3D Lithofacies Model Building of the Rotliegend Sediments of the NE German Basin*

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Abstract

Static 3D geological models are essential to reservoir characterization and dynamic models. We introduce an approach of combining pre-existing and newly generated data to assess lithofacies distributions and sandstone permeability of a clastic reservoir within the Rotliegend II of the NE German basin. The target is at 4300 m depth and situated north of Berlin (Germany) in the vicinity of a former gas exploration well, drilled in 1990 and currently acting as geothermal in-situ laboratory.

This second-hand well was re-opened in 2000 and deepened in two steps to 4309m TVD. An extensive logging program was performed between various stimulations and hydraulic tests. Porosity/permeability data are available from logging data as well as from abundant porosity (290 samples) and permeability measurements (109) on cores.

A basic 3D structural geological model of an area of 120 km^2 was calculated using pre-existing well data and 2D seismic profiles. Detailed well data provided information to develop a 3D lithofacies model, comprising five lithotypes. The facies grids were calculated with a 3D minimum tension technique. In this procedure each facies grid was normalized, calculated against each other, and reconciled by creating a 0-isoenvelop, that clearly defines the facies-type body. The isoshells were set in each fault block of the structural model and processed to a comprehensive 3D structural lithofacies model. This volumetric 3D model allows an assessment of both matrix-driven and fracture-driven permeability. This approach can be applied to any region, where detailed structural and sedimentological data are available.

Introduction

The well Gross Schönebeck 3/90 (GrSk 3/90; NE of Berlin, Germany; Figure 1) was drilled in 1990 assigned to gas exploration in East Germany. The borehole was been closed due to lack of gas. In 2000 the well was re-opened to use the borehole as in-situ laboratory for geothermal low enthalphy reservoir studies. The geothermal reservoir is situated in Rotliegend II strata in part of the NE German Basin (NEGB). The NEGB is part of an extensive basin system which extends from the North Sea towards Poland. It is bounded in the north by the Baltic Shield and in the south by the Variscan fold belt.

Initial basin extension occurred between the latest Carboniferous and the Early Permian and was accompanied by the deposition of volcanic rocks which were subsequently covered by a siliciclastic sequence of alluvial fans, ephemeral stream, playa deposits, and eolian sands (Rieke et al., 2001). Thick cyclic evaporites and carbonates, deposited during the Zechstein, are overlain by a thick section of Mesozoic and Cenozoic sediments. The basic scientific function of the in-situ laboratory consists in the development of hydraulic stimulation techniques in order to enhance the permeability in siliciclastic and volcanic formations of the Rotliegend. In order to assess the permeability of both the sandstone matrix and the fracture porosity, an extensive logging program has been conducted, while the geometry of the reservoir is revealed by 3D structural model building procedures.

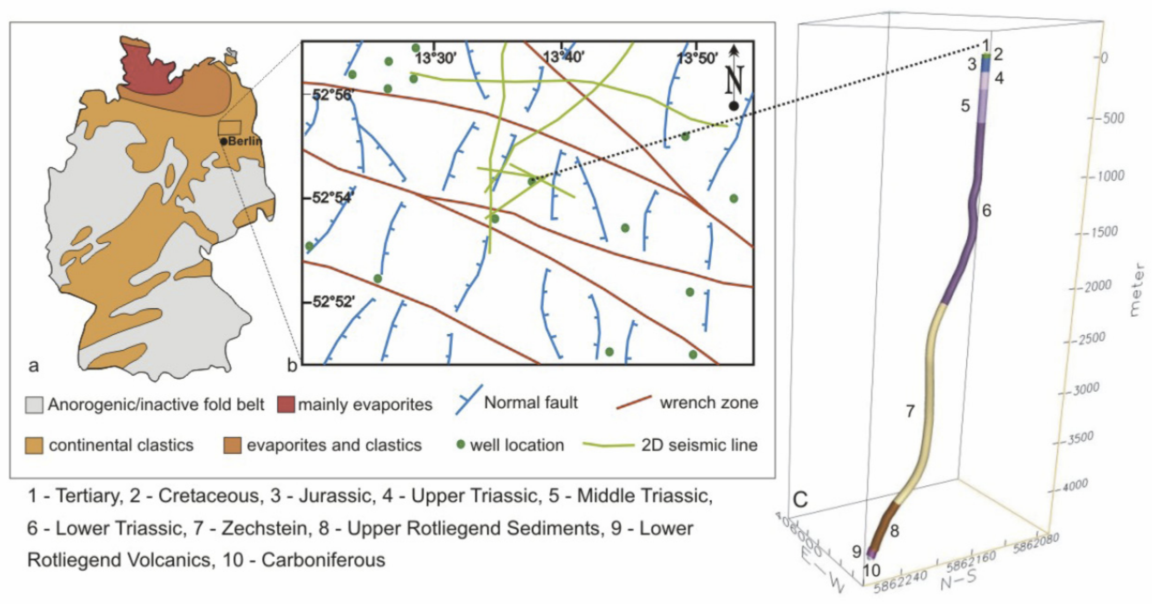

Figure 1. (a) Distribution of Rotliegend sediments in Germany. Box indicates the investigation area (modified after Ziegler, 1988). (b) Rotliegend structural pattern after Baltrusch et al. (1993). (c) Well path of the geothermal well GrSk 3/90.

Methods

Logging Program

The first geophysical logging program was carried out in 1991 to explore a potential gas reservoir in the Rotliegend sediments. Erdöl Erdgas GmbH (EEG) provided logging data in digital format for this project (caliper, spectral gamma ray, resistivity, neutron, density, sonic, and dipmeter). The GeoForschungsZentrum (GFZ) logging operations were performed by the Operational Support Group (OSG) implementing caliper, electric, spectral gamma ray, resistivity, and acoustic measurements. The last logging campaign was executed by Schlumberger during the winter 2003. Two new logging tools were used in addition to the GFZ logging program. The latest porosity measurement was achieved by Reservoir Saturation Tool logs (RST, mark of Schlumberger) and is used for a comparison with laboratory data.

3D Model Building

The basic 3D structural model is calculated, based on data of 6 pre-existing, reprocessed 2D seismic sections and 15 wells (locations in Figure 1). This modeling procedure comprises the development of a 3D conceptual model interpreted from a time-thickness map of the Rotliegend II, and the calculation of a final 3D structural model of the reservoir integrating the seismic section and well data with the conceptual model (Figure 2; see also Figure 4, track lithology).

The calculation of grids has been made with an iterative minimum tension algorithm, the fault model has been developed according specific fault hierarchies and the horizon model was processed according geological intersection rules. Lithofacies data are provided by the well data, resulting in following 5 lithotypes: (1) mudstone, (2) siltstone, (3) fine-grained sandstone, (4) medium-grained sandstone, (5) coarse-grained sandstone/conglomerates. To obtain both the structural and the lithofacies information in one coherent model, an adequate workflow is specified for the 3D lithofacies modeling. (I) Faulted property grids of each facies type are calculated over the entire model range, based on the initial structural reservoir model. Each property grid is the result of the catenation of property grids of each fault block; effectively the fault throw is taken into account (Figure 3a). (II) Each facies grid is normalized between values of 1.0 and 0.0 in order to delimit the property grid closely to the input data (Figure 3b). (III) The normalized grids are calculated pair-wisely against each other to obtain 10 sub-grids. (IV) The sub-grids are reconciled according to their lithofacies type inventory in order to create 0-isoenvelops; that clearly defines the different lithofacies bodies (Figure 3c). (V) The five lithofacies isoshell grids are assigned to each fault block of the initial structural reservoir model, enabling the calculation of a comprehensive 3D structural lithofacies model.

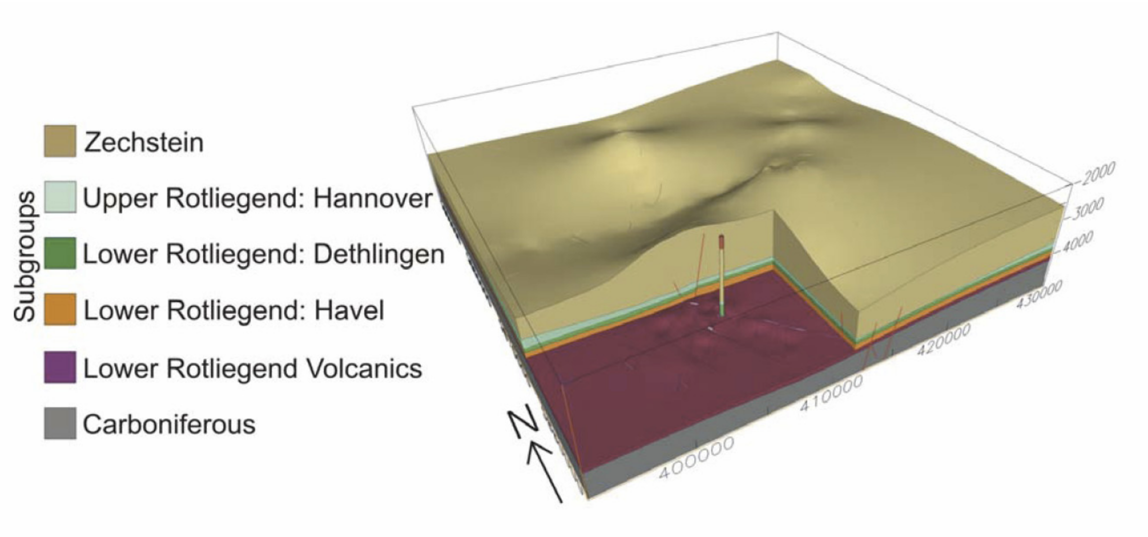

Figure 2. Basic 3D structural model of the geothermal reservoir. The tube is the geothermal well.

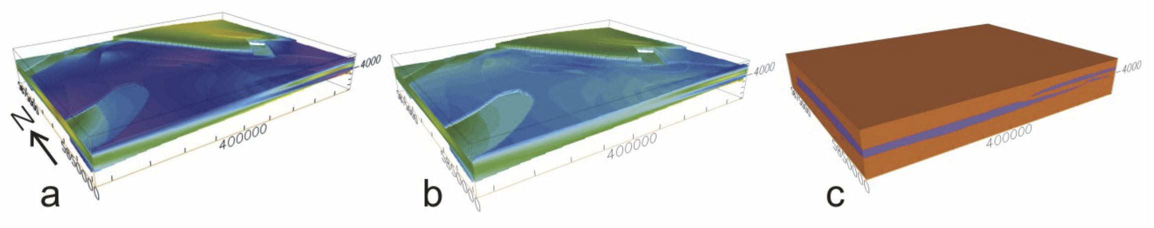

Figure 3. (a) Faulted property grid, (b) normalized facies grid; (c) the pink facies body is defined by a 0-isoshell. All grids represent facies type 3 (fine-grained sandstone).

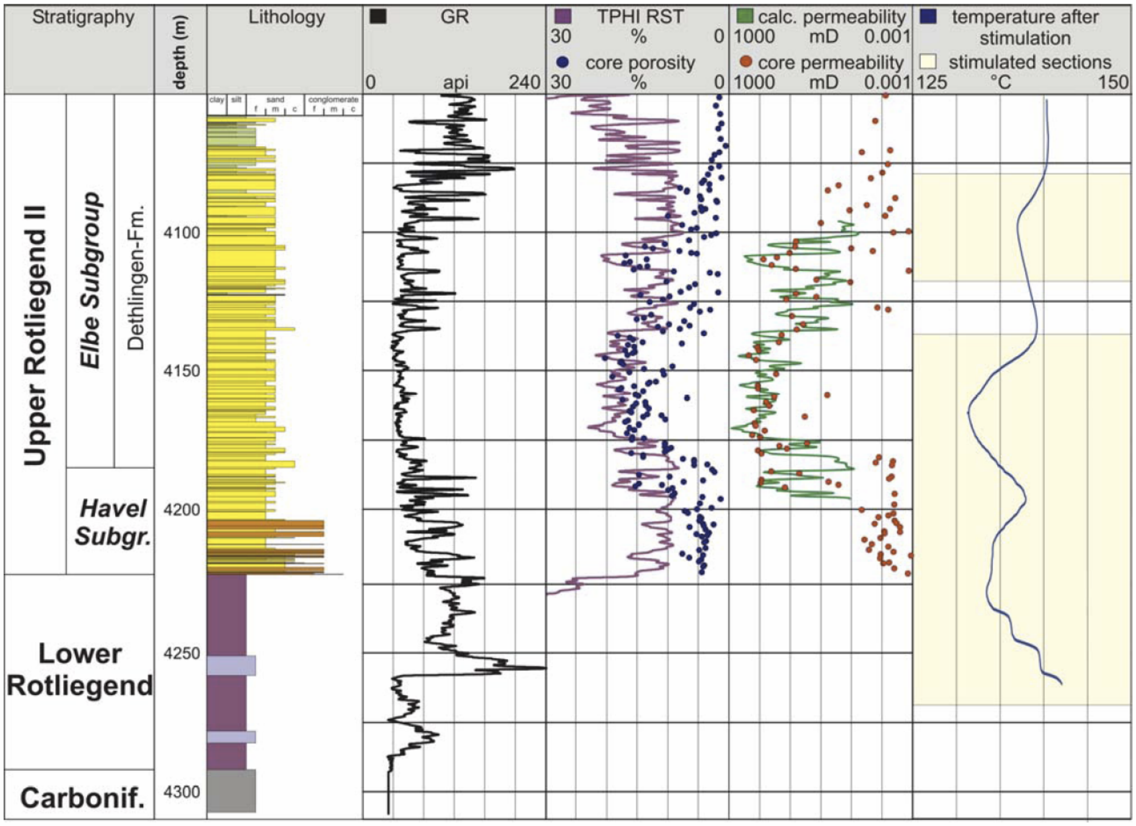

Figure 4. Lithostratigraphic chart of the siliciclastic Rotliegend strata in the well Gross Schönebeck 3/90 and comparison of logging data (Tphi RST) with measured core porosities as well as calculated permeabilities (logarithmic scale) with core permeabilities (porosity: n = 290; permeability: n = 109). The right track illustrates a borehole temperature measurement after stimulation. Bright yellow areas show the stimulated intervals.

Results

Figure 4 shows the lithology distribution and stratigraphic classification of the well Gross Schönebeck 3/90. The volcanic formation of the Lower Rotliegend consists of two different magmatic rock types. The upper series shows higher thorium contents than the lower series and is suggested to be more highly differentiated with a trachydacitic or trachyandesitic character. The lower series is characterized by geochemical properties of a more primitive source and is classified as basaltic andesite. Both of the volcanic rock suites are intersected by a crossbedded tuffaceous or tuffitic layer. The interbedded sediments consist of marls, marly limestones, and mudstones, subordinately interstratified by thin anhydritic evaporite layers.

The sandstones and conglomerates of the Havel Subgroup show decreasing gamma ray values attributed to the depletion of mechanically unstable, chemically altered volcanic rock fragments within a fining-upward cycle of the siliciclastic sediments. The nearly clean sandstones of the Lower Dethlingen Formation (4130-4175m/Lower Elbe Subgroup) show the lowest gamma ray emissions of all measured clastic sediments, owing to their low clay content. The gamma ray values increase continuously upward within the interval of interbedded siltstones/sandstones and reach a maximum value in the mudstones of the Upper Elbe Subgroup.

The petrophysical properties of the target horizons are important for the characterization of the geothermal reservoir. Figure 4 shows a composite log of the sandstones of interest. We used the neutron porosity measurement from the RST data (track TPHI RST) to estimate permeabilities (calculated permeability/logarithmic scale) using the empirical formula from Pape et al. (1999, eq. 22) and observed permeability values from 0.04 up to 110 mD. We repeated this procedure with porosity data calculated from density and sonic measurements and received transmissibilities in the range from 0.25 to 0.70 Dm for a 80m sandstone interval (4100-4180m).

The comparison of logging data (Tphi RST) with measured core porosities as well as a comparison of calculated permeabilities with core permeabilities is shown in tracks 3 and 4 (core porosity: n =290; core permeability: n=109). The results indicate a good correlation between logging data, permeability estimation, and core data. The right-hand track illustrates a borehole temperature measurement representing the current state after the last stimulation experiment. Temperature logs record changes of the temperature field due to injection and production of brines during hydraulic experiments. The bright yellow areas mark the stimulated intervals. Three temperature minima are recognized in identifying productive zones. The upper two temperature signals prove the existence of pay sand horizons. The productivity of the lowermost reservoir horizon indicates a cumulative flow out of porous sandstones (Havel Subgroup) and of the naturally fractured volcanic formation (Lower Rotliegend).

The 3D lithofacies model reveals the spatial distribution of the five lithofacies types that are part of the Rotliegend II siliciclastics (Figure 5). The conglomerates and the medium-grained sand were only deposited south of a NW-SE-striking strike-slip fault and in NE-SW-trending graben structures. The thickness of these facies types increases toward the S to SW. The fine-grained sand type is distributed over the whole model area and shows increasing thickness toward the WSW. The facies type mudstone shows increasing thickness toward the NW and SSW.

The target horizon is in the fine- and medium-grained facies type at an average 4150 m TVD due to its efficient porosity.

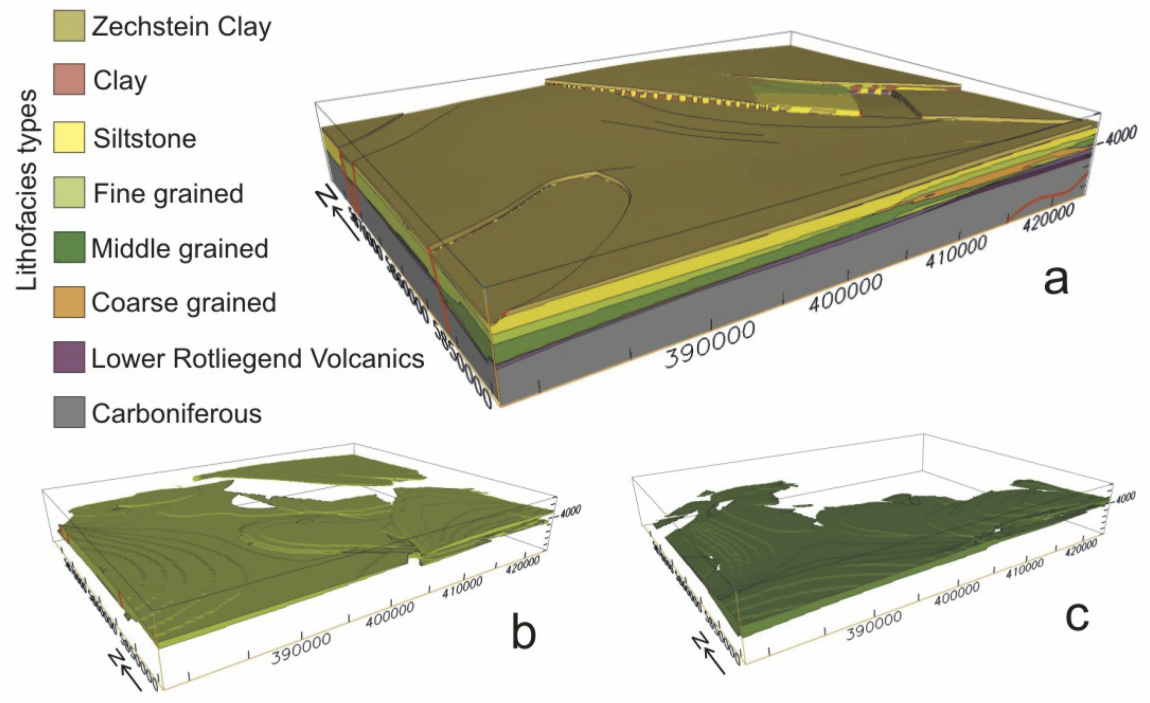

Figure 5. (a) Structural lithofacies 3D model of the reservoir horizon. (b) and (c) demonstrate the spatial extent of fine-grained and medium-grained facies types.

Conclusions

Recent investigations on the state of stress in the NEGB have revealed a constant ± N-S trend of the direction of the maximum horizontal stress S_H in the area north of Berlin (Röckel and Lempp, 2003). The mean direction of S_H was determined in the open-hole section of Gross Schönebeck from borehole breakouts and vertical hydraulically induced fractures to 18.5° ± 3.7° (Holl et al., 2004). Thus only a small acute angle exists between S_H and the NNE-trending faults. Röckel and Lempp (2003) have shown that the current state of stress in the NGB is generally a normal-faulting state; however, transitions to strike-slip faulting-states may not be excluded.

The recent stress regime in the Gross Schönebeck area is not fully known; however, in both possible cases ($S_H = \sigma_1$ or $S_V = \sigma_1$) the potential kinematic behavior of the NNE-trending faults is transtensional, whereas the NW-trending faults may suffer frictional blockade. The N- to NNE-trending faults are considered to be hydraulically conductive due to its shear stresses and resulting high tendency of transtensional slip (see also Zoback and Healy, 1992). Based on this knowledge, a 3D hydrotectonic model is developed for the reservoir (Figure 6), indicating hydraulically conductive structures. This should be taken into account when new potential drilling sites are going to be localized.

The combined use of pre-existing and newly generated data sets provides new understanding for the characteristics of the geothermal reservoir in the Lower Rotliegend formation of the North East German Basin. The multidisciplinary approach included implementation of existing well data, reprocessing of pre-existing 2D seismic sections, interpretation of various newly generated well log data, and reconciliation of all data to a coherent 3D geological model.

The petrophysical properties of the target, the depositional environment, and the reservoir geometry are now well known. These data are crucial for modeling the thermo-hydraulic conditions within the geothermal reservoir during production. Future work will focus on the use of geostatistical models, combining porosity and permeability distributions with sedimentary facies architecture.

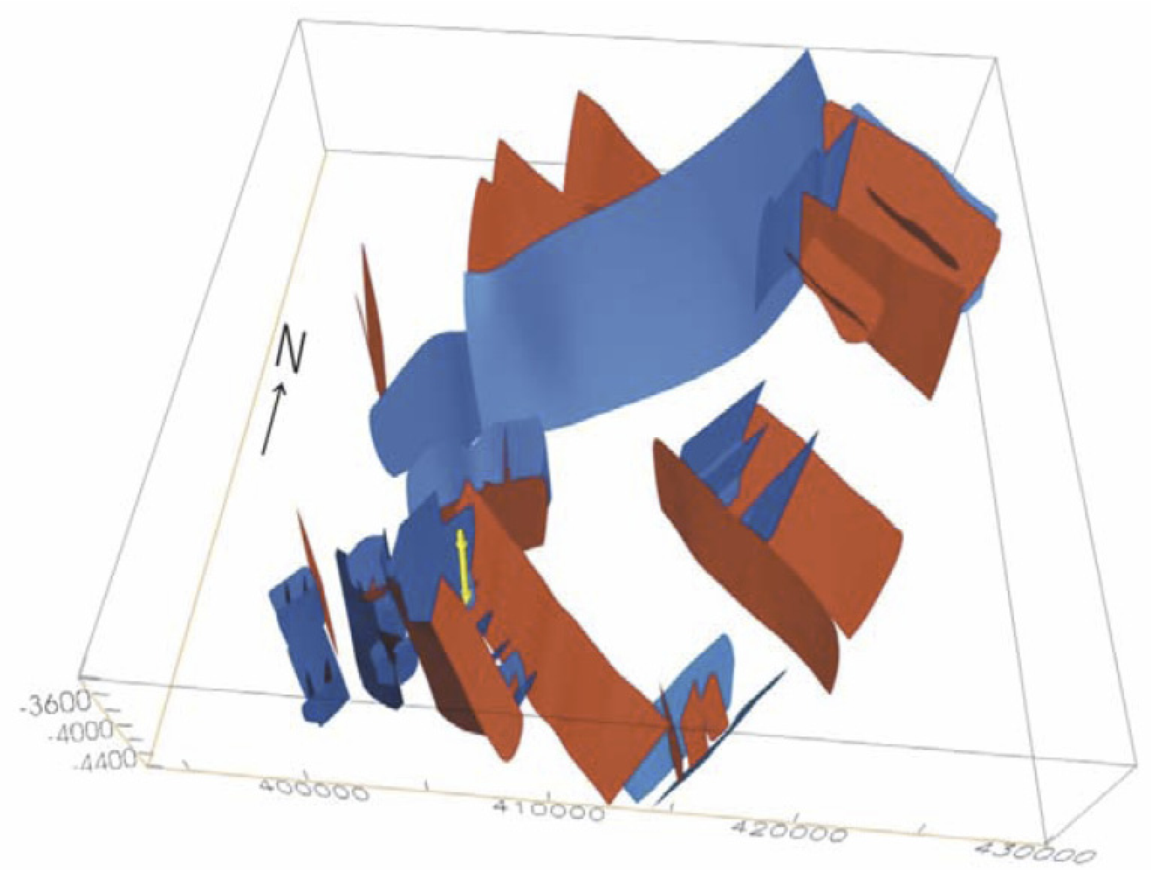

Figure 6. Hydrotectonic model indicating the hydraulic conductivity of the faults with respect to their kinematic behavior within the current in-situ stress field. Red faults: frictional blockade, acting as seals; Blue faults: transtensional, serving as conduits. Yellow tube represents the research borehole GrSk 3/90.

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Acknowledgments

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