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3D Stress and Pore Pressure Modelling for Closed-Loop Geothermal Development in the North German Basin

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Summary

This study investigates the geomechanical characteristics close to the city of Hannover, Germany, where Eavor GmbH (Eavor) is planning a closed-loop geothermal system (an Eavor-Loop™). The project is located in the North German Basin (NGB), which is characterized by complex geological structures consisting of faults and several salt bodies. Salt is known to impact the subsurface stresses, pore pressure and temperature. Understanding these perturbations is essential for successful development of Eavor-Loop systems, as well as conventional geothermal, enhanced geothermal systems, hydrocarbon exploration, and underground storage operations.

For this research, geomecon GmbH in collaboration with Eavor successfully built an advanced geomechanical model in COMSOL Multiphysics®, which is based on the Finite Element Method. The model captures the stress, pressure and temperature perturbations caused by several nearby salt diapirs. The model is calibrated against offset well data confirming an overall normal faulting stress regime at larger distances from the salt diapirs. However, significant stress alterations can be observed closer to the salt diapirs, highlighting the strong influence of salt structures on the stress field in the NGB. The model will be used at a later stage to extract geomechanical properties along the proposed geothermal well paths to analyze optimal directional plans and drilling parameters.

Methods and Workflow

At the onset of the project, Eavor geoscience team provided a 3D geologic model including key horizons, salt, and fault interpretations. This model had been developed in AspenTech's SKUA GoCAD software. Drilling reports and wireline logs for offset wells were also available. A new workflow was developed by geomecon to transfer the SKUA model into COMSOL Multiphysics and to refine the intersections between the lithological boundaries. The resulting regional geologic model was ~7km deep and spanned ~60 x 40 km with a high resolution inner local Area of Interest (AOI) (~20 x 20 km) (*Figure 1*).

Offset well logs were used to establish most of the properties for the 1D Mechanical Earth Models (MEM). The salt layers were modeled as a viscoelastic body with a viscosity dependence on the salt thickness (the salt flows quicker in thick salt bodies). The stress and pore pressure environment from offset well data and literature reviews were used to calibrate the model at certain control points away from the salt.

The COMSOL modelling workflow included an Initialization Study, a Salt Relaxation Study, and a Thermal Study. The Initialization Study was based on a purely gravitational stress field with poroelasticity and heterogeneous pore pressures. This stress induces differential stresses between the vertical and the horizontal stresses in the model which in turn induces salt creep, as larger salt bodies tend to flow over time until all shear stresses have decayed. To capture this, a "Salt Relaxation Study" was then run. The output of this was the expected current day stress regime in the Hannover area. The stress and pore pressure profiles at local offset wells were compared to the final COMSOL model.

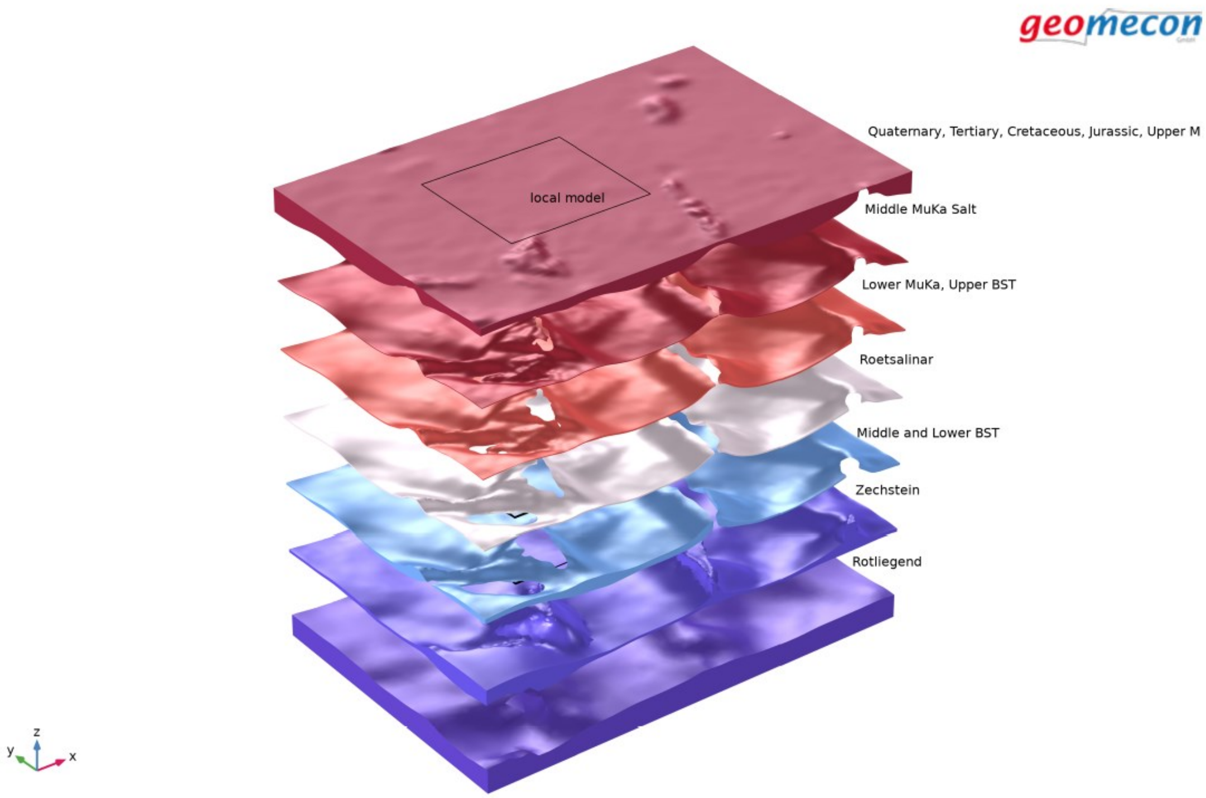

Figure 1: Expanded view of the layers in the COMSOL regional model containing the local AOI (black frame).

Model Initialization

The stress field in the Northern German Basin (NGB) is strongly influenced by the presence of the underlying Zechstein salt formations, leading to a decoupling of the stresses below (pre) and above (post) the Zechstein (Röckel & Lempp 2003, Zang & Stephansson 2010). The focus of this study was for above the Zechstein. There is a known change in the SH azimuth above and below the Zechstein, and it is expected to be a strike-slip stress regime below the Zechstein, and a normal faulting regime above it. The stresses below the Zechstein salt show stress orientations typical for North Central Europe (N-S to NNW-SSE) and are mostly influenced by tectonic effects as the convergence of Europe and Africa and the opening of the Northern Atlantic. The decoupled stresses above the Zechstein are mostly governed by gravitation and elastic effects, as typical for a passive sedimentary basin. This leads to an irregular stress orientation in formations above the Zechstein. As a result, the stress field in the Hannover area is mostly governed by gravitational relaxation and no tectonic forces were applied as boundary conditions.

A normal hydrostatic pore pressure gradient could not be assumed for the Hannover area. In the NGB, pore pressures often increase to over hydrostatic conditions from the lower Cretaceous onward and reach elevated overpressures especially in the Buntsandstein (BST) formations (Röckel & Lempp 2003, Röckel 2019). Mudweights and pore pressure measurements from offset wells could be used to initialize the pore pressure model.

Results

From the study, it was seen that the stress was influenced up to ~3x the radius of the salt diapirs. In the currently planned area for the Eavor-Loop in the local AOI, it was found that the influence of salt is minor except towards the NW, which is affected by a salt cushion in the underlying formation. The COMSOL model results suggest that the stress field is relatively consistent in planned Eavor-Loop area (*Figure 2*). The stress field rotates and changes from normal faulting to strike slip in some areas adjacent to the salt diapers. In the local AOI, the stress is almost entirely normal faulting with a maximum horizontal stress direction towards NE-SW.

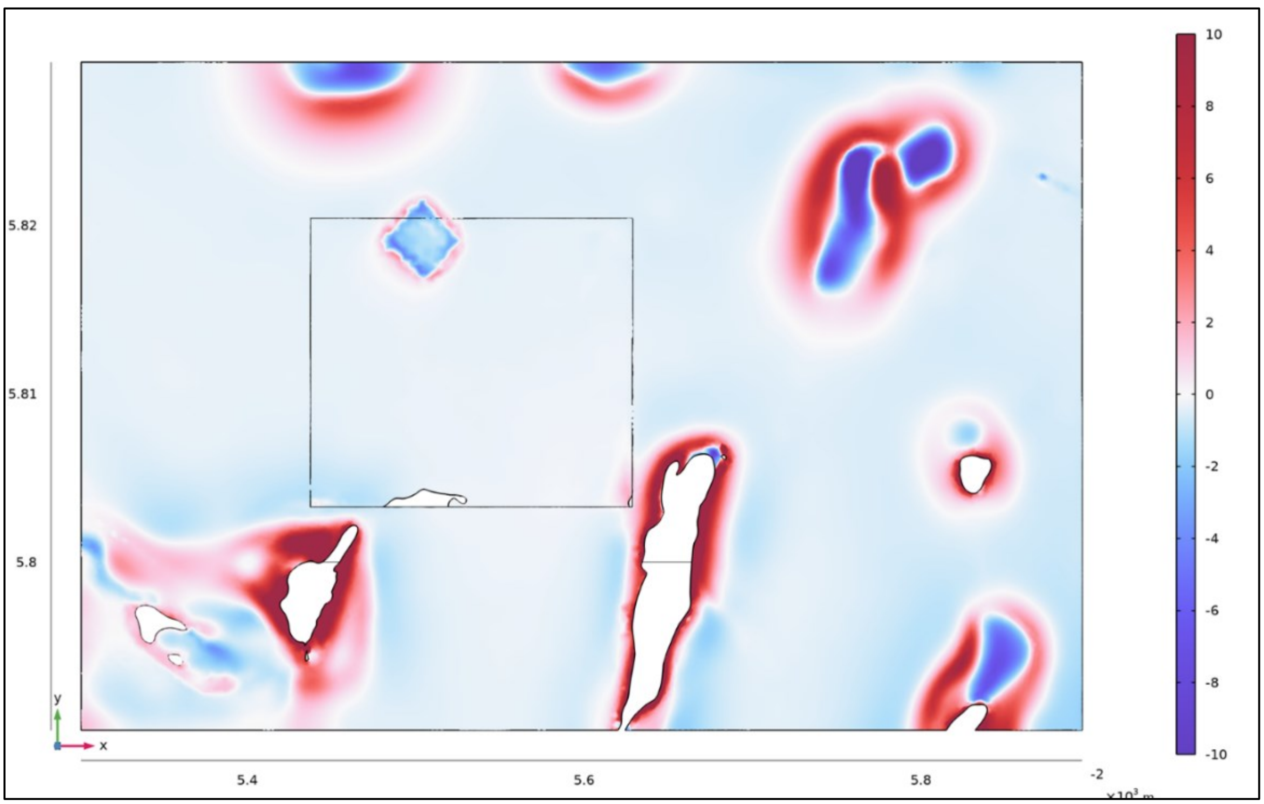

Figure 2: Influence of salt dome relaxation and change of minimum principal stress (Shmin), displayed on the upper BST. Reduction shown in blue, increase shown in red. The local AOI is shown by the square inset.

From the COMSOL model salt relaxation study, the greatest pore pressure perturbation was found between the salt layers, likely due to trapping by the low permeability salt. This resulted in an increase in pore pressure in sedimentary formations to a maximum of 3 MPa. However, the overpressure magnitude is known to be much more than this. As a result, based on these model assumptions, salt dome relaxation is likely not the sole cause for overpressures in the Hanover area. Vertical compaction in conjunction with impermeable formations, faults and salt horizons are assumed to have caused the observed overpressures. To achieve the correct overpressures, the pore pressures had to be initialized prior to salt dome relaxation. These were then compared to the offset well data points and there was good agreement between the measured and modelled pore pressure.

For future work, the COMSOL model will be used to analyze optimal directional plans and drilling parameters for closed-loop geothermal energy development. For each wellbore in the proposed Eavor-Loop, the principal stresses and pore pressures will be exported along the well path and used for detailed wellbore stability modelling.

Acknowledgements

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