

Characterisation of Fault Zones as Geothermal Targets in the Deep North Alpine Foreland Basin (Southern Bavarian Molasse Basin)

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ABSTRACT

The Bavarian Molasse Basin and especially the region of Munich is the first and successfully exploited orogenic foreland basin for geothermal energy in the world. It might serve as a type locality for the orogenic belt – foreland basin type related to the geothermal play type concept introduced by Moeck (2014). At present (status 9/2018) there are 22 operating deep geothermal projects and 2 projects in the construction phase in the Bavarian Molasse Basin. Typical exploration targets in the 2 to 5 km deep carbonate reservoir of the Upper Jurassic are faults – favorably located in reef or massive reef detritus facies. With their heterogeneity caused by deposition, biogenic content, diagenetic alteration and facies-selective fracture pattern, carbonate rocks belong to the most challenging reservoir types. In particular south of Munich, the causes, effects and prediction of this reservoir heterogeneity is an understudied topic. Predicting fault attributes in subsurface carbonate reservoirs requires fault zone drilling and reservoir diagnostics through pore space evaluation in particular from drill cores analysis to identify chemical, mechanical, biological, or depositional processes affecting porosity, permeability and flow units. The sidetrack GEN-1ST-A1 at the project site Geretsried drilled in 2017 is one of the deepest geothermal wells in the South German Molasse Basin and serves as research site. VSP optimized 3D fault zone interpretation, depth specific total mud loss while drilling, hydraulic testing, core analyses and log-core correlation aims to better understand the permeability structure and reactivation potential of a deep fault zone in Upper Jurassic carbonates. The results indicate a high fracture density in low-porosity rock with partly open partly sealed fractures.

1. INTRODUCTION

At the project site Geretsried, 40 km south of Munich, first attempts tried to exploit the deep basin with 4.5 to 5 km deep reservoir rock. The well GEN-1 was drilled

in 2013 into the expected permeable massive reef detritus facies, which was deduced from the interpretation of a 3D seismic survey. After drilling to 6,035 m MD (4,852 m TVD), tight limestones and dolostones were encountered instead, resulting in a non-productive well with 5 l/s at 500 m drawdown. The dolomitic sections in the reservoir are tight and contrast permeable dolostones in the Upper Jurassic at drill sites in the central or northern Molasse Basin. A production test did not reach the values for an economic operation of a geothermal plant. In the year 2016 a research project started at the drill site (Fig. 1) with the operator ENEX, TUM (Technical University of Munich), G.E.O.S and GTN (both consultants) as well as LIAG.



Figure 1: Drill site Geretsried 2017

The main goal of the project is to determine the permeability structure in fractured dolostone across a Y-shaped graben structure, especially at the intersection of the major normal fault and the secondary antithetic normal fault (Fig. 2).

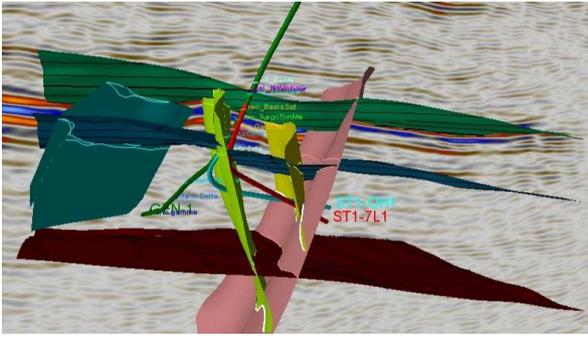


Figure 2: Two versions of the planned sidetrack into the Gartenberg fault zone (red, turquoise) and main borehole GEN-1 (dark green), view from West, Top reservoir (blue), bottom reservoir (brown), Gartenberg main fault (pink), branch faults (lime and greenish yellow), modified after 3D survey, data processing and interpretation by DMT GmbH & Co. KG)

Mud losses while drilling, temperature logging and cutting analysis indicated possible production zones. The sidetrack started at 4,288 m MD depth. The liner comprises the depth from 4,038 to 4,484 m MD, the open hole section ranges over 4,484 to 5,700 m MD. Deviated drilling with high inclination to about 80° ended at 30.08.2017 in a depth of 5,700 m MD (4,735.55 m TVD). For the first time drill cores of total 20 m length were achieved in a geothermal project from carbonates in the deep basin of the South German Molasse Basin. Hydraulic, geomechanical and petrophysical tests on these cores will help to characterize the reservoir of the deep Molasse Basin.

2. GEOLOGY AT THE PROJECT SITE GERETSRIED

2.1 Lithology and facies

Main well GEN-1 and sidetrack GEN-1ST-A1 reached the jointed Purbeckian to Kimmeridgian carbonates (Koch, 2018, Steiger 2018). Detailed facies analysis (Steiger 2018) revealed similar facies deposition in both wells (Fig. 3): grey limestones from the platform, slope and basin show some features which are comparable to the well-known Solnhofener limestone in the outcrop analogue of the Franconian Alb. The lagoonal Purbeckian at the reservoir top is mainly build up by micritic dolomites and dolomite breccias (deduced from cuttings and, Steiger 2018). The Tithonian is characterized by platform carbonates (to 4,780-4,800 m) where shallow water oolites are typical. The transition to slope and basin carbonates in the Kimmeridgian to Tithonian takes place with higher micrite content and bitumen bearing silty limestones. Poorly fossiliferous micritic limestone (micritic sponge spicule facies) in 5,018-5,300 m MD lead over to the microsparry tubiphytes facies), which resemble the Treuchtlinger marble in the Franconian Alb.

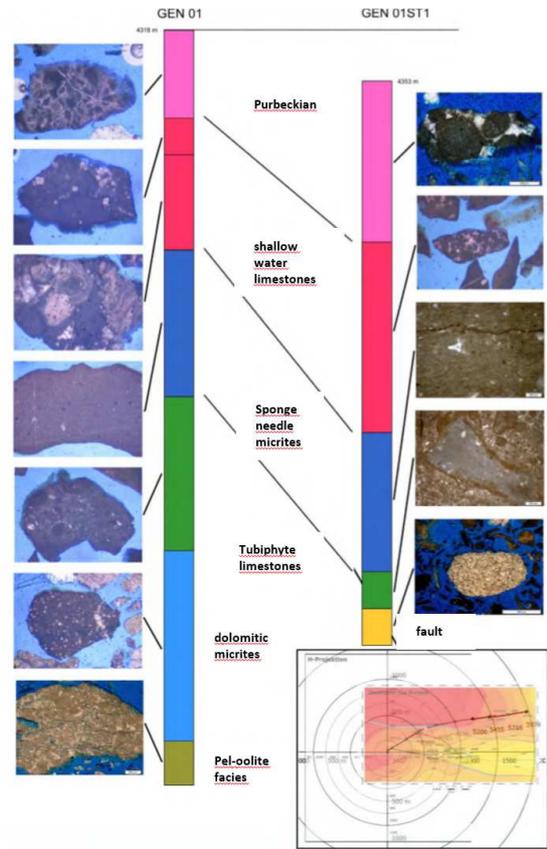


Figure 3: Lithostratigraphy and facies succession (Steiger 2018)

After Steiger (2018) samples from the sequentially drilled cores in this zones show sedimentation conditions of a basin facies (core description see Dussel et al. 2018). Samples from the drilling cores show sponge spiculae facies and tubiphytes facies. A dolomite breccia, which was several times reworked, marks very well a fault zone below 5,386 m MD and underneath lying dolomites. The last drilled facies occurring only in the main well consists of a carbonate pel-oolite facies. In addition, the typical facies of the Swabian and Franconian facies change to the south, and shows a higher content of planktonic organisms and a higher organic content at the earlier carbonate rocks of the Upper Jurassic. Though, the Helvetian facies does not occur in the southern part of the north Alpine foreland basin and must be located further south, as calpionellids are absent. A gradual transition zone of the Franconian platform to the Helvetian shelf in the south of the Molasse Basin can be assumed, which might be influenced by syn-tectonics and eustatic sea-level changes. In addition, the diverse sedimentation environment shows changes in thickness possibly due to synsedimentary tectonics.

2.3 Diagenesis

Based on analysis of facies, fluid inclusions and cathodoluminescence measurements on samples of different boreholes in the Southern South German Molasse Basin Mraz et al. (2019) gave a hypothesis for the temporal evolution of the Upper Jurassic reservoir.

In GEN-1ST-A1 different types of dolomites were developed. In the upper part of the profile, shallow marine carbonates are characterised by possibly an early diagenetic dolomitisation (Steiger 2018). In deeper water compaction and pressure solution occurs. Fracturing with healed carbonatic veins and especially the lower part of the tubiphyte carbonates and below of them as well as the zone between Purbeck and platform carbonates were affected by late diagenesis.

2.4 Structural geology

Fracture characterisation in tight carbonate reservoirs as done for example by Pattnaik et al (2015) is crucial for the reservoir development in the recent stress field. When it comes to the determination in deviated or horizontal well reorientation of cores has to be taken into account. Fracture attributes like aperture, spacing, roughness, frequency, orientation in relation to the recent stress field, cementation are necessary for a detailed structural description of the formation. Siler et al. (2018) underline the necessity of detailed structural interpretation tools for the exploration of structurally controlled geothermal, considering that narrow fractured zones may play an important role in geothermal reservoirs. In Geretsried, the reinterpretation of a 3D seismic survey with new data from a VSP-measurement in December 2016 revealed a geological setup of an Y-shaped graben system (Fig. 4). This fault system is built up by the antithetic Gartenberg main fault 100/70°N and to synthetic branch faults 95/75°S (Fig. 2, Dussel et al. 2018).

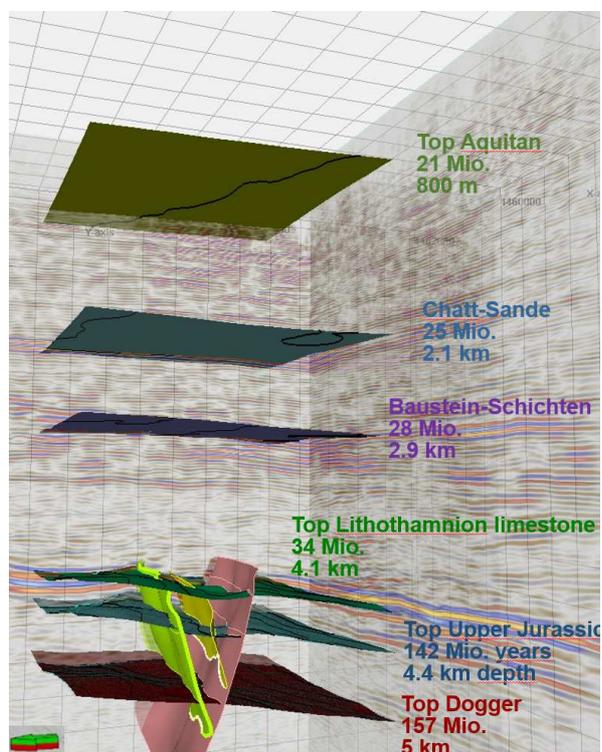


Figure 4: Dominant reflectors at the site with structural setting in 4 to 5 km depth (modified after 3D survey, data processing and interpretation by DMT GmbH & Co. KG), arrow points to North

3. PERMEABILITY STRUCTURE

3.1 Total permeability

Hydraulic testing began on 27.09.2017 and ended on 28.10.2017 (Wolfgramm et al. 2017a, 2017b). After a first cleaning lift, the first acidising of the openhole reservoir section with 200 m³ HCL (15%) and the depth of the injection string was conducted. After cleaning (cleaning lift 2) a jetting tool of Fangmann Holding GmbH & Co. KG was inserted and went in operation at a depth of 5,420 m MD. While pulling the jetting tool a sudden decrease in pressure of 20 bar and another of 60 bar were measured. Unfortunately, a forced gas influx hindered the detailed analysis of these pressure drops. While pulling out the string got stuck and had to be unblocked, especially, suddenly at 4,643 m MD. After pulling out it was obvious that a part of the jetting tool was disrupted and rests in the well (presumably in the depth below 5,307 m MD). The cleaning lift 3 showed a Slug-Flow-production. The second acidizing job was conducted with 183 m³ HCL and the injection string ended in 4,588.3 m MD, 100 m above the end of the last liner section (8 1/2"). Like the third cleaning lift only a slug-flow production occurred in the following cleaning lift. The third acidizing job was conducted with the new biodegradable and reaction-delaying acid SBB007 from Fangmann Holding GmbH & Co. KG. The injection string ended in a depth of 5,079.8 m MD ca. 40 m above the zone of total mud losses in the drilling phase. In the following cleaning lift also slug-flow production occurred. Finally, a six-day lasting Coiled-Tubing Nitrogen packer test revealed maximum water temperatures of 146.5 °C. A first estimation of the productivity of the reservoir shows a value of one power less than the short-term productivity of the well

3.2 Well Inflow zones

While drilling first sneaking mud losses occurred in a depth of 5,054 m MD (2 m³/h). The main inflow zone derived from total mud loss (ca. 107 m³) while drilling was encountered in 5,116-5,118 m MD (4,629 m TVD) which can be correlated to the penetration point of the first branch fault (see Fig. 2). Especially in this zone between 4,617 and 4,631 m TVD coarse crystalline calcite was found in cutting analysis (Koch, 2018). Obviously, the main inflow zone lies both in the sidetrack and the main well GEN-1 in the damage zone of the first drilled synthetic Gartenberg branch fault in different depths.

Below some minor mud losses occurred in GEN-1ST-A1. In total a volume of 873 m³ mud loss was registered. Two minor inflow zones interpreted by sneaking mud losses are also located in the vicinity of the other two faults. Borehole measurements (see chap. 3.3, Fig. 5) proved the inflow zones. Hence inflow zones are strong correlated to E-W striking fault zones. In most parts of the inclined well path no inflow occurs. This shows on one hand clearly that although late diagenetic sucrosic coarse grained dolomite especially non-planar and s-planar dolomites show no liquid path – on the other hand joints and faults are often filled with calcite and dolomite mineralisations (Mraz et al. 2019,

Steiger 2018). Subordinated connected replacements dolomites lead to few porous planar-E dolomites. The occurrence of porous dolomites resulted from solution seems to point to fluid flow nearby faults and fractures. Although a good correlation between total mud loss and the secondary fault exists especially in the zone of mud loss and lowered apparent resistivity (30 Ohmm), the occurrence of sponge spiculae in a basin environment is also described by Steiger (2018) in that zone.

3.3 Log-core-facies correlation

The wireline logging and logging by drilling suite comprised natural gamma, resistivity, temperature, spectral natural gamma, caliper, high-resolution imager (HMI) and full waveform acoustic logging (Tab. 1).

Table 1: Logging in well GEN-1ST-A1 (from casing shoe), LWD = Logging while drilling, GL = ground level, SGR = Spectral Gamma ray, MDA = Monopole dipole array, * no data recording between 4,888 and 5,485 m MD, measured from ground level (599 m asl)

Log	Depth interval (m MD)	Note
GR	4,484 – 5,692	LWD
Resistivity	4,484 – 5,692	LWD
HMI	4,484 – 4,888	*
Caliper	4,484 – 4,888	*
Full Waveform Sonic	4,484 – 5,485	MDA
Temperature	4,484 – 5,485	
SGR	4,484 – 5,467	

The zone of total mud loss (5,116 m MD to 5,118 m MD) correlates with anomalies in the borehole measurements, especially considering Natural Gamma, P-wave slowness, temperature and the ratio of compressional to shear wave velocity (Dussel et al. 2018). Drill coring was conducted sequentially in depths between 5,018.2 to 5,389.9 m MD (Tab. 2). Apparent resistivity in the range of 200 to 5,000 Ohmm together with low API at core depths reflect the tight character of the cored limestones and dolostones.

Table 2: core sections and apparent resistivity ranges derived from resistivity logging (shallow, medium, deep)

Section	Depth interval	Apparent resistivity (Ohmm)
1	5,018.2 – 5,019.3	600
2	5,035.8 – 5,036.51	200
3	5,199 – 5,203	200 - >1,000
4	5,204 – 5,205.1	700 – 3,000
5	5,374 – 5,378	700 – 5,000
6	5,378 – 5,388	500 – 5,000
7	5,388 – 5,389.9	250 – 3,000

The Purbeckian is characterised by an apparent electrical resistivity exceeding 200 Ohmm in general. At a depth of 4,360 m TVD a short lowering of the resistivity to ca. 30 Ohmm coincides with the occurrence of dolomite breccia with stylolites, big nearly idiomorph rhombohedral dolomitic crystals of a joint, which might be interpreted as a void filling (Steiger 2018) and an increase in the natural gamma radiation (40 API). In a zone between 4,400 m and 4,412 m low apparent resistivity of 100 Ohmm correlates with the occurrence of authigenic replacement dolomite (Steiger 2018), where no increase of natural radiation was measured (15 to 30 API). Lowest apparent resistivity (ca. 5 Ohmm) in the Upper Jurassic carbonates was measured in the depth of the total mud loss (5,116 to 5,118 m MD) and between 5,149 m and 5,153 m MD.

In the sidetrack GEN-1ST-A1 compressional slowness shows a uniform shape from 4,484 m MD (casing shoe) until a depth of 4,810 m MD with few short low-velocity zones in 4,515 m MD and 4,725 m MD. From 4,810 until 5,400 m MD the P-wave slowness curve shows a somewhat disturbed run of the curve with slight lower velocities and with a clear velocity lowering between 5,115 and 5,120 m MD (Fig. 5).

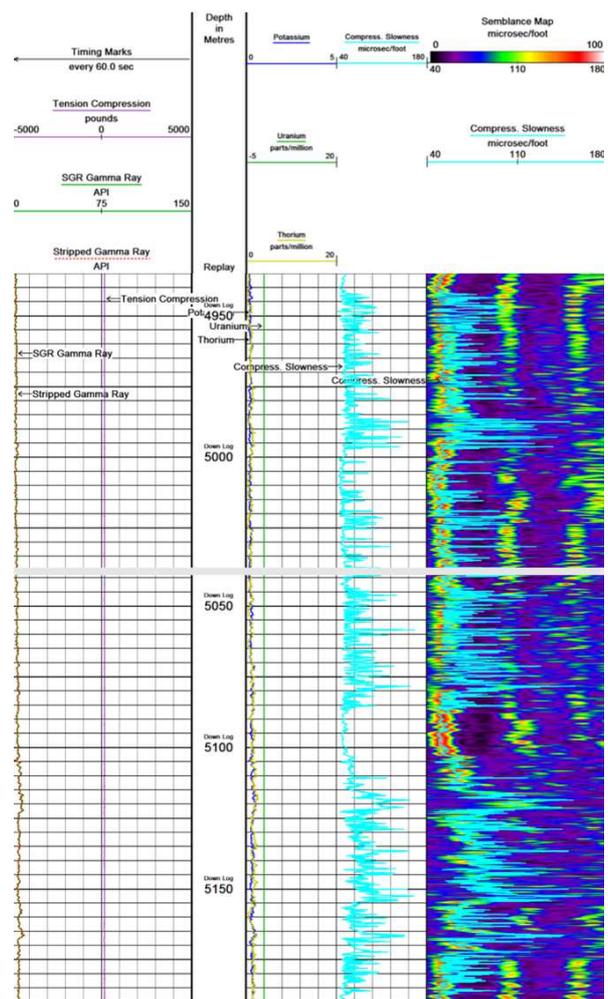


Figure 5: P-wave slowness and Natural Gamma ray in the surrounding of the zone of total mud

loss (5,116 to 5,118 m MD) (cut from Weatherford Spectral Gamma Ray, Dipole Sonic and PCL-Down Log, field print 25.09.2017))

The whole area between 5,100 m and 5,175 m MD shows a low-velocity zone in relation to the normal curve, which might be related to the damage zone of the first Gartenberg branch fault. From 5400 m until the end of the measurement (5,485.1 m MD) the curve exhibits again a more uniform shape.

Already in the commissioning of the logging suite a full-waveform sonic log was ordered, because e. g. as recognized by Che et al. (2015) in oil wells of Tatarstan (Russia) monopole shear and Stoneley wave attenuation is very sensitive to boundaries like fractures or bed interfaces between shale and limestone. In the sidetrack only monopole waveforms were analysable for shear-waves, shear waves and sometimes p-waves show different velocity near- and far-wellbore, which is presumably an indication of alteration or drill mud invasion (pers. Comm. Tippett, Weatherford, 2018). In the main well GEN-1 also monopole data gave good reliable shear and compressional arrivals, shear wave velocity ranged between 2,614 and 3,929 m/s and compressional wave velocity between 5,107 and 7,508 m/s (after Schlumberger 2013).

After simulations done by Jordan and Campbell (1986, in Che et al. 2015) the amplitude of shear waves should decrease in the case of fractured carbonates. Yong and Zhang (2002, in Che et al. 2015) stated that shear wave as well as compressional wave show an affect by the existing of fractured rock.

As concluded in the LIAG-project GeoParaMol (Wawerzinek 2018) the v_p/v_s ratio, which is sensitive to lithology, facies and porosity of rock might be a powerful tool for geothermal targeting based on seismic velocity analysis. Miller (1992) concluded from a literature review that relationships among v_p , v_s , porosity, density, and lithology “are highly variable among carbonates, and thus each geological setting should be characterised individually”. Pickett (1963, in Miller 1992) measured v_p/v_s ratios of 1.9 for limestones and 1.8 for dolomites, which were confirmed in younger studies. Pore geometry (Tatham 1982, in Miller 1992) and silica content (Wilkins et al. 1984 in Miller 1992) also effects the v_p/v_s ratio. Domenica who uses Picketts data (1984 in Miller 1992) stated that v_p is less sensitive to porosity than v_s . A study in the Pekisko limestone from Miller and Stewart (1990, in Miller 1992) revealed no correlation between v_p/v_s and porosity. But Miller (1992) summarized that the three carbonatic formations she studied did not show a correlation between v_p/v_s and porosity, but with lithology.

In the sidetrack GEN-1ST-A1 the v_p/v_s ratio changes abrupt at zone of total mud loss (5,116 to 5,118 m MD) from ca. 1.8 above to ca. 1.9 below (Dussel et al. 2018). A preliminary velocity measurement at one core sample with $v_p = 5955$ m/s and $v_s = 3090$ m/s ($v_p/v_s=1.93$) will

be the first step to better understand the relationship between seismic measurements and petrophysical parameters of Upper Jurassic carbonates in the Southern South German Molasse Basin.

4. FAULT REACTIVATION POTENTIAL

While the concept of hydrotectonics, introduced by Larsson (1975) addresses the importance of the orientation of structural elements in the relation to the recent stress field for groundwater flow, slip tendency of fault planes plays also an important role for sustainable geothermal energy use. The slip tendency analysis (Morris et al. 1996) serves for calculating the reactivation potential of fracture systems. The aim is to calculate the ratio of effective shear to normal stresses of fracture planes in comparison to the expected rock strength. However, uncertainties of the friction coefficients and stress state at depth only lead to an estimation of the fault reactivation potential.

After Reinecker et al. (2010, Fig. 6) and analysis of the Unterhaching geothermal well Uha-2 (Ortiz et al. 2018) the main horizontal stress is estimated to N-S oriented (2° N) in the region around Geretsried.



Figure 6: Regional stress field (cut from Reinecker et al. 2010)

By comparing different 3D seismic surveys in the region, two observations are noteworthy: firstly, normal faults parallel to the Alpine frontal fault do not reflect the present stress field directed in N-S at first glance, which is a typical feature of foreland basins. Secondly, the trend of decoupled overburden of Mesozoic strata to the south is obvious.

In the GEN-1ST-A1 sidetrack two formation integrity tests (FIT) were performed. The first one was executed in the Lithotamnion limestone (Upper Eocene) in 4,260 m MD (ca. 4,148 m TVD) and the second one in the Upper Purbeckian limestones and dolostones in 4,480 m MD (about 4,338 m TVD). With the concept of limited stress laws after friction equilibrium (Zoback, 2010) and on the base of formation integrity tests (FIT) in GEN-1 and GEN-ST-A1, stress polygons in different depths were calculated, which represent the possible stress states. At reservoir depth (ca. 4.5 km) a strike-slip regime prevails ($S_H > S_V > S_h$) (Fig.7).

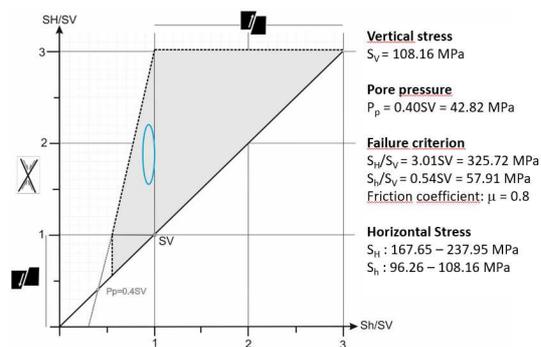


Figure 7: Estimated stress field in situ at reservoir depth (4,500 m TVD)

The three main faults of the Gartenberg fault system at the Geretsried site (Gartenberg main fault 100/70°N, branch faults 95/75°S) were chosen for a slip tendency analysis in order to relate them to the estimated stress state in a depth of 4,500 m. A “worst case scenario” with maximum feasible differential stresses resulted in a very low slip-tendency of the three main ca. E-W striking faults (Fig. 8). This is in accord with the nearly orthogonal orientation of the faults (E-W) in relation to the main regional horizontal stress direction (N-S).

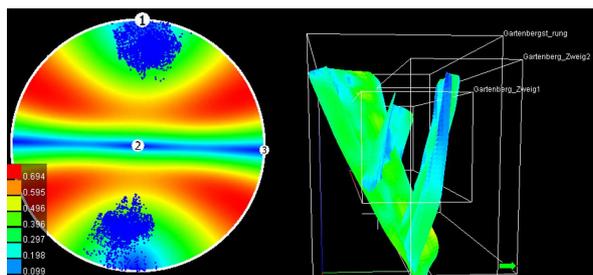


Figure 8: Slip tendency (coloured scale) of the three main faults of the Gartenberg fault system calculated with estimated maximum differential horizontal stresses (see Fig. 7)

Especially carbonates show a high variability in the friction coefficients. After Byerlee (1978) friction coefficients of carbonates range from 0.4 to > 1.0. At drill core plugs from the deep geothermal well St. Gallen (Suisse) friction coefficients of 0.6 to 0.9 were determined for Upper Jurassic carbonates at 4,300 m depth (Moeck et al. 2015). Lower friction coefficients are expected in fault zones, but only if they are active or recently mylonitised (Zoback 2010). The drill cores even where a fault was drilled show partly strong fractured and healed limestones and dolomites.

5. CONCLUSION

Together with a low matrix porosity mostly calcite and dolomite healed joints of the fault zone at the Geretsried site results in a low rock mass/ total permeability. The nearly E-W striking fault zone with a productivity of ca. 5 l/s seems to bear a narrow damage zone where mostly all of the inflow enters the well. Only a minor part or nearly no inflows were registered in the 1,500 m long open hole reservoir section with inclinations to

maximum 85° away from the three drilled faults. The results show very well the fault controlled geothermal system in the Upper Jurassic carbonates at the project site. Furthermore the results indicate a hydraulically active fault in tight reservoir rock, hence a petrothermal rather than a hydrothermal reservoir. Microfacies and carbonate sequence analysis of thin sections from the core and cuttings showed that the decrease in porosity could have been caused by the occurrence of mudstone to wackestone with planktonic organisms affected by diagenesis in the southern area of the Molasse Basin.

While drilling two remarking events happened. Total mud loss occurred in a depth of 5,116 to 5,118 m MD and a dogleg was drilled in 5,385 m MD. The dogleg occurred in the next-to-last coring section in faulted rocks, demonstrating quite well the difficulties in data acquisition from deep wells drilled in fractured zones. Petrophysical and facies analysis state that diagenesis plays a vital role for the reservoir performance. Research on the temporal structural evolution and thereby inherent time dependent processes concerning diagenetic alterations are planned to better understand fault-facies interaction.

As the production rate with 5 l/s is beyond an economic level, a transition from hydrothermal to petrothermal technologies are required. The natural fracture zones acting as hydraulically active mud loss zones can be utilized without hydraulic stimulation. For future explorations in the Southern South German Molasse Basin more research is needed especially in reservoir exploitation technologies and thorough interpretation of 3D seismic surveys considering preferential groundwater flow paths and drill steering of deep nearly horizontal wells. For the possibility of success and the estimation of the reactivation potential it seems crucial to consider and improve the understanding of hydrotectonics in further geothermal exploration. As new analysis of the local stress field derived from fault plane solutions of a site east of Munich, where the stress tensor rotates at a fault zone, further research will focus on the reorientation of the drilling cores and analysis of the image log to specify the prevailing local stress field.

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