Exploration Strategy for a Deep EGS Development in Crystalline Rocks (Germany)

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ABSTRACT

Given the large potential attributed to the EGS technology in general, the State of Saxony in Germany has started an initiative to set up a research and development campaign for utilizing its deep geothermal EGS potential. This project will be in crystalline rocks comparable to other projects conducted in the world, so that cross correlations are expected. Here we report first results from the exploration including thermal rock parameters, thermal models, the modern stress field, and geomechanical parameters.

Introduction

The growing interest in the provision of geothermal energy as part of an energy mix has enforced the German government to provide larger subsidies for the development of heat-mining projects. To increase the number of geothermal power plants, it is necessary to exploit resources beyond conventional hydrothermal systems and to use the Earth's huge energy potential, by developing of Enhanced (or engineered) Geothermal Systems (EGS). Although the EGS technology has advanced in the last decade and many projects have shown that EGS is technically feasible, there is still uncertainty about the success rate of such projects and its economy as well as 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. Thus, the successful development of an EGS requires a joint effort between research and industry.

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. Thus, an EGS project in Saxony would be comparable to the projects at Los Alamos, Fenton Hill, Soultz-sous-Forêts, Australia's Cooper Basin or with the Paralana geothermal energy project conducted adjacent to the Mt Painter region of South

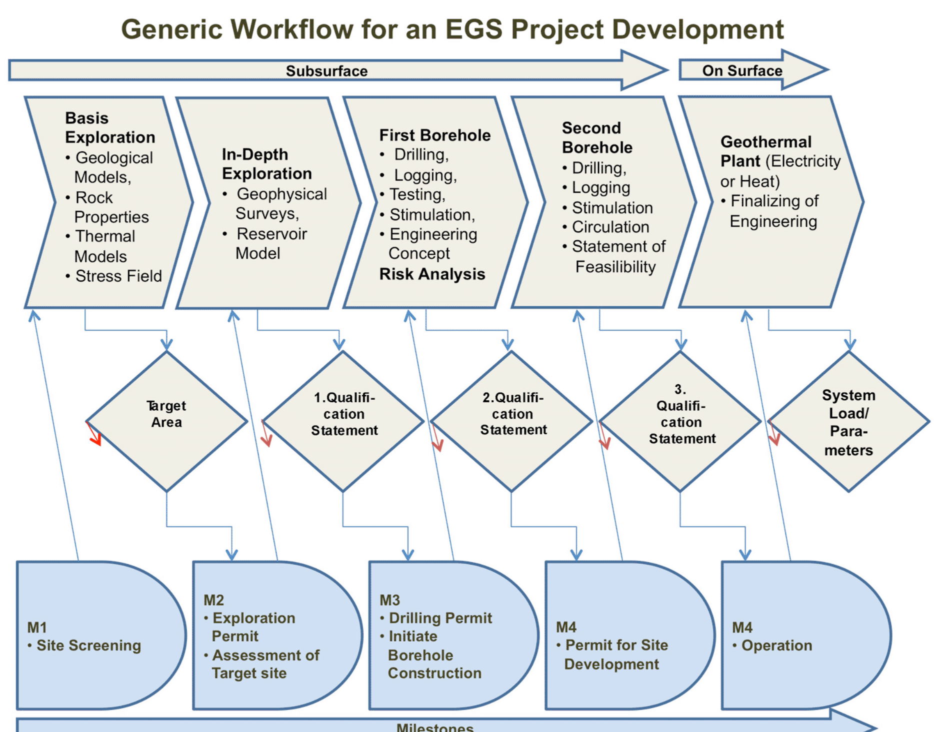

Figure 1. Generic workflow for the EGS project development in Saxony, including milestones and permits issued by regulator based on qualification statements for major tasks.

Australia's northern Flinders Ranges. It is envisioned in Saxony that a first power plant will go into production by 2015, after an industrial investor has stepped in the project.

A roadmap (Figure 1) for this ambitious goal is developed by a consortium of partners, comprising several Federal research institutions, such as the GFZ German Research Centre for Geosciences (Potsdam), the Federal Institute for Geosciences and Natural Resources (Hannover), the Leibniz Institute for Applied Geophysics (Hannover), the Technische Universität Bergakademie Freiberg, 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 of the Environment and Agriculture. It is expected that the project will be successful in the application for R&D grants from the German Federal Ministry of the Environment, Nature Conservation and Nuclear Safety (BMU) for its next stage, which involves and in-depth exploration and thereafter the drilling of the first deep borehole in one of the selected target areas.

Exploration Strategy

A guideline was elaborated to select and quantify sites best suitable for geothermal use and, hence, for baseline exploration (Wolf and Felix, 2009). The site screening process resulted in three prime target areas, being close to energy consumers (Fig. 2). Areas in Saxony exhibiting elevated natural seismicity with earthquake magnitudes $M_w > 2.5$ were excluded in the site selection, to minimize the risk for induced seismicity during reservoir stimulation and production/injection.

The geology of the three target areas is well known down to depths between 1,000 m and 2,500 m, respectively, owing to intensive exploration data available from mining of ore deposits, for which several deep boreholes also were drilled in the past. All areas are rich in tectonic features, such as fracture and fault zones, however of yet poorly known hydraulic properties.

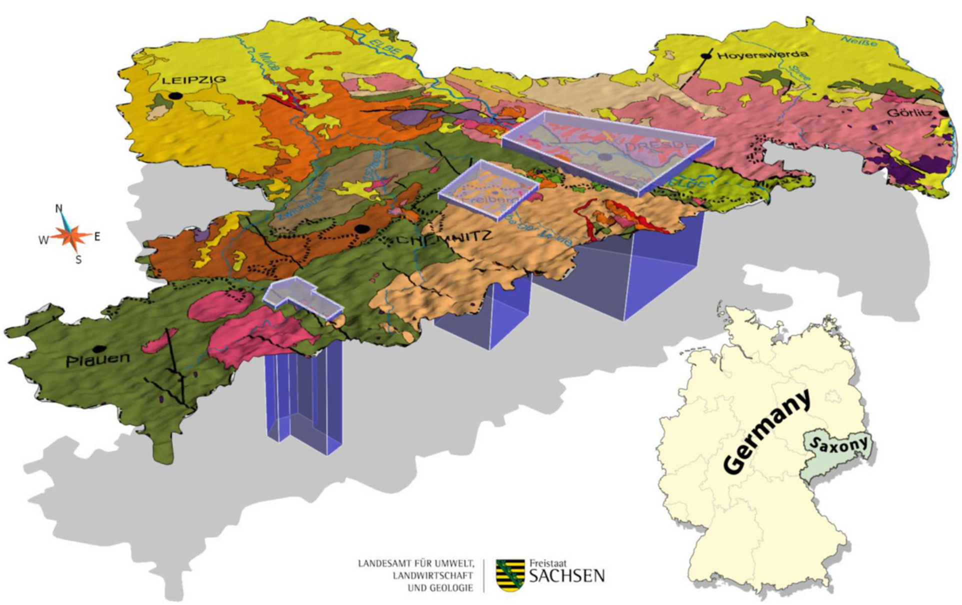

Figure 2. The area of the State of Saxony in eastern Germany, with the location of prime target areas for geothermal exploration. Major cities are shown.

The baseline exploration for geothermal use is targeted to 5 km depth and involves:

- Generation of 2D-geologic/tectonic cross sections and 3D-geologic/tectonic models, using data from deep seismic sounding, boreholes, and underground mining
- Laboratory measurement of thermal properties (thermal conductivity and radiogenic heat production) for representative rock types and calculation of average values for thermally relevant rock complexes/stratigraphic units
- Generation of conductive temperature–depth models (2D, 3D), to identify areas, in which sufficiently high temperatures are to expected at accessible, moderate depths
- Study of the in-situ stress field conditions at the surface and at depth, to predict the local stress field, and to optimize the frac layout and, finally, the design of the underground heat exchanger
- Generation of geomechanical models for the three areas for the tailoring of stimulation techniques.

Temperature at Depth

The southern and southeastern parts of Saxony, were the three target areas are located, belong to the Saxothuringian Unit of the Variscan(Hercynian) Orogen and are mainly composed of metamorphic and igneous rocks of Carboniferous age. Although Saxony exposes a stabilized crust, the conductive surface heat flow is variable, showing moderate to high values (65–110 mW/m²; Förster and Förster, 2000). The area is expected to belong to one single mantle heat flow province, with mantle heat flow on the order of 25–30 mW/m². Large-scale variations in surface heat flow can be almost entirely attributed to upper crustal heterogeneity in terms of radiogenic heat production. This was shown on several borehole locations, where the upper crust was encountered to a depth of about 1 km and temperature logs and drill core were available for the heat flow evaluation. 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.

The HHP granite and monzonite plutons intruded into metamorphic rocks (mostly phyllites, mica schists, and gneisses) of lower heat production. 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 (Behr et al., 1994).

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 laboratory program then was extended to the measurement of rock thermal conductivity, which is an equally important parameter affecting the thermal structure of an area. The resulting comprehensive database of thermal properties now contains 250 thermal-conductivity (k) values and about 150 values of radiogenic heat production (A). Lowest A values (<1 μW/m³) are typical for diorite, gabbro, and chlorite schists representing metamorphosed diabases. 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 qtz-poor phyllite, and highest (<4 – 6 (8) W/m/K) for sandstone, qtz-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 three target areas.

Figure 3 shows an example of a geological cross section in granite for which a conductive temperature-depth model was generated. 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 150°–180°C at depths between 4 and 5 km. Although the metamorphic country rocks show less favorable thermal properties, with higher thermal conductivity and lower radiogenic heat production compared to the granites, they profit in terms of heat due to heat refraction.

Recent Stress Conditions and Geomechanical Parameters

The success and effectiveness of a deep geothermal EGS strongly depends, besides the temperature range and technical layout, mostly on the in-situ stress field and the geomechanical parameters. Both will be investigated in detail for the three target areas by analyzing existing data and by numerical stress field modeling. These stress field models are based on detailed geological maps and corresponding 3D-GIS models generated from geophysical surface data, borehole data, and geological interpretations (extrapolations and interpolations). The basic strength and deformation parameters for most of the geological units will be available from rocks collected from exploration wells, outcrops, and from underground mining up to 2 km depth. In conjunction with rock mass classification schemes, laboratory data will be transformed into rock mass data used for numerical simulations.

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. The 3D-GIS models are used as a basis for the numerical models. The entire process includes the following steps:

- Transfer of 3D GIS models (Gocad) into a special CAD software (Rhino)
- Preparation of the CAD model for the special meshing tool (Kubrix)
- Meshing of model inside Kubix and transfer to the numerical simulation tool (3DEC)
- Application of initial and boundary conditions as well as constitutive laws and corresponding parameters
- Numerical calculations and evaluation of model response.

For the numerical calculations, a 3D-discrete element approach is used, which allows the explicit consideration of joints or planes of weakness. Therefore, two different parameter sets are used: one for the joints and one for the rock matrix. At the current stage of limited knowledge, relatively simple elasto-plastic constitutive laws on the Mohr-Coulomb basis are applied. The models consist of up to several dozens of joints and also several geological units. In total the meshed models consist of several million of elements. The models have a vertical extension of 10 km and horizontal extensions between 10 and 25 km. Figures 4 and 5 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:

- The dominant stress regime is strike-slip
- The maximum principle horizontal stress (S1) has NNW–SSE to NW–SE orientation
- The magnitude of S1 is about twice the other two components.

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

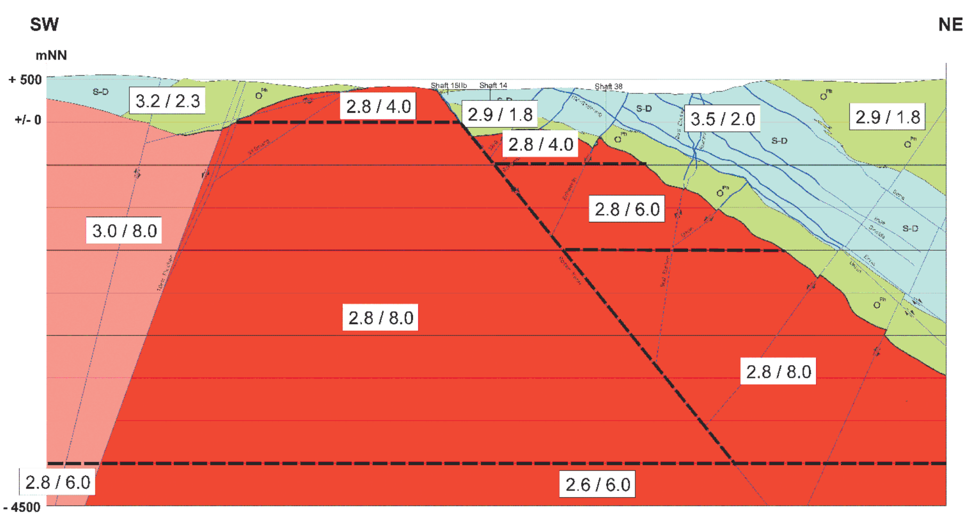

Figure 3. Thermal conductivity (in W/m/K, first number) versus radiogenic heat production (in μW/m³, second number) for a large granite intrusion and its country rock. The 10-km section is part of a larger cross section for which the temperature–depth distribution was modeled.

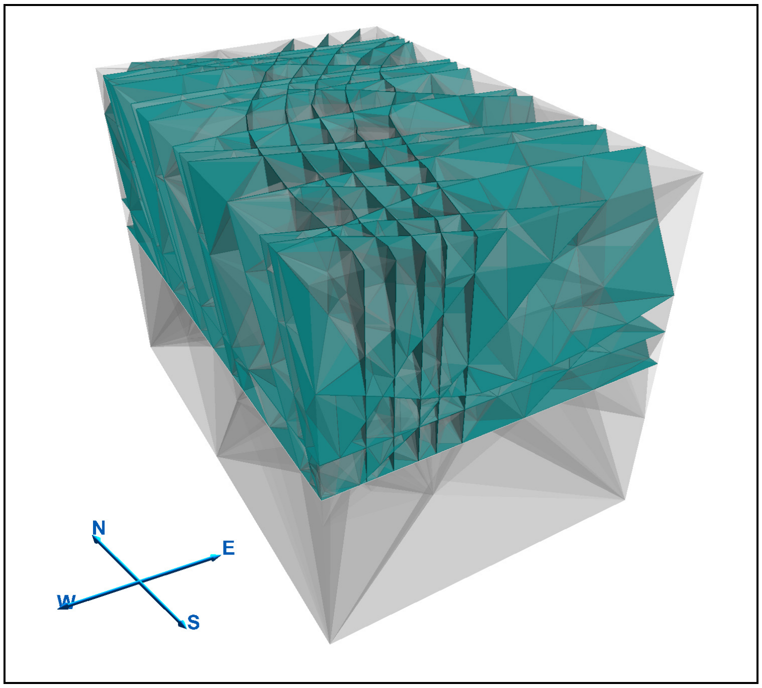

Figure 4. Block structure and colored fracture system of the numerical model (Freiberg area).

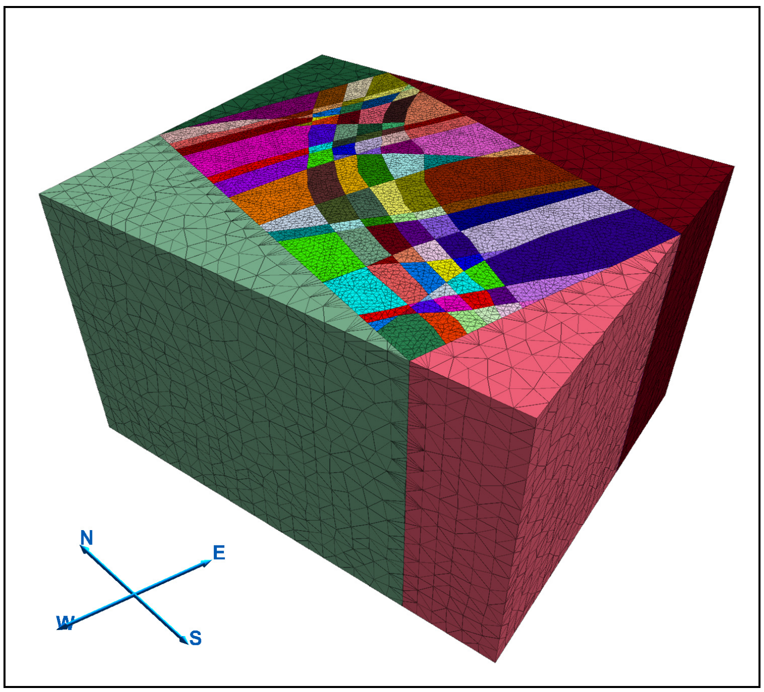

Figure 5. Meshed numerical model (Figure 4) with surrounding rock mass.

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 a planned borehole path.

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 (>50 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 frac stimulation, 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 frac orientation, the choice of an appropriate frac technology (using water or gel proppants, or both) and frac 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.

The concept followed up by the State of Saxony uses in the first stages of project development mostly public funds and involves academic "know how" on the different facets of geothermal exploration, tailored to the actual geological situation in each area. 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.

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