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Characterisation of the Tectono-Sedimentary Evolution of a Geothermal Reservoir – Implications for Exploitation (Southern Permian Basin, NE Germany)

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ABSTRACT

The characterisation of the tectono-sedimentary environment as well as the knowledge of the recent maximum horizontal stress regime in reservoir scale is crucial for projecting directional and horizontal drilling of multiple borehole geothermal systems. This is necessary to initiate optimal conditions for hydraulic conductivity of faults and fractures inside the reservoir.

The in-situ laboratory Groß Schönebeck is installed in a former gas exploration well and part of a interdisciplinary project to develop geothermal technologies necessary for electricity production.

Various hydraulic stimulation techniques were performed in a period of four years (2000-2003) to enhance the productivity in siliciclastic and volcanic formations of the Rotliegend.

1. INTRODUCTION

The well Groß Schönebeck 3 (fig.1) was drilled 1990 and selected for the installation of a in-situ geothermal laboratory because it contains widespread low permeable rocks that attain temperatures necessary for geothermal power generation. The down-hole laboratory is used to develop hydraulic stimulation techniques to enhance permeability in siliciclastic sediments and volcanic rocks of the Rotliegend formation. Hydraulic production/stimulation tests and geophysical logging programms were performed after re-opening the borehole. This paper deals with the characterization of the sedimentary Rotliegend reservoir, including the interpretation of geophysical well logs, facies analysis and determination of structural patterns and hydraulically induced fractures.

Figure 1: Location of the well Groß Schönebeck 3

2. GEOLOGICAL SETTING

The North German Basin (NGB) is part of a large 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 Belt (fig.2).

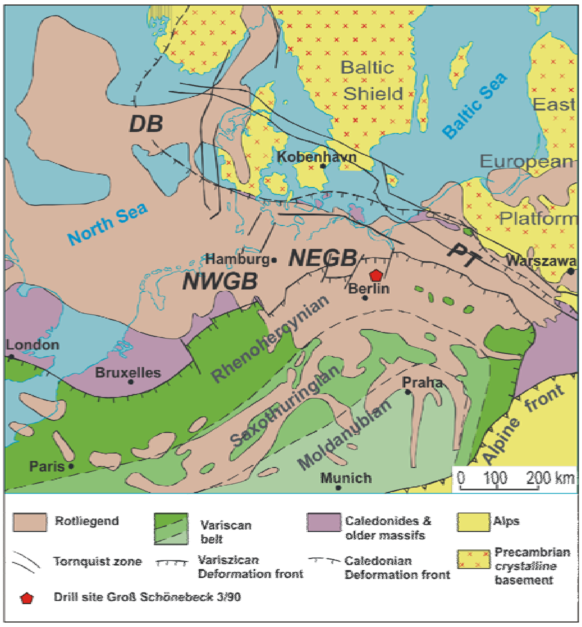

Figure 2: Geology of the Central European basement (modified after Ziegler 1990, Berthelsen 1992). DB: Danish Basin, NWGB: North-West German Basin, NEGB: North-East German Basin,

Initial basin extension occurred between the latest Carboniferous and the early Permian and was accompanied by the deposition of volcanic rocks (Breitkreuz and Kennedy 1999) which were subsequently covered by a Rotliegend siliciclastic sequence of alluvial fans, ephemeral streams, playa deposits as well as aeolian sands. Then cyclic evaporitic sediments were deposited during the Upper Permian Zechstein. Large lateral thickness variations were caused by salt diapirism during Late Cretaceous. The evaporites are covered by Mesozoic and Cenozoic strata.

3. METHODS

The geophysical logging programs include caliper, natural and spectral gamma, resistivity, neutron, density and sonic measurements. A accoustic borehole televiewer (ABF14) was used for structural determinations and fracture detection (Pischner et al. 2004). The last logging campaign was executed by Schlumberger. Measurements with the Fullbore Formation Micro Imager (FMI) provide microresistivity formation images of higher quality than the earlier used ABF14. A quantitative lithology interpretation based on elemental concentration measurements was available from Reservoir Saturation Tool (RST) logs.

The sedimentological interpretation is based on core material and wire-line logs (fig.3). FMI data are used for measurements of sedimentary structures (palaeocurrent directions on trough and tabular cross-bedded sets).

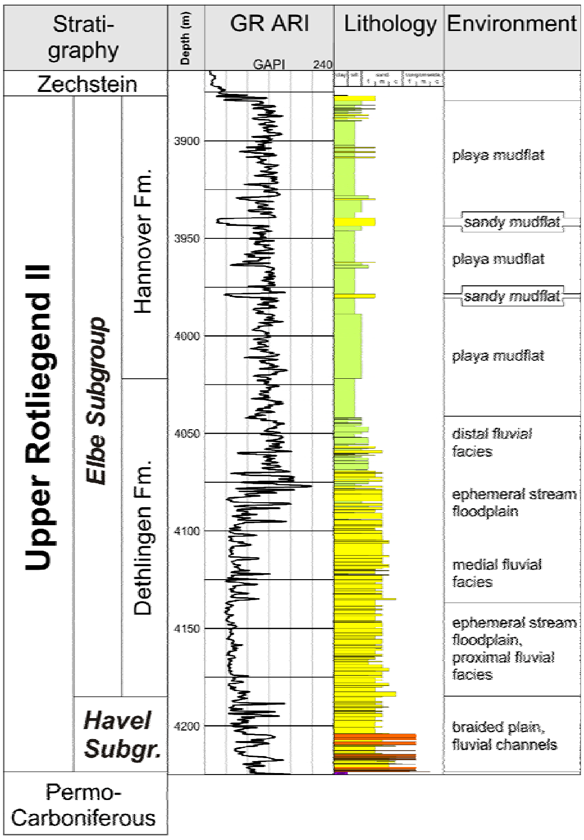

Figure 3: Lithostratigraphic chart of the siliciclastic Rotliegend strata in the well Groß Schönebeck 3.

An overview of the hydraulic experiments and treatments is published by Zimmermann et al. (2003).

To describe the reservoir geology in the vicinity of the geothermal well a 3D model was calculated with the 3D modelling software EarthVision by Dynamic Graphics Inc. The model is based on pre-existing data, namely 15 wells and 5 2D seismic sections. The 2D seismic sections had been re-processed by GGD Leipzig in order to interpret a vertical time thickness contour map of the reservoir horizon (fig.4). To built a coherent 3D model the fault geometries were calculated based on the seismic interpretation. Once the fault framework was correctly modeled the geologic horizons were integrated into the model, based on both the well data and the seismic interpretation. Furthermore a 3D lithofacies model was calculated with EarthVision, visualizing five lithofacies types namely (1) clay, (2) silt, (3) fine sand, (4) middle sand and (5) coarse sand/conglomerate. For this pursue an enveloping isoshell for each facies-type geometry was calculated with respect to the fault pattern. Finally the facies-types were assembled into a coherent 3D lithofacies model.

4. RESULTS

4.1 Sedimentology and tectonic environment

The clast supported conglomerates and sandstones of the Havel Subgroup at the base of the Upper Rotliegend II are interpreted as fluvial sediments of coarse-grained bedload rivers in a braided plain environment. The multistoried channels were deposited in a NNE striking depositional system, controlled by a tectonically generated morphology. Measurements of palaeocurrent directions on trough and tabular cross-bedded sets verify the transport parallel to the graben axis with a mean vector azimuth of 24° (n=95). The sandstones of the Upper Havel Subgroup show a mean palaeocurrent azimuth of 340° (n=37). The fluvial system drained at the end of tectonic movement into a depositional center towards the NW (see fig.4).

The sediments of the Dethlingen Formation (Lower Elbe Subgroup) were deposited in a ephemeral stream floodplain environment. The fine- to coarse-grained sandstones are amalgamated in character and show fining-upward trends to the top of the Formation representing proximal to distal fluvial facies. The palaeocurrent direction distribution is more variable as in the Havel Subgroup and prove the decrease of palaeoslope and flow velocity. Nevertheless, the transport direction is still to the NW (mean azimuth: 290°/ n=1163). Thermal subsidence of the NEGB is responsible for more uniform conditions in sedimentary facies. Channelized and unconfined ephemeral streams are the main sedimentation processes in the study area at this time (Rieke et al. 2003).

The mudstones of the Hannover Formation (Upper Elbe Subgroup) are interpreted as sediments of a mudflat environment. This fine siliciclastics reflect the transition from a rift-related coarse-grained continental sedimentation (Havel Subgroup and Dethlingen Formation) to the transgression of the Zechstein evaporitic sequences (Gaupp et al. 2000). Playa deposits cover large parts of the NEGB during the late Rotliegend and indicates the reduction of sediment supply as a result of peneplanisation of the palaeomorphology.

4.2 Tectonic framework and local stress regime

The main structures of the fault framework consists of NW-SE striking dextral strike-slip faults, which cross-cut NNE-SSW trending graben structures. The latter are considered as sinistral transtensional systems due to associated NNE-SSW en-echelon normal faults; the structural pattern is visualised in the geological 3D model (fig.6). This regional conjugate strike-slip system represents the kinematic response to early Upper Rotliegend platestress, as indicated by syn-extensional sedimentation of the Havel Subgroup conglomerates and sandstones.

ABF 14 and FMI images of the former open-hole section in Groß Schönebeck were scrutinized for breakouts and vertical fractures that indicate the direction of the recent maximum horizontal stress S_H in 18.5° ±3.7° (NNE-SSW; fig.5). ESE-WNW trending thrust faults may be related to the recent stress field and are thus thought to be recently generated faults. The Rotliegend structures might have been reactivated in the recent stress field with similar transtensive kinematics like during their generation.

Related to the recent stress field the minor NNW-SSE to N-S oriented en-echelon faults within the shallow graben structures show transtensile fault movement. Due to its kinematics, therefore, the en-echelon faults are considered to be the potentially most hydraulical conductive structures. A second well of a geothermal doublet system should cross these conductive structures to enhance the effectiveness of the geothermal system. This has to be taken into account for projecting directional and horizontal drilling of multiple borehole geothermal systems in the study area.

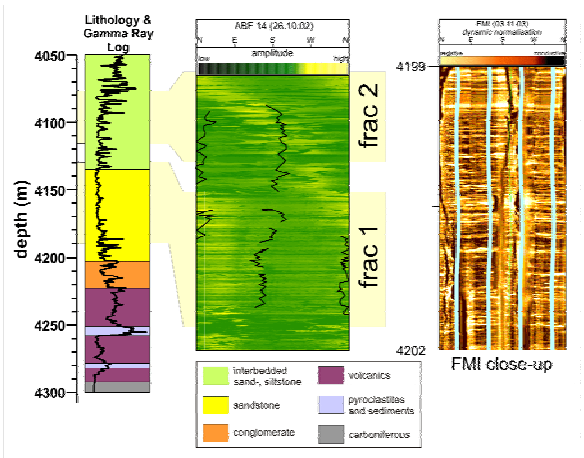

Figure 5: Hydraulic fractured sections of Groß Schönebeck 3. ABF14- and FMI-images illustrate the open fractures parallel to the maximum horizontal

4.3 Geological 3D Model

The 3D geological model of the Groß Schönebeck area reveals the geometries of fault arrangement as described in Chapter 4.2 (fig.6). Moreover the 3D model represent the spatial distribution of the horizons from the Carboniferous to Upper Rotliegend. The total thickness of the Upper Rotliegend II siliciclastic sediments ranges from 120 m in the NE of the study area to 580 m in graben structures in the SW of the area. Increasing deposit thickness in the graben systems indicate syn-sedimentary tectonics during the Upper Rotliegend. The NNE-SSW minor graben structures represent the depositional centres of the Havel-Subgroup. Fault movement ended with the Havel Subgroup sedimentation, consequently the grabens filled up with the end of Upper Rotliegend. The 3D model reveals the post-sedimentary fault movement indicating reactivation of the Rotliegend fault pattern. The NW-SE striking strike-slip fault, the ESE-WNW striking thrust fault and the NNE-SSW trending graben structures may be explained by reactivation of earlier faults in a recent stress field with S_H in NNE-SSW orientation.

The 3D lithofacies model reveals the spacial distribution of the five lithofacies types (fig.7). The conglomerates and the middle sand were only deposited south of the NW-SE striking strike slip fault and in the NE-SW trending graben structures. The thickness of these facies types increases towards the S to SW. The fine sand type is distributed over the whole model area and shows increasing thickness towards the WSW. This type is to be separated in the Dethlingen Formation in the footwall and in the Hannover Formation in the hanging wall. The facies types silt and clay show increasing thickness towards the NW and SSW.

5. CONCLUSION

Recent investigations on the state of stress in the NGB 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 extension 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 actual 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 behaviour of the NNE-trending faults is transtensional, whereas the NW-trending faults may suffer frictional blockade (dextral strike-slip faults in fig.8). The N to NNE trending faults are considered to be hydraulically conductive.

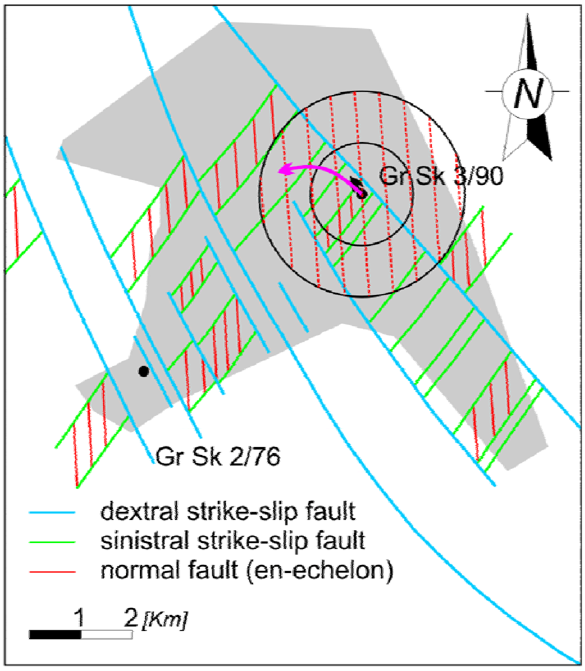

Figure 8: Tectonic sketch-map of the Groß Schönebeck area. The grey colored polygon is the area of the vertical time thickness contour map (fig.4). Red dotted lines are expected structures, predicted as potentially hydraulic conductive. The curved arrow describes the most promising drilling direction.

Depositional centres and fault systems of the Rotliegend strata were identified by reprocessing pre-existing 2D seismic section and are revealed in a coherend 3D model. The coarse grained sediments of the well Groß Schönebeck 3 were deposited into a small shallow graben system. The results of the vertical time thickness contour model are consistant with wire-line measurements. The palaeocurrent directions implicate transport of sediments into a depositional centre towards the NW as indicated in a 3D lithofacies model.

Stimulation experiments in two intervals of the Rotliegend sandstones induced fractures that are oriented subparallel to fault systems generated in the Rotliegend times. As these structures are considered as hydraulically conductive with respect to the recent stress field, the planned second well should cross these structures. Horizontal and directional drilling presents a procedure to optimally exploit the conductivity of both the pore space and fracture systems.

The knowledge of the 3D geometry of the sediment body and the orientation of regional fracture systems, based on pre-existing and newly generated data, may implicate a successful geothermal power production system brought up by drilling an second well.

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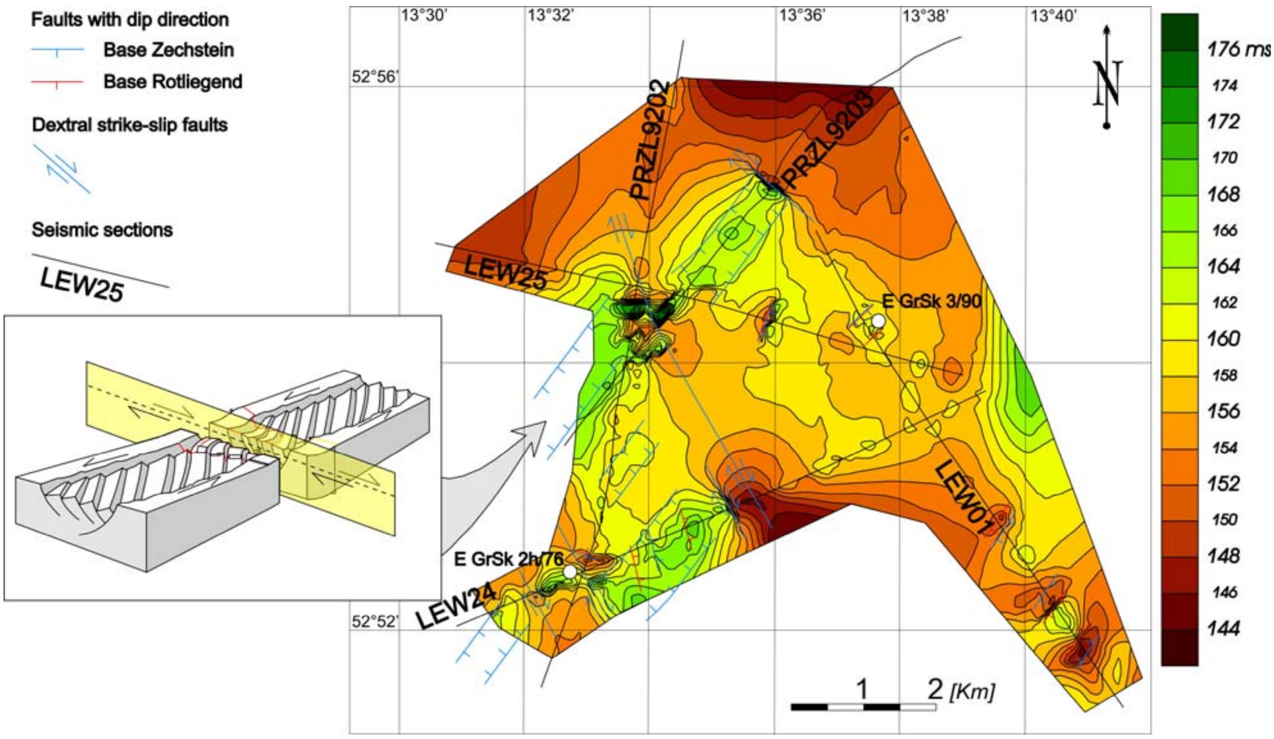

Figure 4: Structural interpretation of the vertical time thickness contour map (Horizo Z1-H6). Graben systems strike NNE-SSW. White circles are well locations (Holl et al. 2004).

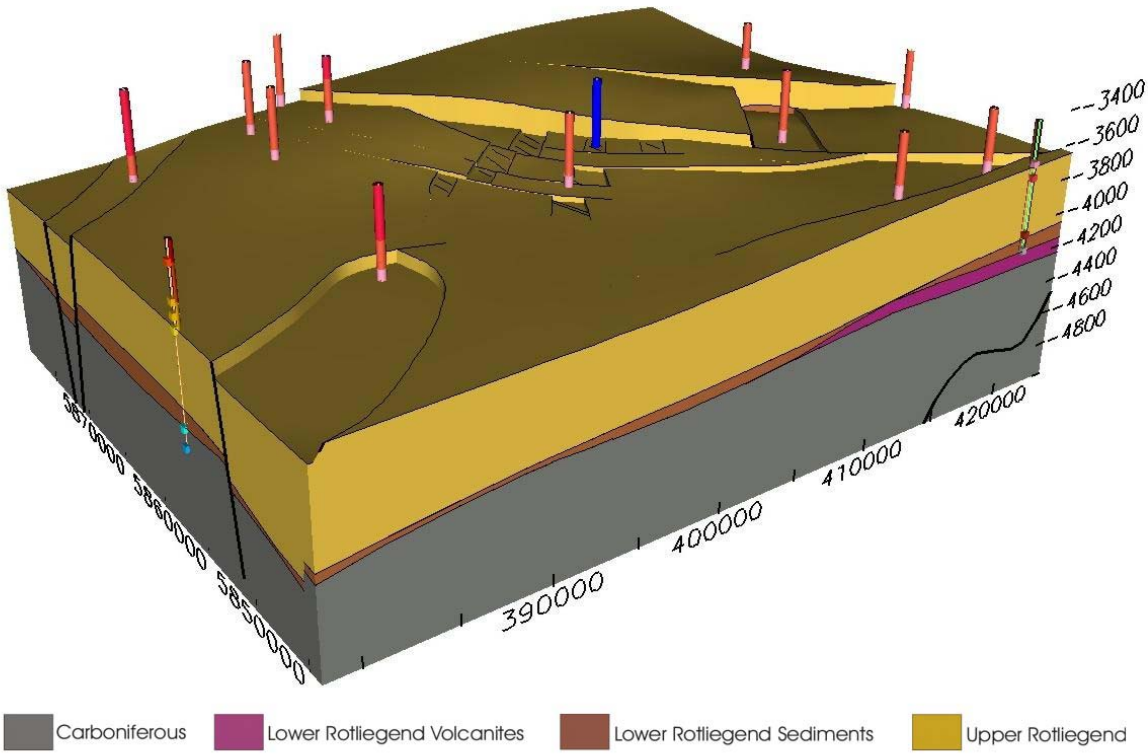

Figure 6: Fault pattern, its kinematics and the strata of the investigation area. Well Groß Schönebeck is marked as blue tube, other tubes represent further wells. Coordinates are in UTM, depth is in meters.

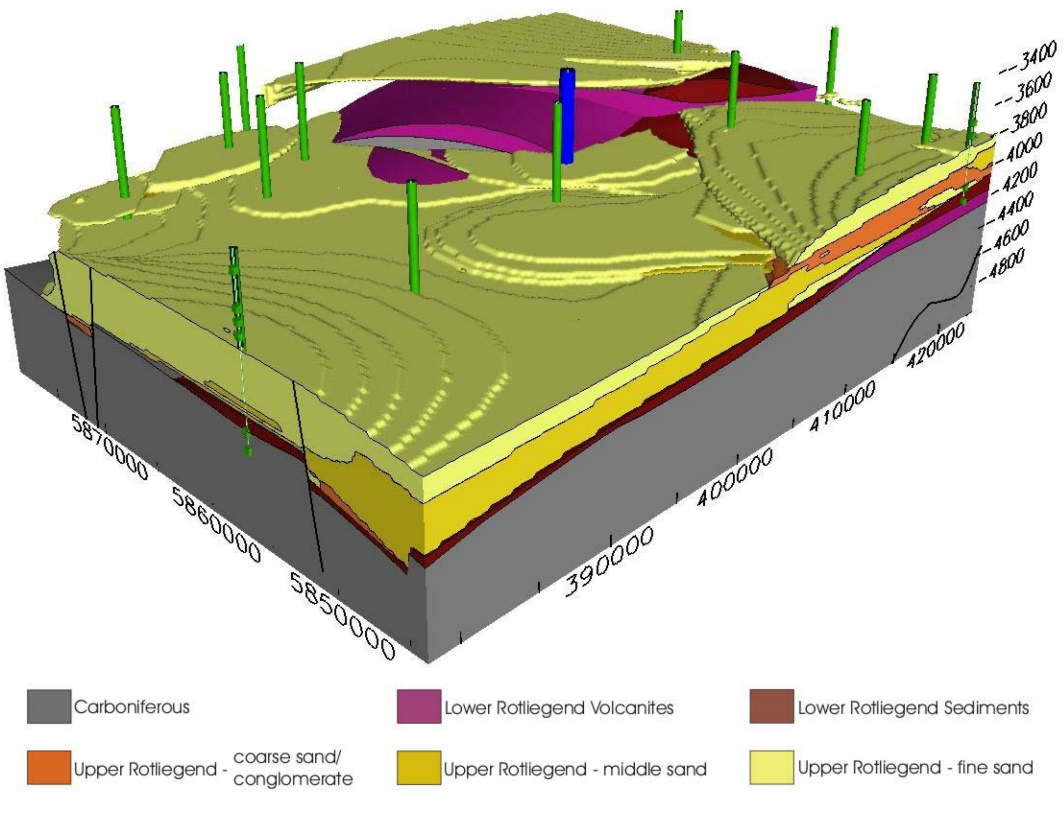

Figure 7: Lithofacies model revealing the spacial distribution of conglomerate to fine sand fraction of the Upper Rotliegend. Coordinates are in UTM, depth is in meters.