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# From Prospecting to Drilling: New Exploration Strategies for Enhanced Geothermal Systems

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## ABSTRACT

Exploration for Enhanced Geothermal Systems (EGS) requires a combination of imaging methods to characterize the subsurface and to develop a geoscientifically integrated understanding of the reservoir. With an integrated geophysical-geological-geomechanical understanding at a variety of scales it is possible (I) to quantify and characterize the reservoir, (II) to define the location of a drill site, and (III) to support the drilling process in terms of geological risk mitigation. Here, we describe an exploration case study from the geothermal test site Groß Schönebeck, approximately 40 km North of Berlin/Germany, located in the Northeast German Basin. The target for exploration is a hydrothermal system in 4,200 m deep sandstones and volcanic rocks undergoing development for an EGS. The initial investigation of the subsurface was based on pre-existing 2D seismic and well data from former gas exploration campaigns. From the existing data we developed a 3D geological model to describe the general structure and main fault systems to a depth of 5,000 m. New geophysical field experiments, using innovative magnetotelluric and wide angle seismic techniques, provided new data and deeper insights into the characteristics of the site.

In 2006 a new geothermal production well GtGrSk4/05 was drilled as part of a well doublet at the Groß Schönebeck site. For the drilling operation it was necessary to develop methods to avoid formation damage and subsequent permeability impairment by mud solid infiltration and borehole breakouts. Previously, experiments on drill cores were designed to simulate the mechanical behavior of some geological formations and to test for the development of fractures and borehole breakouts under varying in situ conditions. With these data we could define specific mud density windows ensuring a safe drilling process. Hydraulic stimulation of a well is commonly used to increase the productivity of a reservoir, i.e. enhancing a geothermal system. A successful application of EGS technologies requires detailed knowledge of the stress field and reactivation potential of existing faults in the reservoir. We therefore applied the so called slip tendency method to estimate the likelihood of fault reactivation in both sandstone and volcanic rock successions which suggested an orientation of NNE-SSW faults with high slip-tendency. These results were confirmed later by microseismicity records during the hydraulic stimulation. This integrated geothermal exploration strategy covers all aspects from geosystem analysis, reservoir characterization, and reservoir geomechanics. Such an integrated approach might be essential for an economic and sustainable exploitation not only of EGS but of all geothermal systems.

## 1. INTRODUCTION

Exploration for Enhanced Geothermal Systems (EGS) is a fundamental part of sustainable and economic exploitation of geothermal reservoirs but with hitherto no sufficient tools, methods, and strategies to image, investigate and characterize – finally to understand integrative - geothermal systems. Basically, a geothermal reservoir is part of a geosystem which reacts to all man-made manipulations from drilling via stimulation to production. From this perspective it is obvious that exploration for EGS requires an integrated approach in different scales, encompassing aspects from reservoir investigation and access by combining new geophysical, geological and geomechanical techniques and methodologies. One of the most critical issues in exploration for EGS might be the stress field which should be understood and characterized before stimulation. The slip tendency analysis is one method to characterize faults in the current stress and under modified stress fields to assess reactivation potential and fault behavior (Morris et al., 1996).

In our integrative study we investigated one of the EGS key sites of the Northeast German Basin located at Groß Schönebeck, north of Berlin, Germany (Fig. 1, see end of text), where Lower Permian red bed sandstones and volcanics are ongoing to be investigated for EGS utilization. Fluvial sandstones of the Lower Permian (Rotliegend) forming potential reservoir rocks are widespread throughout Central Europe deposited on the southern flank of the South Permian Basin System that includes the Northeast German Basin (Scheck and Bayer, 1999). The siliciclastic rocks and subordinately volcanic rocks host hot fluids. However, most of these 4-4.5 km deep aquifers represent low-enthalpy reservoirs with formation temperatures of on average 150°C. This article highlights the characterization, mapping and access of such low-enthalpy reservoirs for the generation of geothermal electricity.

For these purposes, an *in situ* downhole laboratory was established in Gross Schönebeck consisting of a well doublet (Fig. 1). The first well (GrSk3/90), originally completed in 1990 as a gas exploration well and reaching the 4,300 m deep Lower Permian of the NE German Basin, was abandoned due to non-productivity in 1991. It was re-opened in 2000 and hydraulically stimulated in several treatments between 2002 and 2005 (Legarth et al., 2005). Logging campaigns (with caliper, spectral gamma ray, resistivity, sonic, bore hole televiewer, FMI) revealed detailed reservoir characteristics of the Lower Permian sedimentary and volcanic successions (Holl et al., 2005). In 2006 the second well of the doublet, GrSk4/05, was drilled accomplishing drilling technologies to minimize formation damage and subsequent permeability impairment of reservoir rock (Huenges and Moeck, 2007). In 2007 an extensive hydraulic stimulation was carried out in the new well combined with recording of induced microseismicity. In the following chapters we describe the geothermal field development at the Groß Schönebeck site since 2005. This includes the re-evaluation, re-processing, 3D modeling and re-interpretation of existing data combined with newly generated data from magnetotelluric (MT) and 2D refraction seismic surveys, access the reservoir by drilling a second well to install a well doublet for a thermal water loop, and geomechanical modeling to characterize faults with respect to the current stress field.

## 2. METHODS

### 2.1 Geological system analysis

The Northeast German Basin structure is dominated by Upper Permian salt of some 1000 meters thickness. The Lower Permian sandstones and volcanic rocks that host hot thermal fluids lay below those salt successions forming salt ridges, diapirs and salt lows. The challenge is to define geophysical exploration methods to image and characterize those deep subsalt reservoirs. We use an integrated approach of re-processed 2D seismic data, originally gathered for gas exploration, combined with MT and seismic tomography. With the 2D seismic the subsurface structures are imaged while MT and seismic tomography can be used to identify highly mineralized fluids, higher fracture density and/or porosity. The new geophysical exploration campaign is described in more detail in this volume (Munoz et al., Bauer et al.) so we focus to the geological modeling based on 2D seismic.

The objectives of reprocessing of 2D reflection seismic were (I) new correlation of the reflector horizon Z1 in the Lowermost Upper Permian (II) correlation of Rotliegend reflectors below the Z1 reflector (III) identification of minor fault throws and fault pattern (Fig. 1, end of text). Combined with well data analysis the potential reservoir rock shall be defined and mapped through 3D structural geological modeling with the software earthVision (developed by Dynamic Graphics). Coherency analyses were deduced by the Geophysik GGD (Gesellschaft für Geowissenschaftliche Dienste mbH) and the Institute of Geophysics/University Leipzig to get additional interpretive results for the Lower Permian fault pattern. The results of coherency analysis substantiate discontinuities in the seismic signal and serve therefore as indicator for open fractures and fault zones (White, 1994)

### 2.2 Reservoir geomechanics

The knowledge of the stress field is a critical issue in the development of engineered reservoirs. It is especially important for the development of (EGS) where hydraulic stimulation is accomplished to increase the permeability and hence the productivity. Where no information on stress magnitudes is available stress models can be developed assuming that in situ stress magnitudes in the crust will not exceed the condition of frictional sliding on well-oriented faults (Peska and Zoback, 1996; Moeck et al., 2008). Moreover, geometrical constraints (fault throw and fault intersections) of mapped 3D fault pattern (from seismic surveys) indicate limited variation of stress regimes, ranging from normal faulting ($S_V>S_{Hmax}>S_{hmin}$) to transtensional ($S_V=S_{Hmax}>S_{hmin}$) to strike slip ($S_{Hmax}>S_V>S_{hmin}$) or reverse faulting ($S_{Hmax}> S_{hmin} > S_V$) (Moeck et al., 2008).

Additionally to the regional stress field, the in situ stress field can be determined by the analysis of borehole breakouts. The analysis of existing combined with new well data of the well GrSk3/90 showed borehole breakouts in 4,100 m depth in the Upper Rotliegend successions. Since near-balanced drilling was planned to minimize formation damage in the new well, a fracture mechanical study integrating core-testing and numerical modeling was carried out for securing the borehole stability (Moeck and Backers, 2007).

Once the stress field has been determined by borehole data (borehole breakouts or tensile fractures) or by frictional constraints and 3D fault models, faults can be characterized with respect to their orientation in the current in situ stress field. The slip-tendency method is a technique that permits the rapid assessment of stress states and related potential fault activity of mapped or suspected faults in a known or inferred stress field (Morris et al., 1996). The likelihood of slip along a fault plane is a function of the frictional resistance on the sliding surface, which is governed by rock properties and the ratio of shear to normal stress on the surface. The values of slip and dilatation tendency can be compiled together with the maximum slip tendency of each fault and in the three possible stress regimes as mentioned above (Moeck et al., 2009).

### 2.3 Drilling strategies

Hydraulic-thermal modeling based on data from the first well, along with regional structural analyses, identified the best possible well path geometry for the second well (Zimmermann et al., 2007). The borehole was designed parallel to the minimum horizontal stress direction and perpendicular to potentially hydraulic fractures to increase productivity and hence to decrease auxiliary energy requirements for the thermal water loop in the planned doublet. Furthermore, this setup provides a low risk of a temperature short circuit of the system within the projected thirty years of utilization. The new drilling operations required (I) a large hole diameter due to the deep static water table of the reservoir and the respective withdrawal during production (housing for the submersible pump), (II) directional drilling to intersect the target horizon at the derived off-set from the existing hole and to increase the inflow conditions through well inclination in addition to later multiple hydraulic fracturing, and (III) a drilling mud concept and near-balanced mud pressure conditions aligned to the reservoir rock to minimize formation damage.

## 3. RESULTS

### 3.1 3D geological model

The general geological setting of the study area is dominated by salt ridges and lows (Fig. 1B-C, end of text). The Groß Schönebeck field is located in the subsalt region within the NE-SW trending Barnim Low. The internal structure of the Barnim Low is now detailed described by the 3D geological models (Fig. 1B-C). In this region the Lower Permian fault pattern consists of NW-SE oriented major faults and N-S to NE-SW trending minor faults. The geological models help to define further potential geothermal fields taking into account increased thickness of the Elbe Basis sandstone in depositional centers near paleomorphological highs. The MT survey helps to identify highly fractured zones that are obviously related to salt lows which are the result of salt migration towards generally NE trending salt ridges. The evaporitic remnants in these salt lows are presumably brittle anhydrites and carbonates accommodating a high density of faults and fractures (Munoz et al., 2008). The resulting 3D geological model is used for a tetrahedrons mesh based reservoir simulation model that is currently under development.

### 3.2 Completion of the well doublet

After drilling through 1,600 m thick Upper Permian evaporitic strata the installed 9 5/8 inch liner collapsed. Presumably, this failure was caused by additional stress components from anisotropic stress from the well inclination of ~20° in connection with the presence of highly ductile rock salt (temperatures of 110°C in 3800 m depth). The borehole design had to be adjusted due to the loss of one casing dimension in the evaporites subsequently completed with a 7 inch liner after side tracking. Therefore, the borehole was deepened with 5 7/8 inch diameter into the geothermal reservoir of the Lower Permian section. Borehole wall breakouts at 3940 m forced a cleaning run and an alignment of mud pressure as predicted by the geomechanical study (Moeck and Backers, 2007). Another reason for increasing the mud weight was the occurrence of $H_2S$ within the fissured lowermost Upper Permian formation.

Finally, the well reached the target point in the Lower Permian volcanic rocks along the modified well design at a depth of 4,400 m (Fig. 2). The Lower Permian sediments reached a thickness of 340 m. The 3D geological models, that were previously calculated reveal the Groß Schönebeck field at the flank of structural high of the sandstones (Fig. 1B). Reservoir sandstone layers with permeabilities up to 100 mD (calculated from PND log) lay in the succession of the Elbe Base sandstone and have a vertical thickness of >80 m.

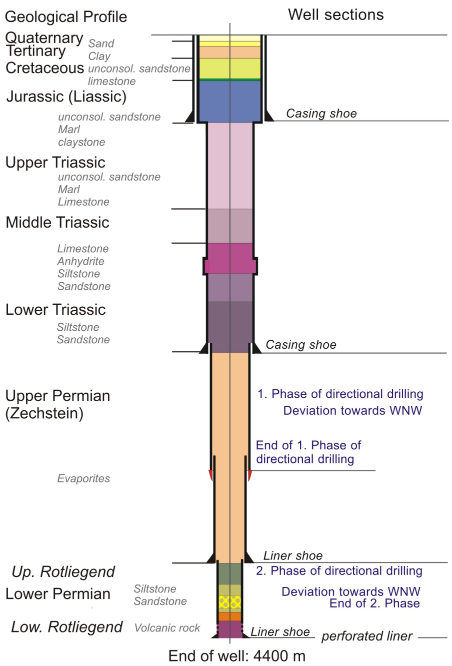


**Fig. 2. Completion scheme and geological profile of the new well GtGrSk4/05.**

### 3.3 Reservoir characterization

A log correlation of both wells EGrSk3/90 and GtGrSk4/05 shows no significant change of thickness or bedding. The well inclination of up to 49° implies an effective thickness of up to 150 m within this permeable sandstone. The planned well deviation along the minimum horizontal stress direction (in 288°) optimized the hydraulic fracturing treatments (Fig. 3). The hydraulic stimulation of volcanic and sedimentary rocks is detailed described in Zimmermann et al. (2008) (see also Zimmermann et al., this issue). Based on previous hydraulic-thermal modeling, a minimum distance of 450 m between the ends of the two wells was realized to avoid a thermal breakthrough of the injected cold water directly into the production well.

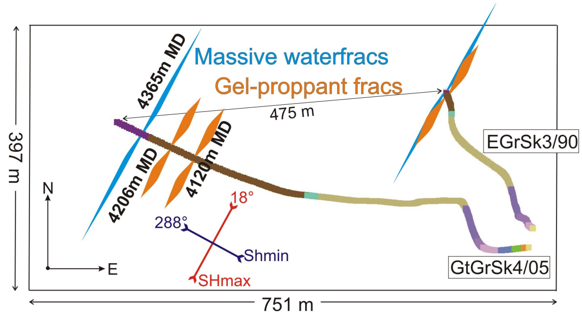


**Fig. 3. Top view of well doublet at the Groß Schönebeck site, illustrating the hydraulic fractures of both wells. The depth values along the fractures a re in measured depth (MD, i.e. well path length) GrSk4/05 was stimulated in 2007, GrSk3/90 was stimulated in 2002 and 2003. The hydraulic fractures trend along the maximum horizontal stress in 18° (as determined from image logs).**

The numerical model of borehole breakouts under different mud weights indicate mud densities of 1.10 to 1.95 g/cm³ where no significant breakouts occurred. Below that range numerical breakouts were achieved in direction of the minor horizontal stress; above that range fracturing is initiated. The slip-tendency analysis suggests critically stressed NE-SW striking normal faults in a bimodal distribution in the sandstone layer (Fig. 4A, see end of text). Faults in the underlying volcanic rock, however, show very low slip tendency and are supposed to be re-activated only with a significant increase of the fluid pressure (Fig. 4B, see end of text). During massive water stimulation in the Lower Permian volcanic layers of the geothermal well GtGrSk4/05 seismic recording was accomplished in the off-set well EGrSk3/90. The surprisingly low microseismic activity was recorded with moment magnitudes $M_W$ ranging from -1.0 to -1.8. This result might be explained with the low slip-tendency of faults in the volcanic layer. Slip tendency reflects the frictional coefficient and sliding is expected with values of 0.8 in the particular reservoir depth (Byerlee 1978). Since the slip tendency in the volcanic layer is about 0.5, a significant increase of fluid pressure of about 24.5 MPa is necessary to induce slip along preferential fault planes along NE-SW direction and bimodal dip. During a massive water stimulation (Zimmermann et al., this issue) first failure occurred with 20 MPa additional fluid pressure along a failure plane with strike/dip N17E/52SE (Fig. 4C). 24.5 MPa fluid overpressure was calculated by slip tendency for first failure. Although this difference may be explained by error bounds it could also indicate a high fracturization degree of the volcanic rock near a reactivated fault (fault F28 in Fig. 4C). The very low magnitude seismicity recorded during stimulation, however, is consistent with the results from slip tendency analysis (Moeck et al., 2009).

## 4. CONCLUSION

We understand a geothermal reservoir as part of a geosystem on the one hand and as geomechanically reacting part of the subsurface on the other hand. The understanding and characterization of geothermal reservoirs through integrated geological models in different scales is the key element of our exploration strategy. The aim is to support the reservoir engineering and management by integrated models and to define site specific exploration strategies.

Our aim is to integrate all the available knowledge from former exploration campaigns with data re-processing and modeling, drilling and reservoir treatments.

Despite its uncertainties the 3D model remains the most detailed geological model of the Groß Schönebeck area until more or newly generated data are incorporated to a new model. New geophysical exploration is needed to detect and image highly fractured zones and water bearing fractures. For this purpose, newly developed MT and 2D seismic experiments are ongoing in the vicinity of Groß Schönebeck. The latest results of these exploration methods are promising in terms of defining potential geothermal fields since possibly highly fractured zones related to salt lows can be identified (Munoz et al., this issue; Bauer et al. this issue).

One critical aspect in EGS exploration is to map and characterize faults with respect to the current stress field since extensive hydraulic stimulation, which is the specific EGS approach, can induce undesired seismicity by changing stress conditions. For fault reactivation assessment we applied the slip tendency method to characterize fault slip likelihood and slip. Results from the slip tendency analysis combined with geomechanical parameters show that faults in the volcanic succession of the reservoir have a low tendency to slip indicating that high additional fluid pressure is needed to reactivate potential strike slip and/or normal faults. The study demonstrates that the slip tendency analysis provides an appropriate method to investigate, characterize, and understand fault behavior of engineered reservoirs, such as Enhanced Geothermal Systems.

In this study, technical and scientific challenges are successfully met, and the lessons that were learned provided essential knowledge for developing future exploration and drilling strategies in deep sedimentary geothermal systems, especially in the Central European Basin System.

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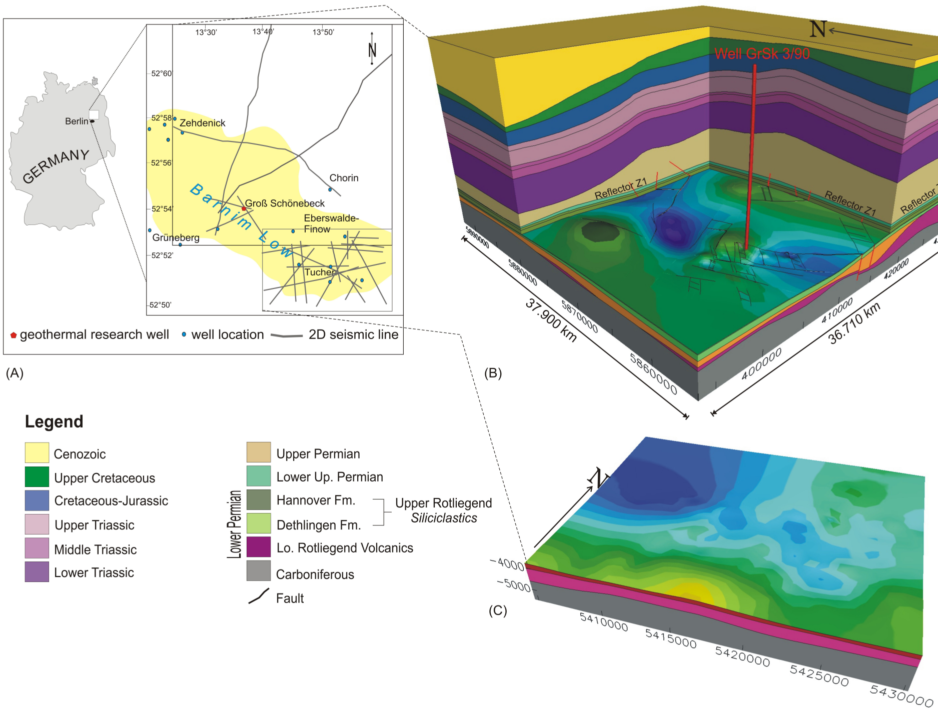


**Fig. 1. (A) The geothermal test site is located in the center of the Barnim Low, which was a field of extensive gas exploration in the 1970's-1980's. The seismic lines and wells shown are now used for 3D modeling and re-interpretation. (B) New 3D geological model of the Groß Schönebeck area. The existing well GrSk 3/90 is located at a structural high within the Barnim Low. (C) New 3D geological model of the Tuchen Low at the SE of the Barnim Low.**

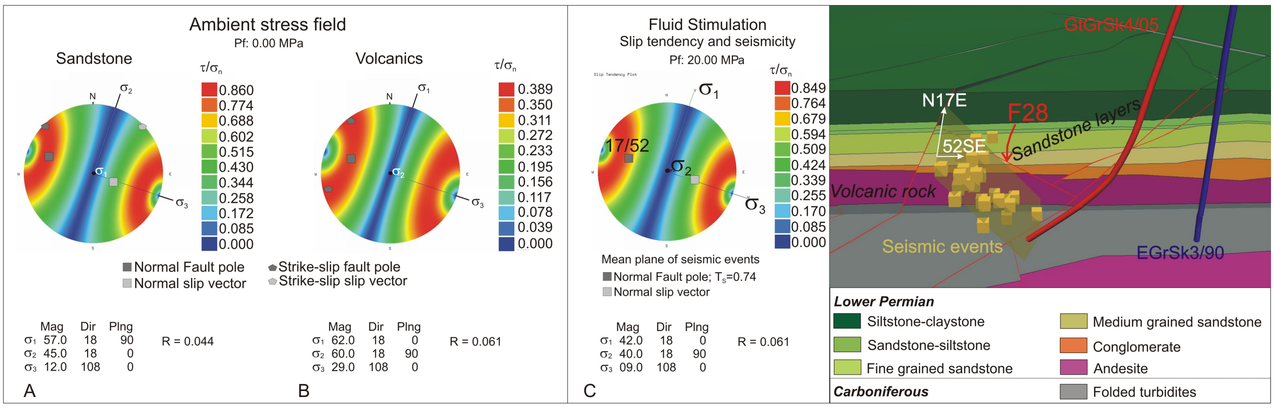


**Fig. 4. (A) Slip tendency in the sandstone and (B) slip tendency in the volcanic intervals in the ambient stress field. (C) Slip tendency under fluid stimulation. The geological 3D model shows the vicinity of a fault (F28) that may be reactivated through stimulation.**