allow for a casing diameter of 9 ⅝ inches or larger down to the final depth. This is to minimize hydraulic pressure losses during the production tests and stimulation operations that will be carried out. This borehole arrangement should ensure a flow rate of 30 gallons/s.

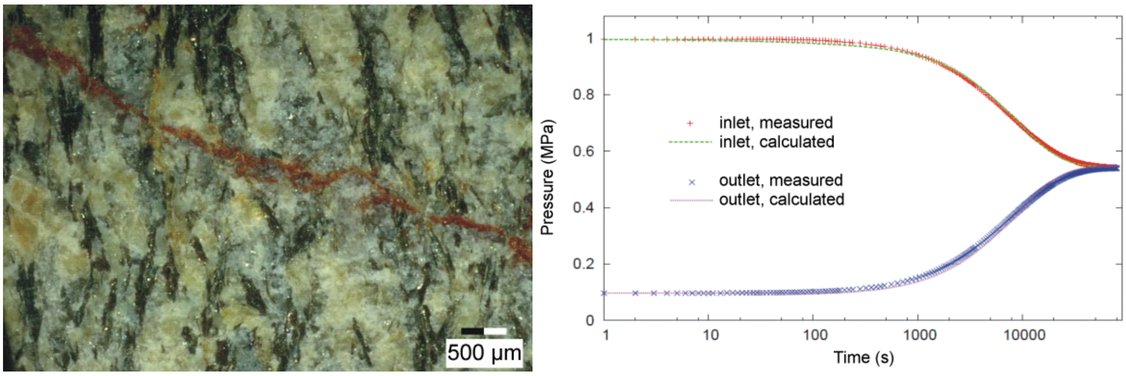
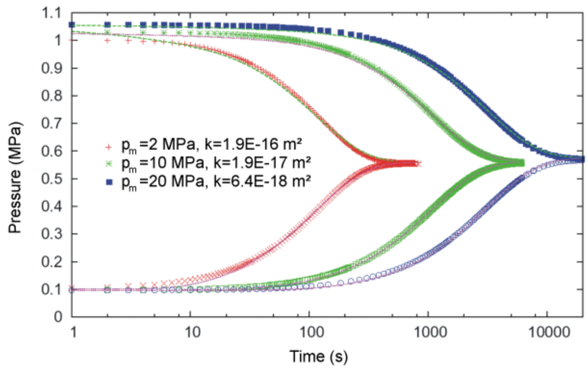


Figure 9: Measured and calculated pressures of a fractured gneiss sample with the unsteady-state two-box method (Dillenard, J. & K. Kranz, 2009).



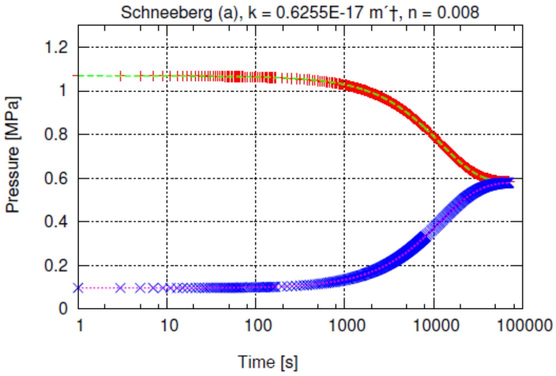


Figure 10 (left): The gneiss sample under different mantle pressures in the unsteady-state two-box (Dillenard, J. & K. Kranz, 2009).

Figure 11 (right): Granite from the Aue-Schneeberg region, k= 6.26 m-18, porosity n=0.8%

We determined the porosity and gas permeability of 6 granitic and 3 metamorphic (phyllite) rocks with the following results:

(1) Granite (depth interval from 27m to 102m), location "Schneeberg", porosity: 0,5…0,8%, gas permeability: 1,04 10-17…6,25 10-18 m²

(2) Phyllite (depth interval from 51m …205m), location "Schneeberg", porosity: 0,1…8%, gas permeability: 1,5 10-16…3,2 10-18 m²

Figure 11 (above) shows the results for the permeability measurement and indicates the very low values. Later on, after drilling operations, this laboratory work will be closely correlated with the core material of the borehole. If we consider, and that show all our lab-measurements, that the generation of cracks (fracturing) increases the permeability more or less in the order of 2, the difficulties in underground development are visible.

4. OUTLOOK

In general, the technical and economic feasibility of the use of the Earth's deep geothermal potential (up to a depth of 10 km) in near-zero-porosity and -permeability rocks constitutes a big challenge. One of the most critical issues for power production is the fluid-flow rate (>100 L/sec) that needs (i) to be generated in an artificially created underground heat exchanger at temperatures >130°C and (ii) to be sustained over the lifetime of geothermal power plant. The creation of a sustained system of open fractures by fracturing operations, under the precondition of minimum seismic hazard, requires research and development on reservoir engineering to be done in collaboration with universities, research facilities, and industry. Issues to be followed up are the determination of the stress tensor by borehole logging for an optimal fracture orientation, the choice of an appropriate fracturing technology (using water or gel proppants, or both) and fracture regimes (e.g., a cyclic change of flow rates), and the placement of the borehole doublet near fracture/fault zones, favorably oriented in the in-situ stress field. After the drilling of the first borehole, being both an exploration and research well, the second phase will turn the project into a developing state, requiring both research and development based on mixed budgets (federal funds and private investments). It is expected that a sound evaluation of the geological conditions, will help to identify the feasibility of such a project to create a road map for investments towards an efficient system development.

5. CONCLUSION

The petrothermal research project (EGS) in the State of Saxony (Germany) consists of geological information of the granite plutons in the Saxothuringian "Ore Mountain" region for the purpose of assessing the possible geothermal use of the existing system of fractures subsequent to hydraulic stimulation treatment. At the first step the project includes drilling a highly inclined and large-caliber research well in the fault regions of the granite body ("Schneeberg1"), associated with core recovery, as well as a

comprehensive scientific support program for the purpose of petrographic characterization and assessment of the technical and economic feasibility of petrothermal deposits in granite formations in Saxony. All basic data were published in 2010 by the Saxon State Office for Environment, Agriculture and Geology (LfULG Freiberg): www.smul.sachsen.de.

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