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4D-geomechanical Simulations (VISAGE^{TM}) to Evaluate Potential Stress Relocation in a Geothermal Targeted Fault System in Munich (South Germany)

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ABSTRACT

This study investigates the potential of seismic events for newly planned wells based on coupled thermal-hydraulic-mechanical (THM) simulations, through the evaluation of risk to relocate stress during the testing and production phase.

In an initial stage of this study the stability of the targeted fault system was assessed by defining failure criterion along the fault planes under the present stress regime. These areas are expected to potentially react plastically and form a seismic hypocenter.

The 4D-geomechanical simulations were undertaken utilizing the software VISAGE™ using one-way coupling. Firstly, different test and production scenarios including pressure and temperature distribution in the reservoir were simulated with ECLIPSE™ based on permeability parameter variation. From this a thermal and hydraulic worst-case (maximum pressure drop resp. increase and maximal cooling) was defined according to the mechanical stress and used as input for the mechanical simulation in VISAGE™. Six short term and three long term pumping tests as well as the later production scenario with two different settings of injector and producer were assessed.

The results of the 4D modelling show after 50 years of operation that the cooling impacts the stress regime and therewith the stability of the fault system in the vicinity of the injector much more than its pressure change.

The client's requirement was for worst case examination due to the urban setting of the wells. Despite the data used being from a pre-drilling stage with inherent uncertainties for modelling, we are of the opinion that the results are sufficiently reliable for process understanding. Therefore, we conclude that the stress relocation with a maximum pressure and temperature change in a pre-drilling phase was achieved. Short term risk mitigation measurements were then proposed to re-arrange producer-injector order and re-plan well paths and targeting for one well. Long term a "Reservoir Management System" to monitor induced seismicity shall be installed.

1. INTRODUCTION

The South German Molasse basin is one of the most favorable geothermal regions in Germany due to the presence of the Upper Jurassic Malm Aquifer. In the Munich city area, its top is found at depths between 2000 – 2800 m with temperatures of 80 °C – 110 °C. In the Greater Munich region, there are to date 14 operational projects with 32 wells, these have demonstrated that a yield of 80 l/s – 120 l/s can be expected and thus that conditions are favorable for efficient direct use supplying municipal district heating networks.

Although the region is known to be seismically inactive, a number of projects have nevertheless experienced induced seismic events in their vicinity, and of those projects experiencing these events only two were felt by the public (Megies & Wassermann., 2017).

The Munich Municipal Energy Supplier, SWM Services GmbH is the developer and the operator of several geothermal heat and power producing projects in and around the city of Munich. SWM commenced the construction of Schäftlarnstrasse (SLS) one of the largest geothermal heating plants in Europe in 2015. At the end of 2017 shortly before drilling six wells in the inner city a significant (ML >2,1) earthquakes occurred in the Molasse.

The planning has foreseen the targeting of a prominent fault system, the "Münchner Versatz" with three out of the six wells. The question raised if injecting the cold water with the foreseen pressure (based on thermo-hydraulic simulations) would lead to an increased risk of induced seismicity.

To understand the process and assess the risk of stress relocation leading to induced seismicity through operation at the location of the Schäftlarnstrasse (SLS) a simulation shall elucidate the situation before drilling and help to develop, if necessary, a mitigation strategy for the scenarios during testing and operation.

2. DATA AND METHOD

2.1 SIMULATION WORKFLOW

The 4D-geomechanical simulations were undertaken as per the flow diagram in utilizing the software VISAGE™ using one-way coupling (see Fig. 1). Thermo-hydraulic input parameters were taken from a previously performed reservoir simulation model in ECLIPSE™ based on a PETREL™ model.

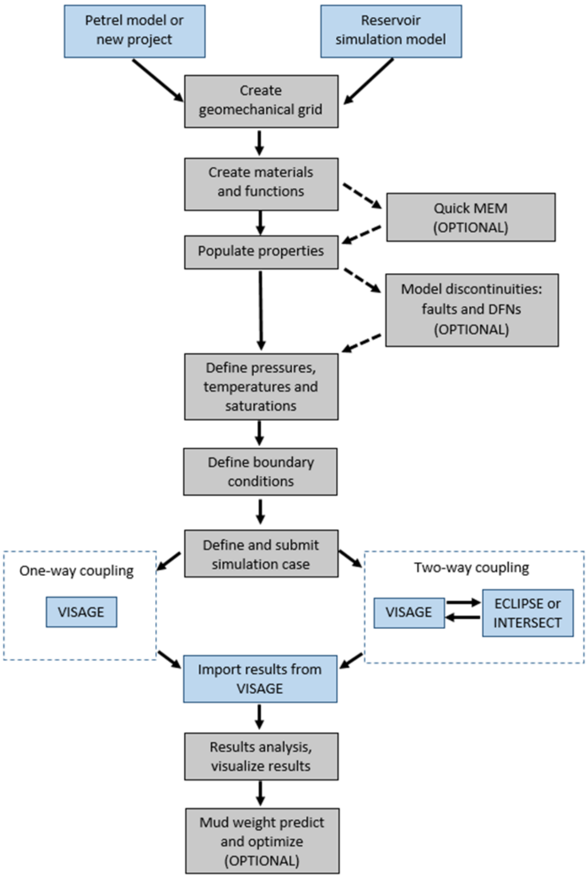

Figure 1: "Reservoir Geomechanics" workflow for 3D/4D simulations with Visage™ starting from a Petrel™ model (Schlumberger, 2016).

2. STUDY AREA AND DATA USED

The study area (Fig. 3) is located in the central part of the South German Molasse basin where the Upper Jurrasic Carbontes are used as a geothermal reservoir. At the SLS location they were expected to be at a depth of around 3.000 m TVD with mainly tertiary overburden of typical marls and partially sands and limestone.

3D seismic data was acquired for the inner city area of Munich in 2015. Input parameters could be used from several offset wells. In the planning phase for SLS three wells targeted faults, and three were selected based on seismic texture indication on favourable litho-facial expressions.

Due to pressure compensation of neighbouring producer and injector wells in operation a cost effective trefoil arrangement was planned. However it shall be determined after drilling results if the well will be a producer or injector, based on its yield and temperature.

Therefore only two variants are possible with either two producers or injectors in the faults system.

2.2 SIMULATION MODELL

The simulation model is shown in Fig 2. Thermal-hydraulic simulation model was created with a size of 191,0 km². The corner-point grid contains 3.339.360 cells (279 x 266 x 45) with zig-zag type faults. Geomechanical simulation model has a size of 1.626,3 km² with a finite-elements-net of 6.869.960 knot points (295 x 284 x 82).

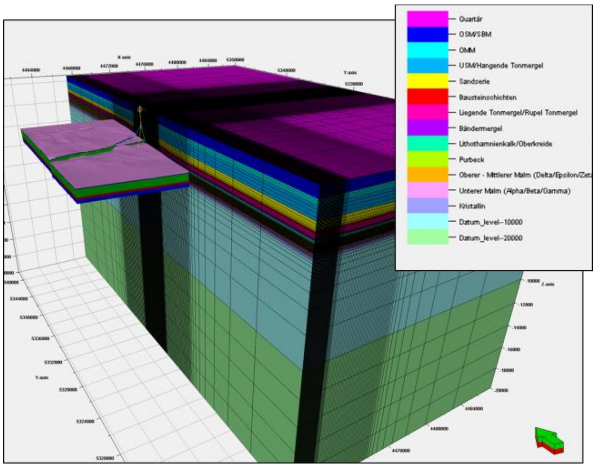

Figure 2: 3D View of the eastern part of the geomechnical simulation model (right block) with assigned geomechanical zones, and the imbedded thermo-hydraulic model (small block left).

2.3 GEOMECHANICAL PROPERTIES

Geomechanical properties were determined from P-wave velocities. Six wells were available with sonic- or Vp-Logs in different sections. A density-log could be used from one Offset-Well. Dynamic and static Youngs' modulus as well as the Poisson ratio were determined from the available data and then used to calculate rock strength (Castagna et al., Greenberg & Castagna, 1992, Brotons et al., 2015, Ziegler et al., 2016, Chang et al., 2006, Hoek, 1966, Robertson, 1988, Konietzky & Wang, 2018).

2.4 STRESS REGIME

The stress regime is of a strikes slip character with a stress orientation of N 359,6° ±12,3° for the maximal horizontal stress (SHmax), as a base of evaluation of stress indicators from different image and oriented caliber logs throughout the region. Figure 5 shows the input data for the geomechanical simulation. The magnitude of the minimal horizontal stress (Shmin) was determined with 0,18 bar/m from Formation Integrity Test (FIT).

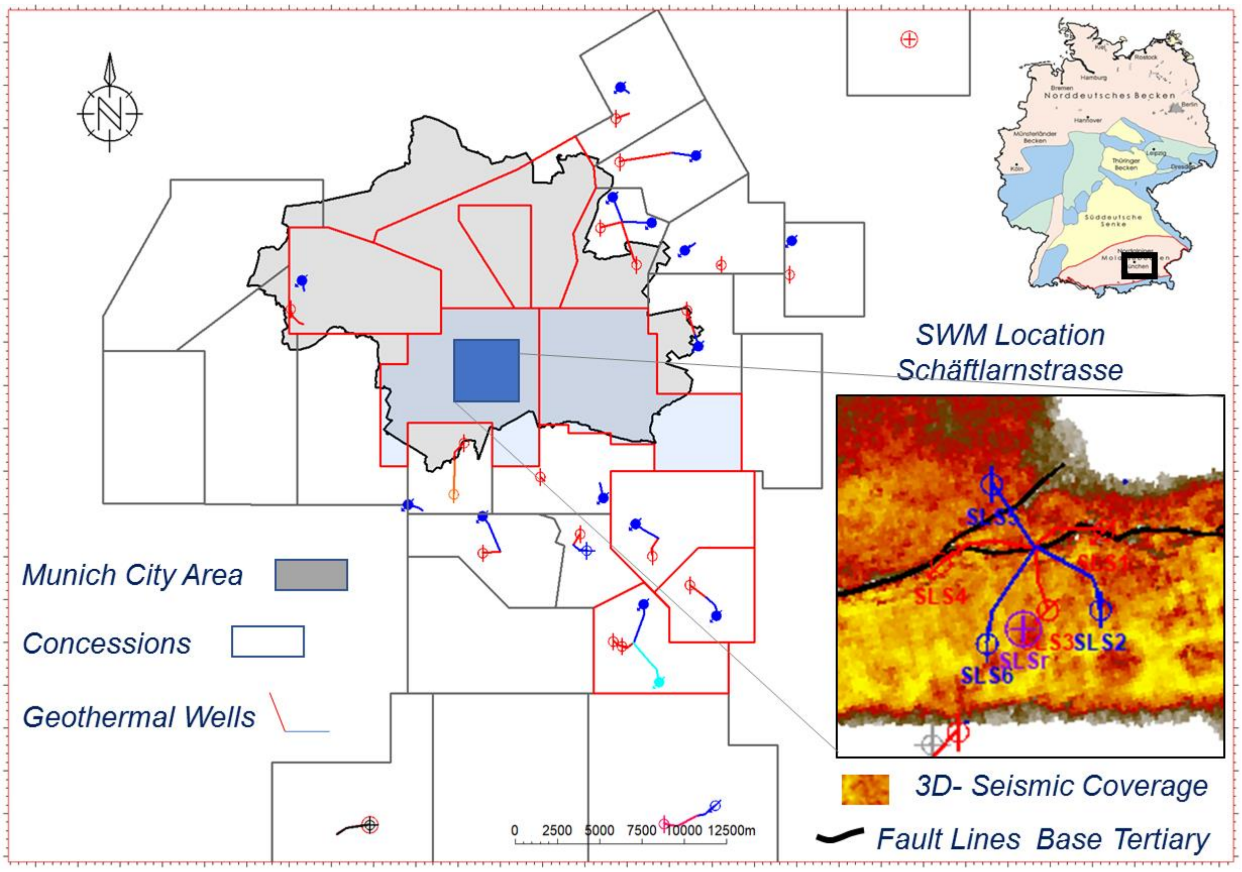

Figure 3: Munich region with geothermal concessions and off set wells (producer red, injector blue). Right below is a map of the location of the Schäftlarnstrasse (SLS) with two producing wells from the fault system (one of the two operation variants – see text).

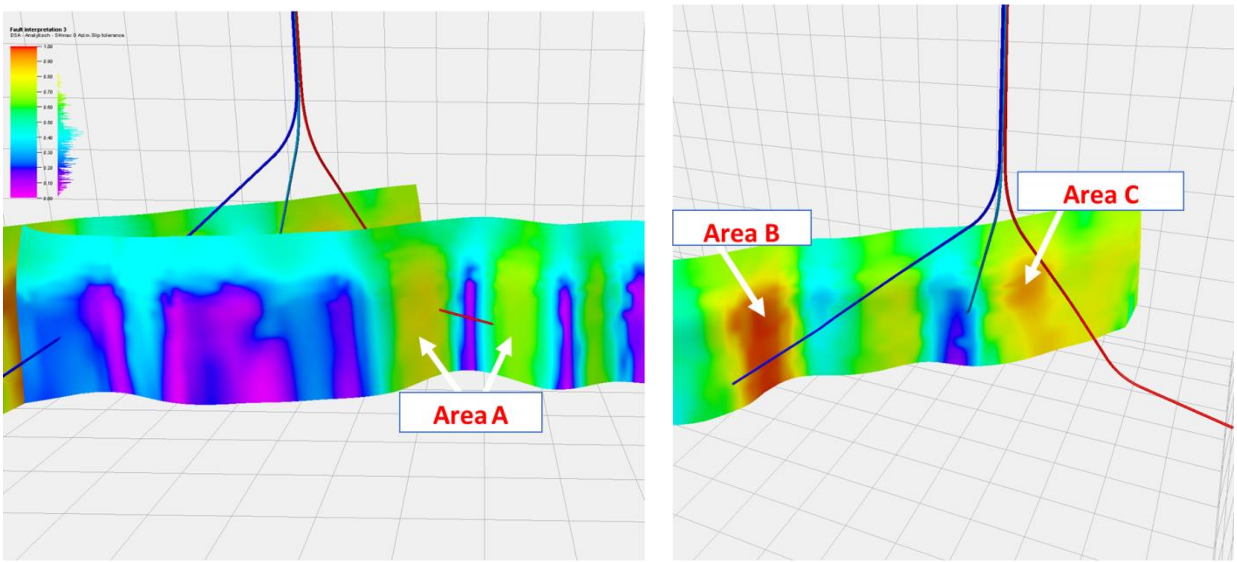

Figure 4: 3D view of the calculated slip tolerance (ST) in the base case along the fault surfaces with the determined critical areas A, B and C. Remark: for a better orientation only three wells are displayed, for both images the view is the same resp. from the south, on the right image the front fault is transparent.

The only available Leak Off Tests (LOT) were possibly influenced by an overpressure zone. Since no further data was available, the calculation of the magnitude of the maximal horizontal stress (SHmax) was based on the worst-case assumption that the reservoir is critically stressed with a friction coefficient for the faults of 0.6 (Zoback, 2010).

The magnitude of the vertical stress (Sv) was calculated from an estimated density log and verified with the density log from an offset well in the South of the Munich Area.

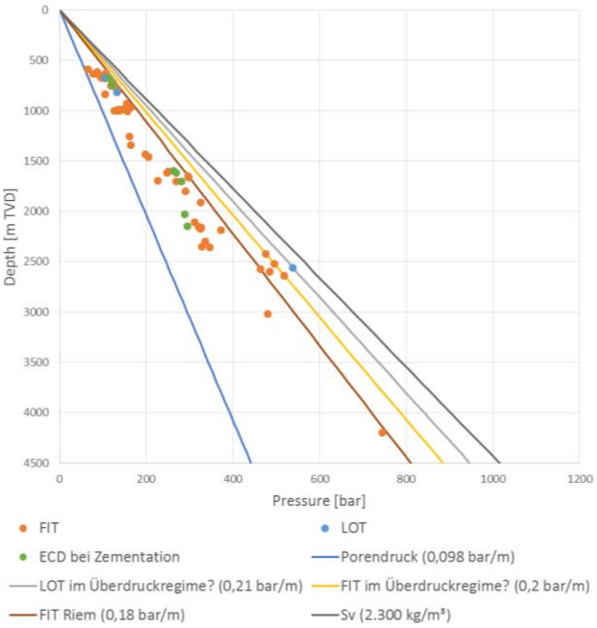

Figure 5: Depth vs. Pressure diagram with data interpretation used for the determination of stress parameters for simulation.

2.5 SLIP TENDENCY ANALYSIS

As base case the median value of the maximum horizontal stress SHmax with an orientation of 359,6° azimuth was used. The results of the analytical stability analysis of the fault system are shown as Mohr diagram or polar diagram in Fig. 6 and as slip tolerance (ST) along the fault surfaces in Fig. 4.

The polar diagram shows that the critically oriented fault areas have a strike-slip regime of ±30° to the north and a vertical dip.

The evaluation of the slip tolerance (ST) along the fault areas results in three areas which could reach a critical state (cf. Figure 7). Area B has the highest slip tolerance with values up to 0.99, which corresponds to a critically stressed condition.

In order to demonstrate the sensitivity of the orientation of the maximum horizontal stress SHmax to the stability of the fault system an analytical stability analysis of the fault system with a change of the direction of SHmax 12.3° azimuth and 345.9° azimuth was additionally performed. It showed that with the first the stability of the fault system targeted by the SLS wells would increase whereas with the latter it would be in a more critical condition compared to the base case.

2.6 THERMO-HYDRAULIC SIMULATION

From the results of the geomechanical simulations it turned out that all testing scenarios are uncritical, therefore the following concentrates on the production scenarios.

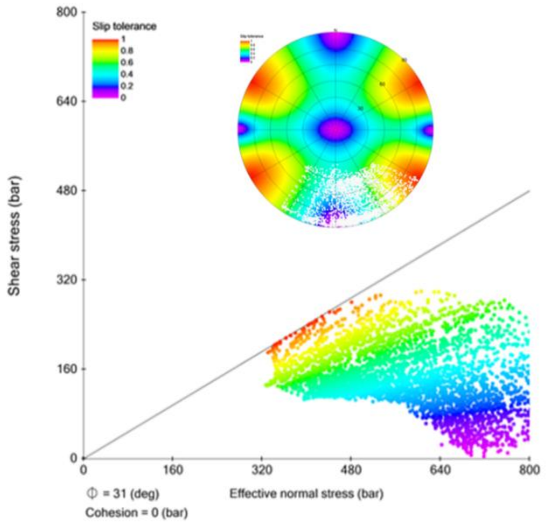

Figure 6: Diagrams for the analytical stability analysis of the targeted fault system.

Total duration of production is simulated for 50 years, the operating water level defined at 700 m below ground, taking the friction losses of the respective borehole into account. Injection temperature is fixed to 60 °C and production rate is limited to 150 l/s.

Table 1: Overview of the thermos-hydraulic simulated production scenarios 1 and 2; in red producer and in blue injector wells.

	Wells 1,3,5	**Wells 2,4,6**	Number of parametrization, hydr. activity of fault
PS 1	700 m	$-Q_{prod}$ 60 °C	11, without 5, with
PS 2	$-Q_{prod}$ 60 °C	700 m	11, without 5, with

According to the effectiveness of a trefoil arrangement two production scenarios (cf. Figure 7 for PS 1) were investigated for each of them with 11 different permeability parameterizations in the reservoir section and 5 more for a preferred propagation of the cooling front along the fault system due to a higher permeability. Table 1 gives an overview of the simulated production scenarios. Overall 32 simulations were done, the injection rate (-Qprod, cf. Table 1) results from the partitioning of the simulated overall production rate according to the production specification in Table 1.

Basically, the simulations were run under the requirement of a hydraulic worst case with a maximum pressure release resp. increase in the reservoir and a thermal worst case of maximal cooling of the reservoir.

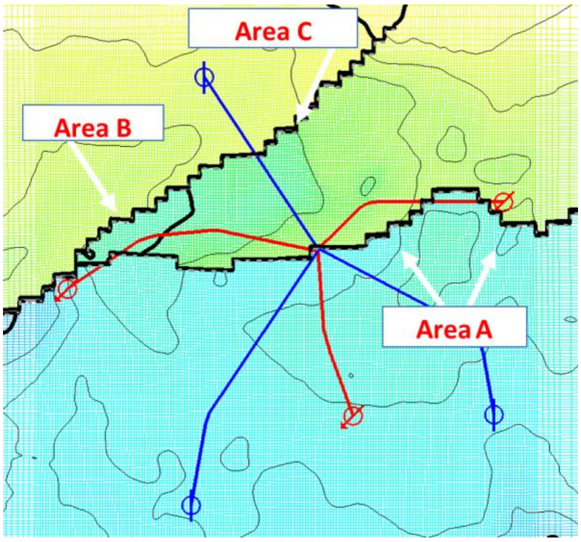

Figure 7: SLS map location at top reservoir of the thermo-hydraulic simulation grid with zig-zag type faults, producer/injector arrangement according to PS 1 (producer red), critical areas A, B and C from slip tendency analysis are also shown.

3. RESULTS

3.1 PRESSURE

Figure 8 shows out of 16 simulations the worst-case scenario of PS 2 (injector red) of pressure change around the producer and injector wells in the reservoir after 50 years of operation.

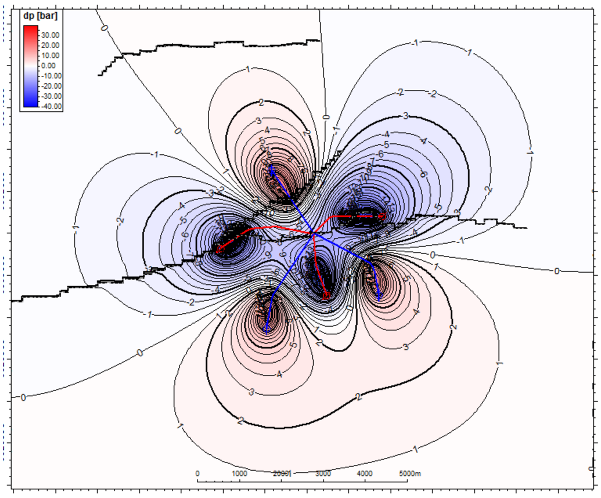

Figure 8: Pressure drop resp. increase in [bar] in the reservoir under hydraulic worst-case conditions, for this simulation no hydraulic fault influence was assigned.

The Mohr diagram in Figure 10 shows that the failure criterion under the hydraulic worst-case scenario is reached in one point.

3.2 TEMPERATURE

Figure 10 shows the maximal cooling after 50 years of operation of the PS 2 under hydraulically worst-case conditions.

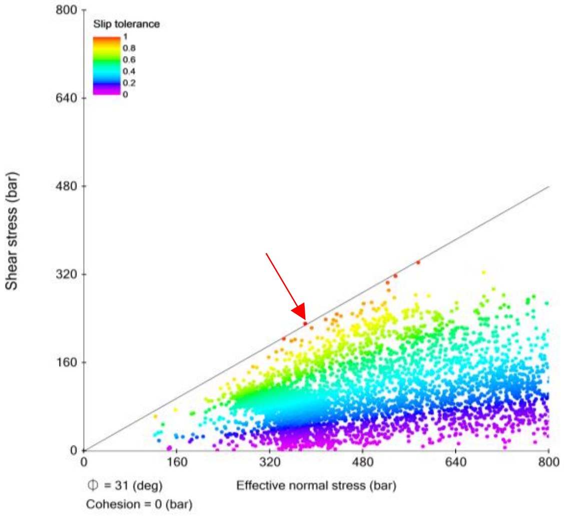

Figure 9: Hydraulic worst-case after 50 years of production, no cooling effect.

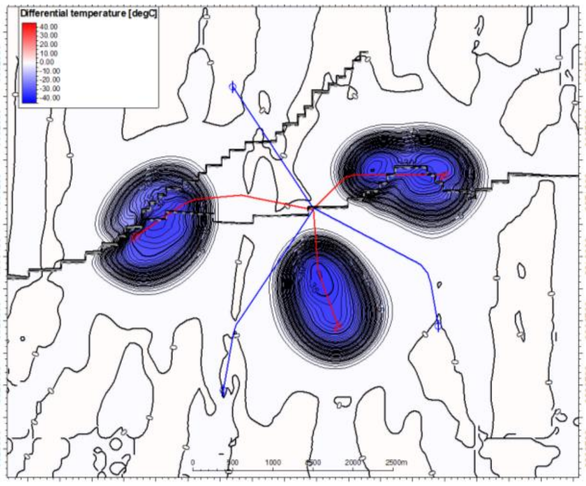

Figure 10: Maximum cooling under hydraulically worst-case conditions; no fault influence

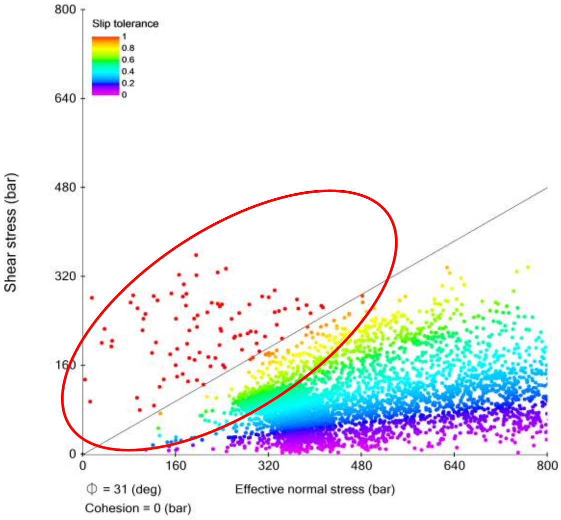

Figure 11: Thermal worst-case after 50 years of production, with cooling effect and maximum pressure

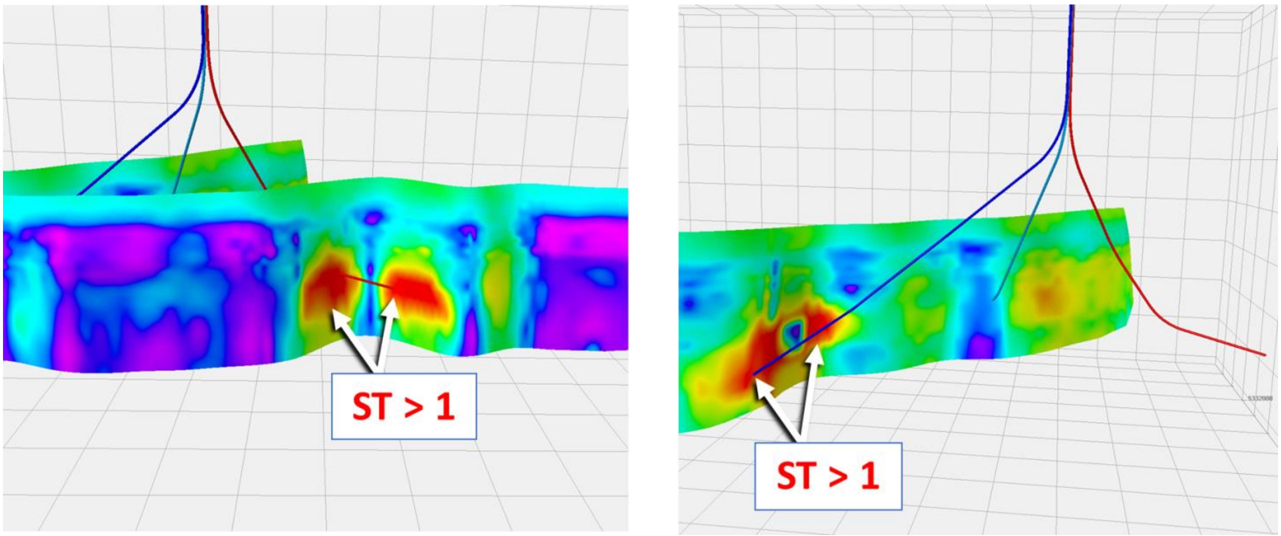

Figure 12: 3D image of the simulated slip tolerance along the surfaces of the fault system after 50 years of cold water injection in the thermal worst-case of the PS 2 without hydraulically active faults.

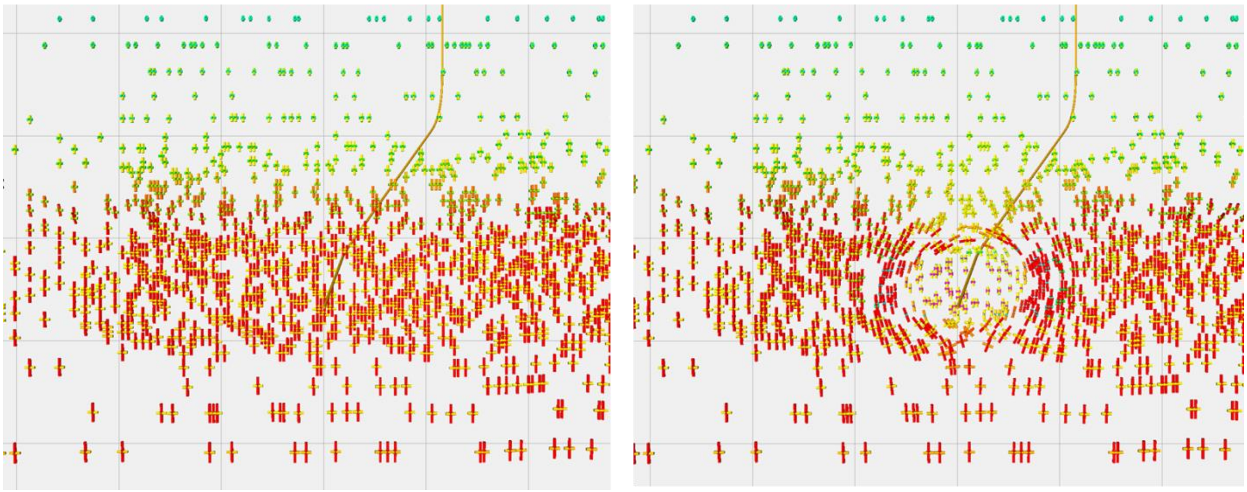

Figure 13: Image of a vertical section of simulated tensors of the effective stress around the injector borehole in the hydraulically (left) and thermal (right) worst-case of the PS 2 to demonstrate the change of stress due to cooling after 50 years.

Compared to the pressure, the temperature clearly exceeds the failure criterion, as Figure 11 shows, and the fault system under this condition tends to become unstable. The parameterization of the fault zone with a higher permeability had no significant effect on the results.

Figure 12 shows in a 3D view colour coded fault planes according to the simulated failure criterion (ST>1). Figure 13 demonstrates as a vertical section simulated effective stress tensors around one injector well under the hydraulically and thermal worst-case.

4. DISCUSSION

The results clearly show the temperature effects on stress relocation in a geothermal doublet system in the Upper Jurassic reservoir in the Southern Bavarian Molasse Basin.

The observations on the induced seismicity that have already occurred in the greater Munich area (Seithel et al 2019) support this statement. The events are mostly assigned to an injection well and occur after several years of operation. Accordingly, the successive propagation of the cooling front around the injection well would be a possible indication for a slow or time-shifted process, as can be seen in the model. In addition, the geomechanical model shows why, contrary to expectations, no rapid reaction with induced seismicity occurs with a rapid pressure increase in the reservoir.

On the other hand the results should not be overestimated due to the fact that there is no evidence from seismic monitoring data as well as using only pre drilling data, which determines the overall uncertainty of the investigations. The latter has of course a corresponding effect on the forecast accuracy of the simulation results. Since these are thermal-hydraulic geomechanical coupled simulations, which in turn are based on an interpreted geological model, the uncertainty of the parameters can have an increased influence on the result in contrast to a non-coupled simulation e.g. only hydraulically.

In addition sonic and density logs from which geomechanical properties were derived are limited since they have not been carried out as a standard measurement. Core material which is used in laboratory tests is also not common in geothermal exploration. On the other hand, P-wave velocities (vp) could be used from neighboring boreholes for geomechanical properties, as often applied in the hydrocarbon industry. In the further course of the project, the uncertainty of the hydraulic, thermal and geomechanical parameters will be successively reduced by the measurement program of the SLS boreholes in order to increase the accuracy of the simulation results.

5 CONCLUSIONS

Though the undertaken simulations are based on pre drilling data and contain reasonable uncertainty, results can be assessed valid with respect to the overall objective of the study.

Hence the SWM Services GmbH as the operator of the geothermal wells has, though the simulations are based on a worst-case scenario, decided to fully limit the risk by choosing the PS 2 and re-plan the injector well from a fault to a litho-facial dominated target.

In a long term perspective the operator is aiming to install a “Reservoir Monitoring System” with the capability of recording high resolution induced seismicity.

REFERENCES

Brotons, V., Tomás, R., Ivorra, S., Grediaga, A., Martínez-Martínez, J., Benavente, D. and Gómez-Heras, M.: Improved correlation between the static and dynamic elastic modulus of different types of rocks, *Materials and Structures*, **49**, (2016), 3021-3037.

Castagna, J. P., Batzle, M. L., and Kan, T. K.: Rock physics-The link between rock properties and AVO response, in: Offset-dependent reflectivity—Theory and practice of AVO analysis, Castagna, J. P., and Backus, M. M. (Ed.), 135 – 171, *Soc. Expl. Geophys.*, (1993).

Chang, C., Zoback. M. D. and Khaksar, A.: Empirical relations between rock strength and physical properties in sedimentary rocks, *Journal of Petroleum Science and Engineering*, **51**, (2006), 223 – 237.

Greenberg, M. L. and Castagna, J.P.: Shear-wave velocity estimation in porous rocks: theoretical formulation, preliminary verification and applications, *Geophysical Prospecting*, **40**, (1992), 195 – 209.

Hoek, E.: Rock Mechanics – an Introduction for the Practical Engineer Parts I, II and III, *Mining Magazine*, **144**, (1966), 236-243.

Konietzky, H. & Wang, F.: Thermal behaviour of rocks, *TU Bergakademie Freiberg*, Freiberg, (2018).

Megies, T. and Wassermann, J.: Einzelprojekt 2 – Untersuchungen seismischen Überwachung hydrogeothermaler Systeme bei dichter räumlicher Lage der Bohrerlaubnisfelder am Beispiel der Situation im Süden München, München, *PTJ*, (2017).

Robertson, E. C.: Thermal Properties of Rocks, *Open-File Report USGS*, **88-441**, (1988).

Schlumberger: Petrel user assistance, *Schlumberger*, (2016).

Seithel, R., Gaucher, E., Müller, B.I.R., Steiner, U., Kohl, T.: Probability of Fault Reactivation in the Bavarian Molasse Basin, Geothermics, (2019) (in review).

Ziegler, M. O., Heidbach, O., Reinecker, J., Przybycin, A. M. and Schenk-Wenderoth, M.: A multi-stage 3-D stress field modelling approach exemplified in the Bavarian Molasse Basin, *Solid Erath*, **7**, (2016), 1365-1382.

Zoback, M. D.: Reservoir Geomechanics, *Cambridge University Press*, Cambridge, (2010).