

Characterization of a Deep Fault Zone in Upper Jurassic Carbonates of the Northern Alpine Foreland Basin for Geothermal Production (South Germany)

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ABSTRACT

The fractured and karstified Upper Jurassic carbonates of the South German Molasse Basin, the northern foreland basin of the European Alps, constitute the most important reservoir for deep geothermal energy use in Germany. Over the last 15 years more than 20 deep geothermal heating facilities and power plants were successfully installed. Currently, new wells are drilled deeper and nearer closer to the frontal fault of the Alpine fold belt. The new targets are associated with challenging drilling and detailed target determination like damage zones and intersection of faults of Y-shaped graben structures. One of the wells into the deep basin is the well GEN-1ST, drilled into 4.7 km deep dolomitic carbonates. An intensive research program was carried out to determine the permeability structure across the drilled fault zone including vertical seismic profiling, core drilling and logging.

1. INTRODUCTION

The Bavarian Molasse Basin in South Germany is the most important region for the use of deep geothermal energy in Germany. 21 geothermal projects, most of them located in the Munich region, operated in 2017 with an installed capacity of 270.4 MW thermal and 32.2 MW electric (Weber et al., 2016). Two of them are power plants, 15 heatings and four heating-power plants. Six projects are in the construction or planning phase. The geothermal reservoir consists of Upper Jurassic carbonates. As generally stated by Moeck (2014) for the orogenic belt/ foreland play type especially lithology, facies, diagenesis and tectonics control the permeability structure of the reservoir. Since the beginning of the geothermal production with the conversion of the petroleum borehole Erding 1 (1998) to thermal water use for spa purposes, extensive efforts were launched to investigate the potential geological targets in the 600 to 650 m thick Upper Jurassic carbonates in 2000 to 4000 m depth (Schulz et al., 2004, Böhm et al., 2013, Lüschen et al., 2014). After nearly two decades of successful geothermal exploration in the region of Munich the high geothermal potential of the southern South Molasse Basin in Germany shall be economically utilized by newly developed exploitation concepts. Similar to the Deep Basin in Alberta/Canada, the target horizon is in a depth greater than 4500 m and exhibits a challenge in exploration and drilling. While the Upper Jurassic in the Munich region is drilled and characterized through several geothermal wells, the deep basin carbonates are still understudied. Due to the large depth, the reservoir porosity might be low due to compaction and diagenetic processes. Effectively, deep reservoirs are expected to be fault- and fracture-controlled. The geothermal well Geretsried GEN-1 (see Figure 1a) was the first commercial well drilled 2013 into the deep basin Upper Jurassic. The geothermal site Geretsried covers a large 3D seismic survey and is located 40 km south of Munich, east of the lake Starnberg and close to the Alpine orogenic belt at the transition of the unfolded Molasse Basin to the folded Molasse Basin (Fig. 1b). The exploration concept focused on rock facies, the so-called massive reef detritus facies and ended in a non-productive well with a flow rate of less than 5 l/s. At that time it was with its 6036 m length (MD) the longest geothermal borehole in Europe. The dry well GEN-1 was plugged in August 2013 and the negative results from this prominent project provoked a considerable draw-down in the whole geothermal market in Germany. The results of this well indicated a tight carbonate rock with dolomitic intervals. Therefore, a new exploration concept was developed for Geretsried targeting a normal fault and its adjacent damage zone. Already in 2013 first ideas grew to turn Geretsried into a research project to analyse and understand the permeability structure of the underexplored deep part of the Upper Jurassic Malm aquifer. Since carbonate rocks are generally known as fractured, diagenetically and facies controlled reservoirs, the focus of the research ambitions was on the permeability structure of fault zones, facies classification and fault zone diagenesis.

In 2015 the research proposal Dolomitkluft was submitted to the German Federal Ministry for Economic Affairs and Energy for a joint project with partners from industry and scientific institutions. The Dolomitkluft proposal was accepted and the joint project started in May 2016 with funds from the German Federal Ministry of Economic Affairs and Energy. Main tasks of this research project is re-evaluation of 3D seismic data after vertical seismic profiling in the well GEN-1, drilling a side-track from the main well into the nearby fault zone, drill coring, logging and hydraulic testing in several steps. The research project Dolomitkluft (i.e. dolomite fracture) addresses the geothermal development, testing and analysis of the first fracture dominated dolomitic aquifer in the deep Malm of the Bavarian Molasse Basin. Several research topics are dealt out among the partners of the joint project, Enex, LIAG, GEOS, GTN and TUM. Enex is the license owner of the test side and coordinator of the joint research project. The scientific lead has the LIAG.

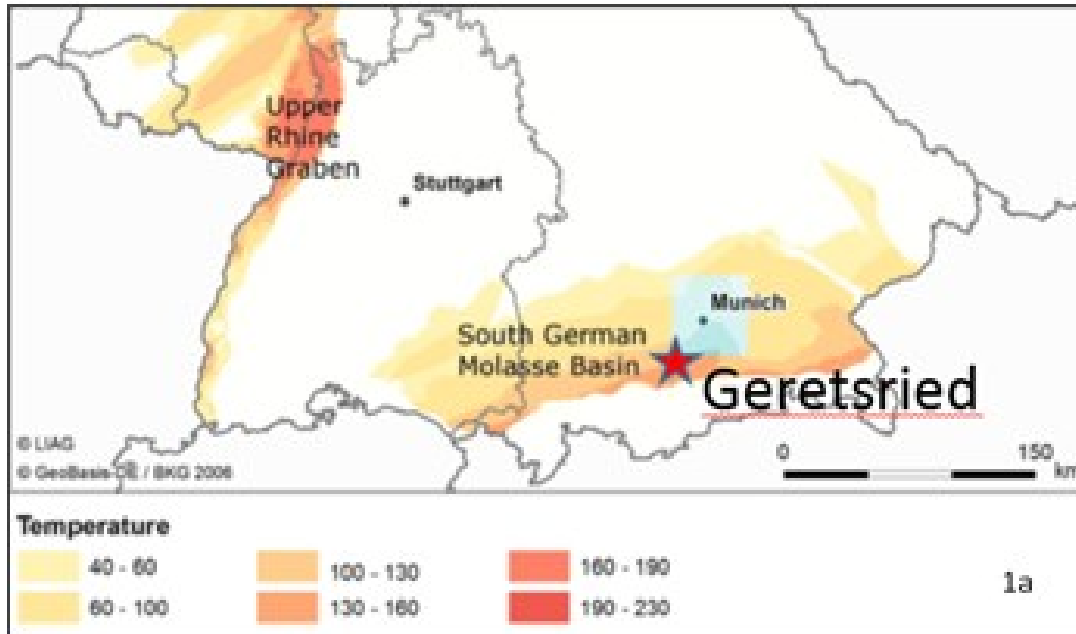


Figure 1a: Location of borehole Geretsried GEN 1ST-A1 (base: map of a 3D thermo-hydraulic model in the Munich region (blue dyed) in the realm of German regions with hydrothermal resources (proven and assumed), and associated temperature ranges (modified after Suchi et al., 2014), (www.geofis.de), in: Dussel et al., 2016).

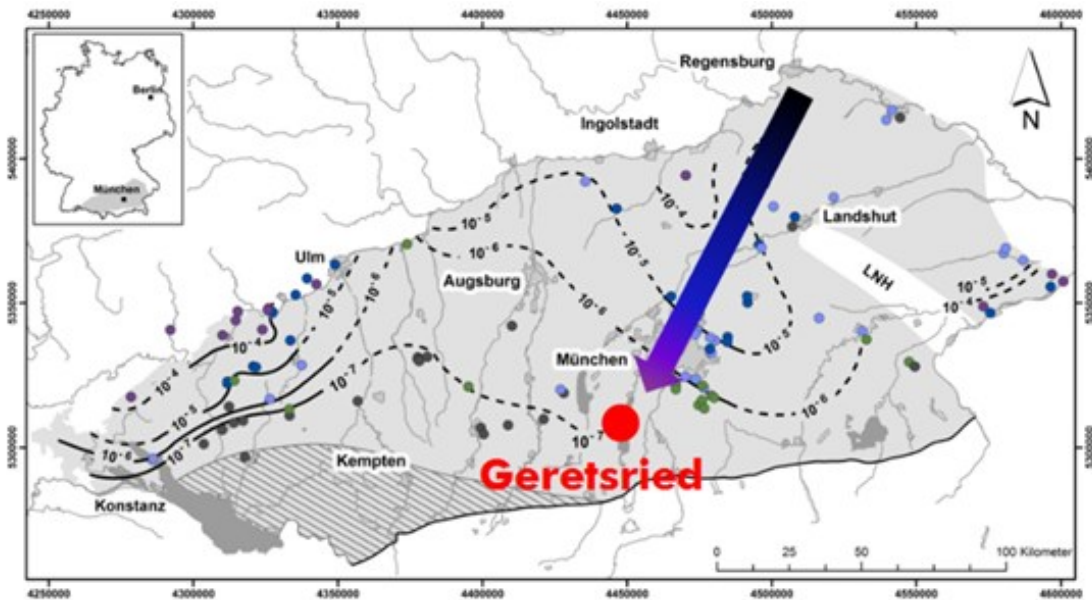


Figure 1b: Distribution of the subsurface Upper Jurassic (Franconian and Swabian facies) in the Molasse Basin with isolines of hydraulic conductivity in m/s. Arrow indicates the reduction of hydraulic conductivity from NE to SW. Dashed area: transition to Helvetian facies with expected very low hydraulic conductivity (modified from Birner et al., 2012).

Deep fault zones are hitherto scientifically understudied: the dimensions of damage zone, fault core and the permeability variability in these fault zones compared to intact rock are not well quantified. The interaction between fault kinematics, diagenetic processes and facies types affecting the reservoir quality criteria porosity and permeability in depth are not well known. Therefore, a drill core section was planned along the sidetrack covering intact reservoir rock, damage zone and fault core of the 5000 m deep fault. Structural geological, geomechanical, geohydraulic and seismic analysis will help to characterize the fault zone. The results will be crucial for future geothermal development in the Malm and fault controlled geothermal play types in general.

2. THE PROJECT DOLOMITKLUF

The exploration concept of the project Dolomitkluft considers faults and its damage zone as main conduits for fluids. In the Molasse Basin, mainly normal faults serve as production zone for geothermal wells (Moeck et al., 2015) (Fig. 2a), contrasting the concept of critically stressed faults as major fluid pathways (e.g. Barton et al., 1995). Normal faults in foreland basins play a special role in the tectonic setting since the strike of foreland basin normal faults is parallel to the frontal fault of the adjacent mountain belt (Moeck et al., 2015) and is obviously inconsistent with the stress regime in foreland basins (Cacace et al., 2013; Moeck et al., 2015). In the Molasse Basin, the trend of normal faults is E-W (Moeck et al., 2015) while the direction of the maximum horizontal stress is N-S (Reinecker et al., 2010), resulting in presuming high normal stresses and contraction on E-W normal faults. One reason for the extension along these faults might be lithospheric bending which is alongstrike the mountain belt. Elevated permeability along these normal faults could be explained by the intersection of syn- and antithetic normal faults, crossing normal faults (Ferrill et al., 2009; Budach et al., 2017) and growth of damage zone in intersectional fault areas. The project Dolomitkluft aims to drill through intersectional fault areas of a major normal fault, dipping to North, and antithetic normal faults, dipping to south (Figure 2b). Drill core sampling through intact rock, expected damage zone and fault core shall clarify the increase or change in permeability towards fault zones, helping hydraulic reservoir models in parametrization of fault zones.

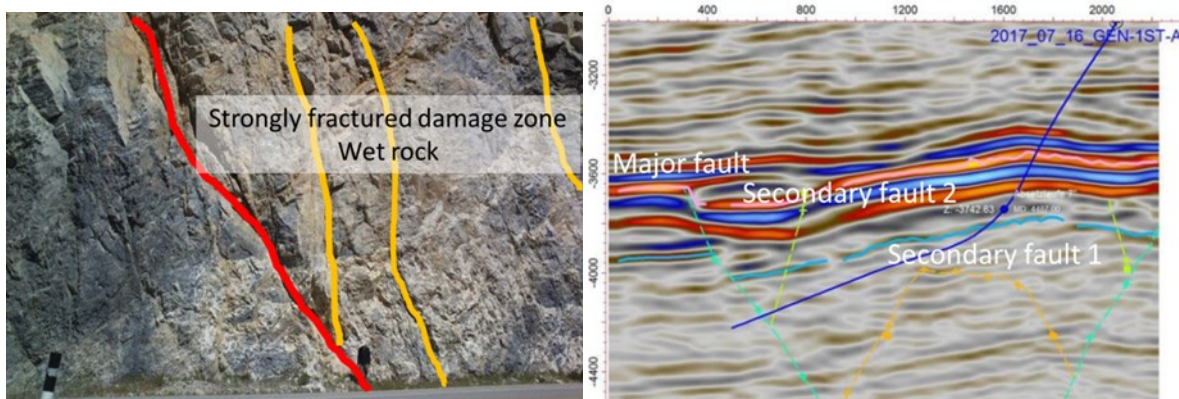


Figure 2: Syn- and antithetic normal faults. Left 2a: major normal fault (red) with secondary faults (orange) in carbonate rock (Cathedral formation, Alberta, Canada). Strongly damaged zone with high number of fracture intersections between secondary faults. Right 2b: well path of sidetrack GEN-1ST through expected damage zone and intersectional fault area.

In order to achieve the economic and scientific goals of the overall project, the following tasks as a part of the entire work were already performed from 2016 to 2017:

- Re-opening of the main well GEN-1 for vertical seismic profiling from 4200 m depth to ground level.
- Building a new seismic velocity model, time-depth-conversion and re-interpretation of 3D seismic data focusing on a graben structure close to the main well
- Drilling of the sidetrack GEN-1ST, including the scientific program of FIT tests, coring, intensive cutting sampling for later thin sections.
- Appointment of an independent mudlogging, an independent drilling engineer, and an independent reservoir engineer for comprehensive expert supervision with respect to the funding goals
- Supply of all necessary permits (mining law, laws pertaining to water, public right, and private right)
- Supervision of the entire project during preparation and execution. Personal presence at drilling site / project management tasks / documentation of the drilling data / providing necessary information from borehole GEN-1 / Public Relations

Main tasks of the Leibniz Institute for Applied Geophysics (LIAG) are to deliver (I) a seismic velocity model representative for the Southern Molasse Basin for an optimal fault interpretation; (II) dimensioning of fault zones for a numeric TH reservoir model; (III) for the first time in a geothermal drilling in the Molasse Basin sampling of core material from the reservoir for scientific investigations which will be performed also by Technical University Munich (TUM); (IV) frac-simulation as proof for the EGS utilization potential of dolomites; (V) stress field analysis, kinematic fault analysis, quantification of fault reactivation potential; (VI) planning/assignment/petrographic analysis of drill cores from the reservoir drilled through a fault zone and thin section analysis of cutting and core material in cooperation with TUM; (VII) input of comprehensive data sets into LIAG's geothermal information system GeotIS; (VIII) public relation through professional outreach (e.g. brochures), workshops for knowledge transfer.

3. UNDERGROUND MODEL

Fault zones, carbonate lithoclastic-oolitic-packstone-facies with reef mounds (so called reef-facies or Franconian facies), dolomitization as well as karstification are considered as the primary controlling factors of the Upper Jurassic reservoir of the South German Molasse Basin (Dussel et al. 2016). The main borehole Geretsried GEN-1 was drilled into an undisturbed facies zone which was interpreted from

a 3D seismic survey as reef facies. However, micritic mudstones were encountered with the main well in 2013 which showed very low permeability (productivity < 5 l/s). To minimize the exploration risk for the planned sidetrack a VSP (Vertical Seismic Profiling) measurement (Fig. 3) was executed by DMT/ Weatherford in December 2016 to optimize the velocity and associated underground model, especially the focused fracture zone in the vicinity of the borehole GEN-1.

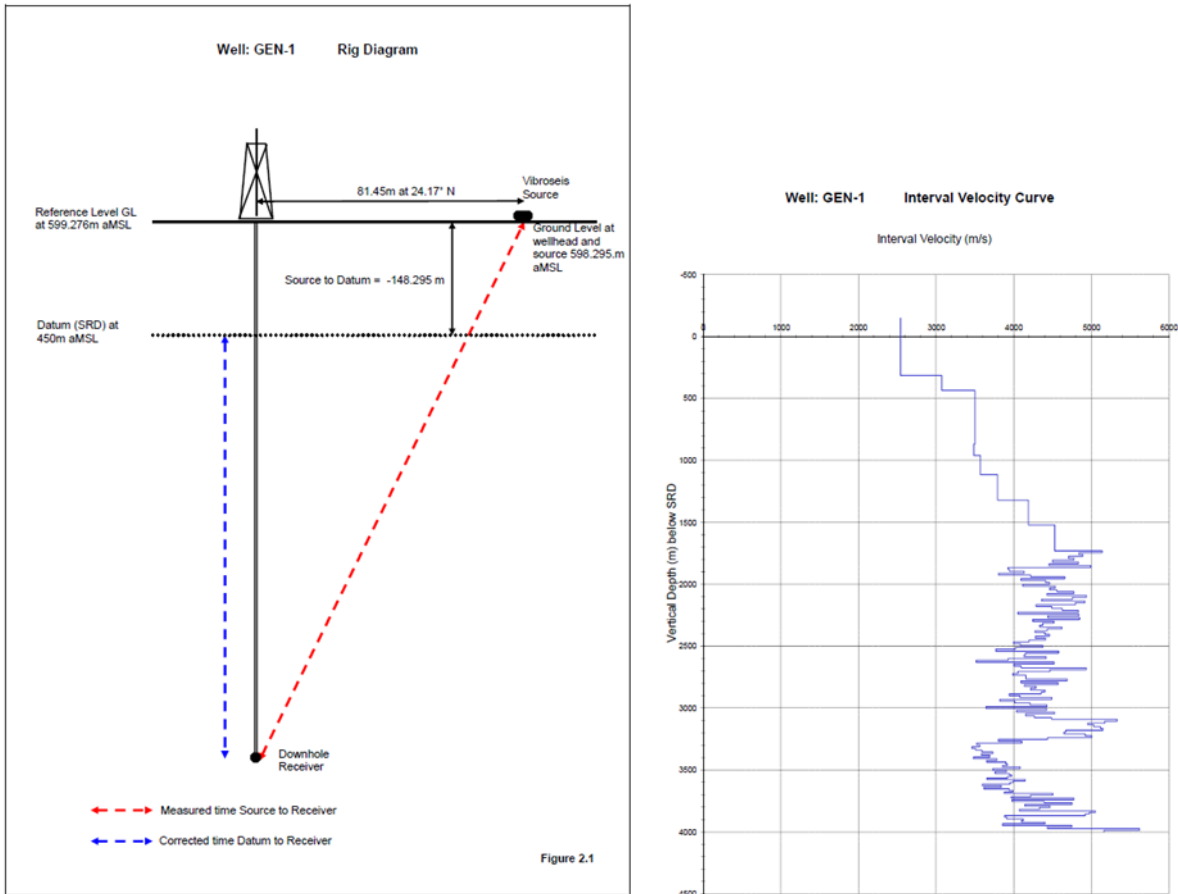


Figure 3: VSP-measurement (DMT/ Weatherford commissioned by LIAG): rig diagram with local data (left); resulting interval velocity curve (right).

By a shift of 72 ms hitherto interpreted horizons could be specified, especially Top of the Upper Jurassic could be defined ca. 100 m higher than in the old seismic model (Figure 4). Furthermore tectonic structures in the target zone could be represented more in detail. A half graben structure was interpreted, which showed an intensive damage zone with secondary faults. After discussion of different potentially prospective drilling targets it was decided to drill into the intersection zone of two faults (Gartenberg main fault, Gartenberg secondary fault) in a depth of ca. 4.5 km (Figure 5).

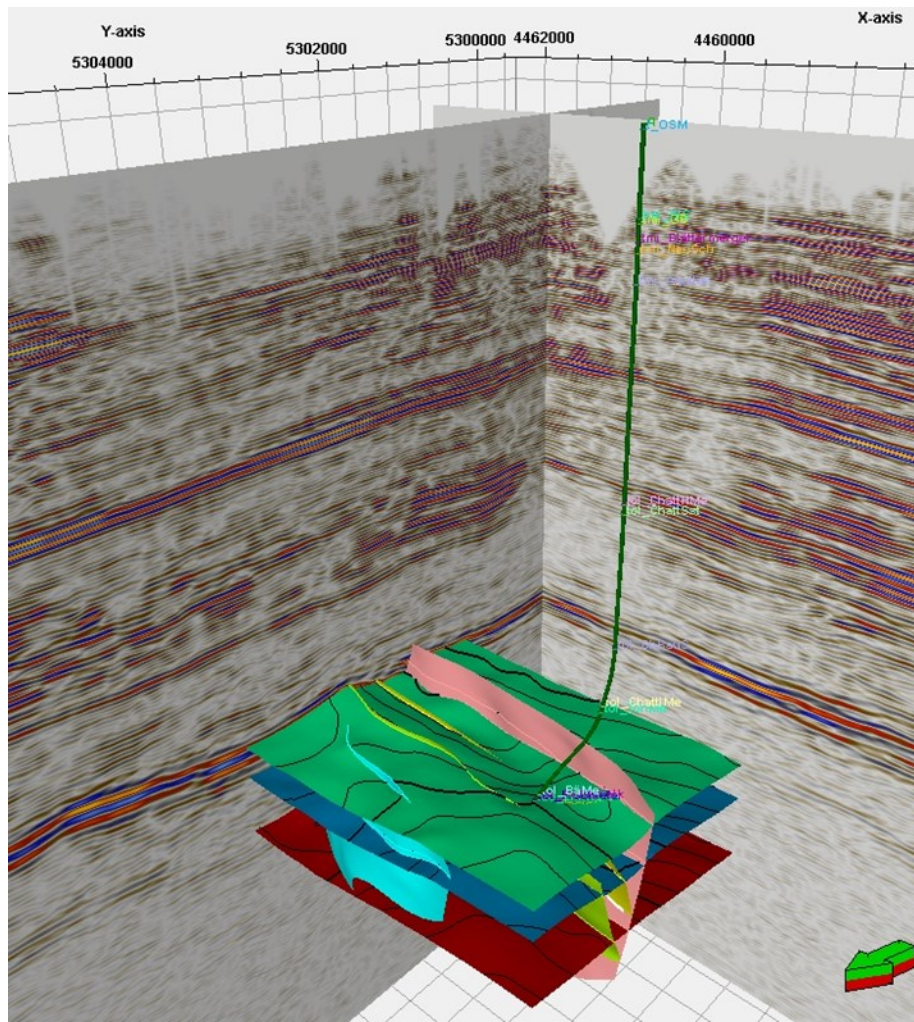


Figure 4: 3D underground model in 4 to 5 km depth with seismic volume (DMT GmbH & Co. KG), old well path GEN-1 (dark green), Formations: Lithothamnion limestone (green), Top reservoir (blue), Base reservoir (brown) as well as fault planes, arrow points to North.

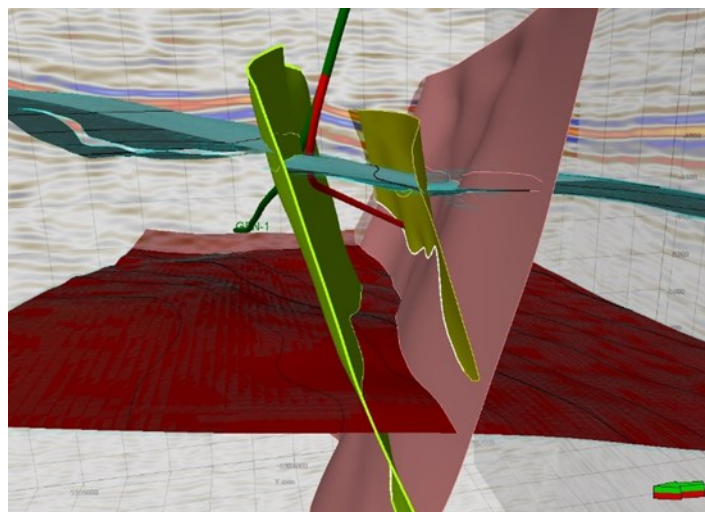


Figure 5: fault zone in ca. 4 to 5 km depth (DMT GmbH & Co. KG). Old well path GEN-1 (green); planned Sidetrack GEN-ST (red) with target in the intersection of main and secondary fault. Reservoir thickness from Top reservoir (blue-green) to Base reservoir Malm (brown) ca. 600 m, arrow points to North.

4. DRILLING AND CORING

In April 2017 operations for the drilling of the sidetrack in the borehole Geretsried GEN-1 started. After different considerations (e.g. high gas pressure zone in Tertiary Rupelian clays) the sidetrack was drilled from a position deep as possible in the already existing borehole. 230 m steel casing had to be milled from the deepest (4.) section. In June 2017 drilling of the sidetrack began after setting a packer and a whipstock in ca. 4260 m depth in Tertiary layers. The last drilling section was displaced in the marly mostly dolomitic carbonates of the Purbeckian (lowest Lower Cretaceous), which represents by its hydraulic connection to the Upper Jurassic the Top of the potential reservoir. In the Upper Jurassic the borehole was deviated to ESE and SE with an inclination of ca. 70° in order to reach the target, the intersection zone of two interpreted faults (Figure 5). In the middle of August 2017 a first core was taken by ALS Corpro from a depth of 5018 m MD (measured depth). In contrast to grey cuttings from conventional drilling, a dark grey micritic, limestone with calcitic healed joints was encountered (left box in Figure 6). Microscopic fissures contain some calcite mineralization, so that open segments and small voids remain. Sequential coring was planned, because core sticking might happen in the highly fractured damage zone of the fault. Finally, 20 m core was taken in several sections in a range of about 370 m. Core sections in different quality were taken in the following depth ranges in measured depths meter: 5018.2-5019.3 (intact and fractured rock); 5035.8-5036.51 (fractured and intact rock); 5199-5203 (intact and fractured rock); 5204-5205.1 (fractured and intact rock); 5374-5378 (intact rock); 5378-5388 (intact rock and fault rock); 5388-5389.9 (fractured and fault rock) (Figure 6). As indicated in the core sections, the aim of coring was achieved as intact rock, fractured rock and fault rock with intensive shear fracturing is encountered.

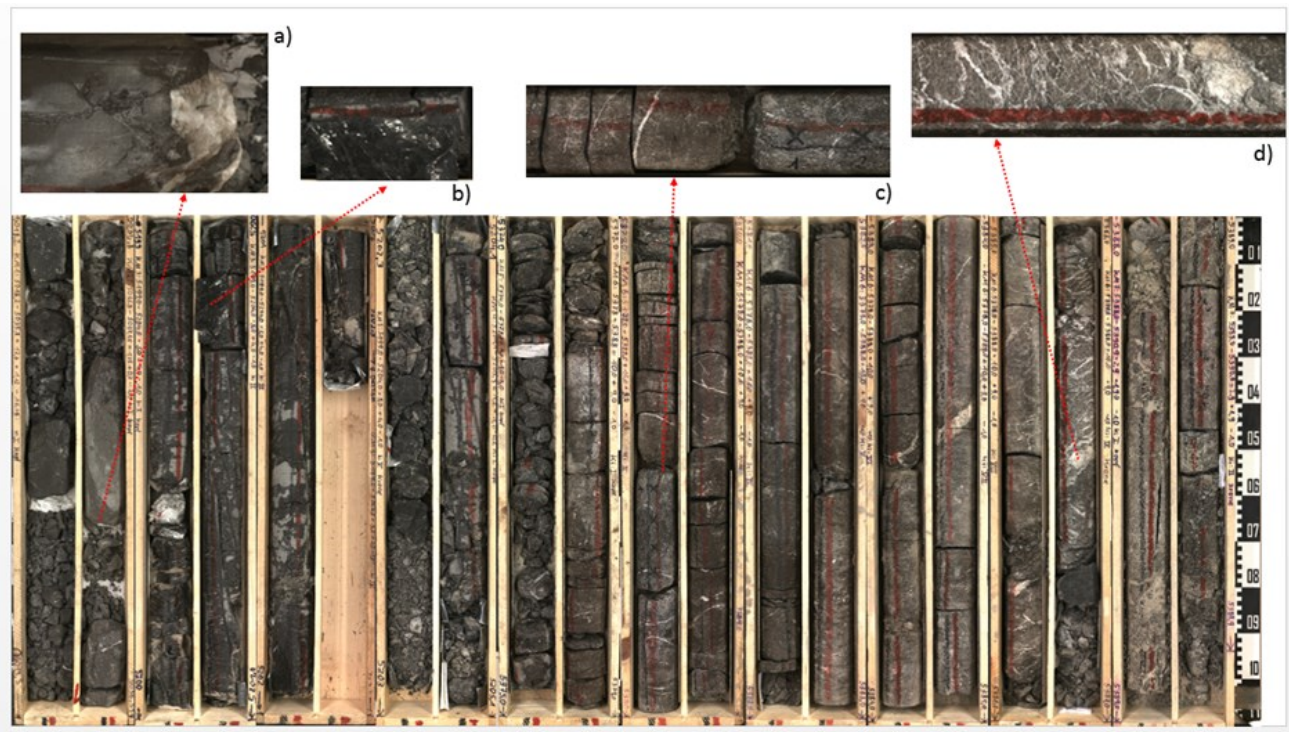


Figure 6: Carbonate cores of well Geretsried GEN-1ST-A1. a) with calcite filling; b) bituminous mirror slickenside; c) color transition brown-grey to grey; d) heavy faulted and healed; note that black and red drawings for orientation Top/Bottom.

The cores comprise mainly tight micritic mudstone with small amount of clay and/or bitumen. Especially in the upper part of the first core section, liquid bitumen rested in fractures and caused a typical hydrocarbon smell. Calcite-healed fractures, fissures and shear fractures are distributed over all core sections. Calcite veins contain pyrite filling and indicates high organic content. Finely distributed pyrite occurs also in the matrix of the carbonate sediment. Furthermore the limestones are partly component bearing wackestone to packstone and fossiliferous, in other sections components are very rare. In some sections slickenside surfaces were cored (see Figure 6b). Furthermore different stylolite generations, sometimes very porous, were recognized. Against the original plan a dogleg was drilled, so that an inclination of ca. 85° occurred and the ultimate target, the intersection zone was reached just a little bit above the original planned location. After Wolfgramm et al. (2017) in depths between 5391 and 5512 m dolomite was encountered. Drilling was finished in September 2017 at a depth of 5700 m MD after drilling through the main fault (fig. 5). In November 2018 the cores were scanned with the image corescanner of the LBEG in Hanover and in Dezember 2018 with the Geotek Multi Sensor Core Logger of the BGR in Spandau. In 2018 the cores will be analyzed in detail for structural details, different sedimentological environments of Upper Jurassic times, petrophysics, diagenesis, hydraulics and geomechanics (see sect. 6).

5. PERMEABILITY STRUCTURE

Encountering the fault zone, distinct mud losses were recorded during drilling. Notably in a zone at about 5100 m depth total mud loss occurred. In total more than 800 m³ mud losses were recorded while drilling. Borehole measurements after drilling prove a permeable

inflow zone at about 5100 m MD (Figure 7). Particularly a temperature decrease (Figure 7, green line) indicates the cooling of the rock caused by intruded drilling mud.

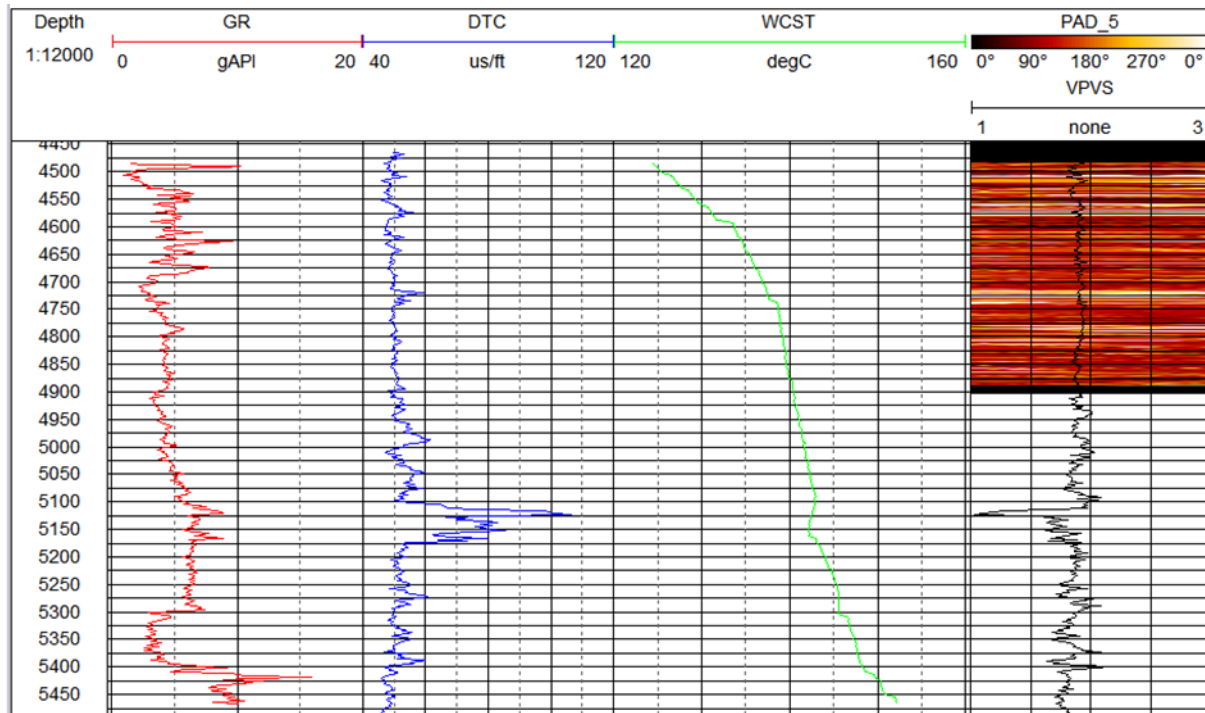


Figure 7: Borehole measurements in GEN-1ST-A1: Natural gamma ray (red); sonic (blue); temperature (green); part of an image log which had to be interrupted (brown); v_p/v_s ratio from sonic (black line)

After three acidizing jobs with HCl and the newly developed biodegradable acid SBB007 from the company Fangmann a six day production test was conducted with Coiled-Tubing Nitrogen Lifting (Wolfgramm et al., 2017). The hydraulic test results in a transmissivity of $6.5 \cdot 10^{-7} \text{ m}^2/\text{s}$ and a productivity index of about 0,04 l/(s*bar), which ranges wide beyond an economic use. The injectivity is by a factor five significantly higher as the productivity.

6. DISCUSSION

The sidetrack Geretsried GEN-1ST-A1 crossed about 1000 m Upper Jurassic carbonates from intact rock to damage zone to fault core. The temperature log and the mud losses indicate fractured permeable rock in 5100 and 5300 m depth. Static mud losses indicate further injectivity. The low productivity indicates fractures as fluid pathways, confirming the fractured controlled reservoir rock. However, the fractures are obviously not connected to a good reservoir rock with high porosity, resulting in a very low productivity index. The drawdown in the well during production was significant with about 1000 m. Acidizing could not enhance the productivity indicating a low porosity reservoir. Rapid acid losses during acidizing is another indicator for a fractured controlled reservoir. The production test indicates that a large drawdown causes a closure of fractures in the near-wellbore area, causing a reduction in well connectivity to the reservoir. Proppants might be inappropriate since the marly limestone is too elastic for proppant support.

The facies and diagenetic processes in this tight carbonate might explain the low productivity. First results indicate that dolomite growth occurred however there is no high temperature dolomite. Idiomorphic dolomite rhomboeders grow in the matrix reducing the primary pore space. The majority of dolomitization occurred along fractures and stylolithe seams, suggesting former fluid flow along fractures and stylolithes with transport of Mg-rich obviously meteoric water (Mraz et al., submitted). The results are however worthwhile for any reservoir modelling as the thickness of a deep normal fault could be evidenced with the main fault and a maximum thickness of roughly 80 m containing calcite-healed secondary fracture porosity in its damage zone. Porosity and permeability tests on core material will reveal the increase of permeability from intact rock to fault rock, although in this case permeability is not sufficient for a productive well.

7. OUTLOOK AND CONCLUSION

For further characterization of carbonates and fault zone the following core analysis will be performed:

- Density, porosity
- Permeability, poro-elastic properties
- XRF, REM, EDX, thin sections, fluid inclusions (microthermometry), cathodoluminescence

- Ultrasonic measurements
- Thermal conductivity

Slip tendency analysis will be conducted for the fault system and core scan measurements will be correlated with borehole measurements and facies analysis. The EGS potential will be investigated in this project although induced seismicity occurred already in geothermal wells near Munich, lowering the acceptance for EGS, hydraulic fracturing and fault zone injection in the Molasse Basin. Besides the EGS-option alternative concepts for geothermal energy use will be analyzed like a deep borehole heat exchanger as well as other potential geothermal horizons. All available data (VSP, hydraulic tests, petrophysics, geomechanics, facies maps) will be implemented into the public internet portals of the LIAG, the Geophysics Information System (FIS GP) and the Geothermal Information System for Germany (GeotIS). The remaining cores are available for further scientific research in particular deep fault zone studies.

The drilling results indicate tight carbonate reservoir rock in the southern deep Molasse Basin. Existing fractures do not support sufficient flow rates for economic use. Effectively, drilling in the deep Molasse Basin exhibits a high exploration risk. New innovative exploration concepts and methods might be considered to minimize the exploration risk in this region. The preliminary results demonstrate that research on hydrothermal systems is still required although or even because there are already existing production sites. Future geothermal field development and the extension of geothermal use implies detailed investigation of exploration methods targeting high porosity domains, recharge and discharge zones in geothermal reservoirs, and test drilling to ultimately provide guidelines for successful geothermal production from deep reservoirs in Germany and worldwide.

ACKNOWLEDGEMENTS

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