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Geothermal Development of Fracture Dominated Aquifers: the Case Study of the Deep Well Geretsried (Germany)

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ABSTRACT

The German Molasse Basin hosts a high geothermal potential particularly in its southernmost part where the well-known Upper Jurassic carbonate Malm aquifer lies in 4.6 – 5 km depth. While the Malm aquifer is already exploited in the Munich area, the knowledge for sustainable geothermal development and economic exploitation of the southernmost part is still limited.

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. The test site is located in the district Bad Tölz-Wolfratshausen, about 40 km south of Munich and east of the Lake Starnberg. The first drilling operation started in 2013 with the longest geothermal well in Europe with a 6036 m long well path. While the temperature was as expected with 155 °C, the productivity was significantly lower than expected and turned out as beyond any economic level. The dry well GEN-1 was preliminarily 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 research project Dolomiktluft re-opened the well for Vertical Seismic Profiling (VSP) in 2016. After re-evaluation of the 3D seismic, a sidetrack was drilled from the dry well GEN-1 in 2017, targeting a graben type fault zone. Deep fault zones are hitherto scientifically understudied: the dimensions of damage zone, fault core, 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, drill cores were taken from different sections between 5000 and 5300 m depth at a total of 20 m covering intact reservoir rock, damage zone and fault core for petrophysical, geomechanical and petrographic analysis. Total mud losses during drilling operation indicated permeable fracture zones in the reservoir section. However, a production test carried out after three acid jobs resulted in a high draw down and low productivity. The results indicate a tight fractured controlled reservoir rock where permeability is impaired primarily by diagenetic processes in a low-porosity carbonate facies. Further research is planned inferring the transition from hydrothermal to petrothermal methodologies

1. INTRODUCTION

The high geothermal potential of the southern South German Molasse Basin was to be made economically viable by new exploration concepts in the joint research project Dolomite fracture. Using the existing non-producing borehole GEN-1 at the Geretsried location (Fig. 1) in the district of Bad Tölz-Wolfratshausen as an example, the development target "crossing fault zones" for the approx. 4.5 km deep-lying Oberjura (Malm) was developed including re-evaluation of existing data and branch drilling (Sidetrack) with an in-situ research program. The project operator was Enex Geothermieprojekt Nord GmbH & Co KG. In the joint research project with the partners Enex, GTN, GEOS and TUM, it was therefore to be shown that fissured dolomites of the deeper Malms are suitable for economic geothermal use in the area of fault zones. The Dolomite joint project was an operational project with the topics (I) seismic exploration, (II) cores, (III) cleaning / acidification of the reservoir section, (IV) hydraulic borehole tests (step test), (V) diagenesis / facies / tectonics and (VI) reservoir modeling.

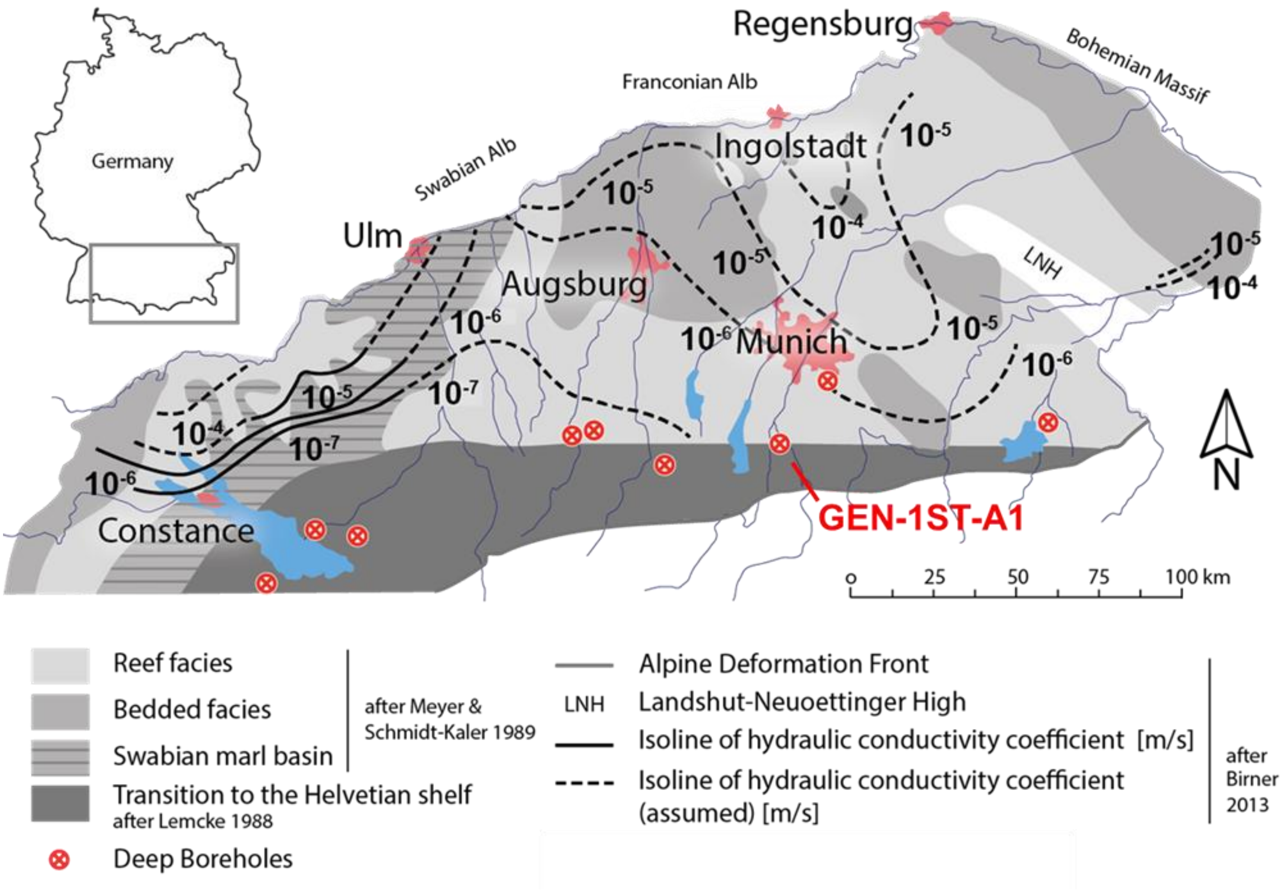

Figure 1: Location of the sidetrack Geretsried-1ST-A1 (map from Mraz, 2019)

For all topics, conclusions can be drawn from the Dolomite fracture project and recommendations made for future geothermal projects, not only in the Molasse Basin (Dussel and Moeck, 2019, Dussel et al., 2019, Dussel et al., 2018). In order to achieve the goals the joint project “Dolomitkluft” was based on 7 work packages:

- WP 1 – Reliability of 3D Seismics
- WP 2 – Influence of fault zones in Upper Jurassic dolomites
- WP 3 EGS potential of Upper Jurassic dolomites
- WP 4 Diagenesis of fault zones
- WP 5 Stimulation and test of fracture dominated Upper Jurassic dolomites
- WP 6 Potentially hydraulic productive structures in the recent stress field
- WP 7 Technical safeguard and public

2. IMPROVEMENT OF A 3D SEISMIC SURVEY

By means of a VSP-measurement carried out in December 2016 in the old Geretsried GEN-1 geothermal well, which was drilled in 2013, the seismic velocity model for the Tertiary and Cretaceous was improved. An optimal ratio of economic efficiency and high data quality should be achieved at a high coverage rate of the VSP measurement at depth of exploration. Therefore, a measuring distance of 15 m from the cement bridge at 4287 m to 2000 m MD was chosen, and from 2000 m to 100 m MD 7 check-shots were measured with the 4-level Slim Wave Hydrophone near the reflector. A total of 207 measurement points were measured in 14 hours with very good data quality. The new 3D-velocity model verified by the measurement differs from the existing velocity model: Thus, the surface seismic model has to be moved up based on the Corridor stacks by 72 ms to get a consistent image. The evaluation of shear waves also enabled the comparison with v_p and v_s velocity models from the Greater Munich region (Wawerzinek and Buness, 2018). Thus, the seismic velocity model at the Geretsried site is available for the former planning of new wells in the Southern German Molasse Basin for more accurate predictions of the depth of formation boundaries. In addition, the v_p/v_s ratios provide further information to improve the determination of the depth of possible induced seismic events. For the geothermal field Wolfratshausen and thus for the drilling environment the geological structure model could be clearly defined with the help of the exact seismic velocities of the formations (Fig. 2). As a consequence, the drill path of the sidetrack GEN-1ST-A1 could be laid out in detail shortly above the crossing zone of two faults of the Gartenberg faulting zone in the Upper Jurassic reservoir. The zones of significant mud losses during drilling confirm the hydraulic permeability of the crosscutting zone.

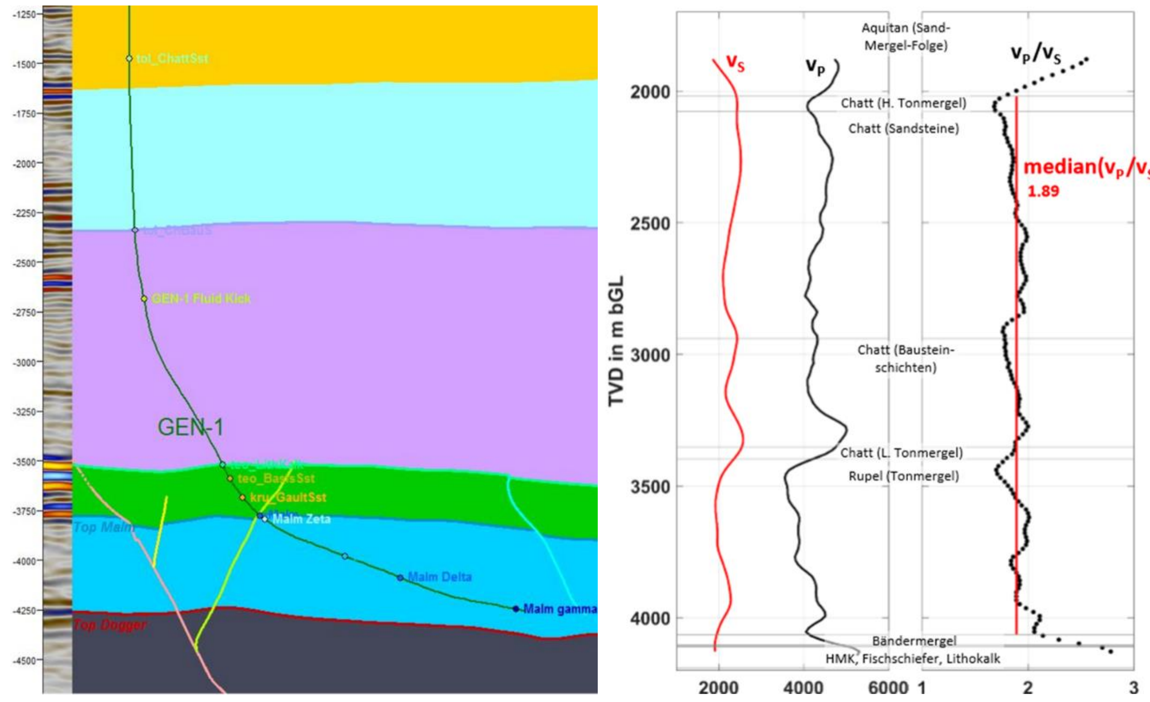

Figure 2: Left: Zone model after new interpretation with well path of the old well GEN-1 and with interpreted Gartenberg fault system (green and pink) (DMT, 2017), right: smoothed interval velocities (60m) and inferred v_p/v_s-relations of Tertiary formations. The median of the v_p/v_s-relations (red) was calculated for the depth interval 2020 – 4065 m (Wawerzinek and Buness, 2018).

3. CORING

It is unique that deep drilling cores were obtained for geothermal reservoir characterization in the German Molasse Basin (Fig. 3). The task was to drill the sidetrack to ca. 5700 m MD with the target crosscutting fault and coring 300 m over several sequences in a strongly inclined well path (70-80°). The sidetrack has reached the target point, although the inclination of the borehole has meanwhile built up to 87 °. This occurred due to an incorrectly working directional drilling motor. For the coring a conventional 5.5 "core drilling system with 3.5" core diameter and a 6 " borehole diameter was used. The system permits core sections up to 50 m through internal half-shell aluminium liners. The longest core section was gained at moderate bit load and increased torque. The cores were turned into various sequences from intact mountains to disruption as planned. Sequential core drilling was carried out for the first time in a deep inclined geothermal well of the German Molasse basin over a range of approx. 370 m. In the approximately 70-85 ° inclined open hole section resulted core gain was 18.6 m due to core sticking (the original plan was coring of 330 m). The coring was executed in 7 core sections at depths between 5,018 and 5,390 m MD (measured depth) and the yielded limestones and dolomites of the Upper Jurassic are disturbed, fractured and veins are in most cases mineralized with calcareous, dolomitic or subordinate pyritic cements (see Fig. 3-5).

Figure 3: Retrieval of the drilling cores in aluminium half-shell liners, sawn to 1 m pieces.

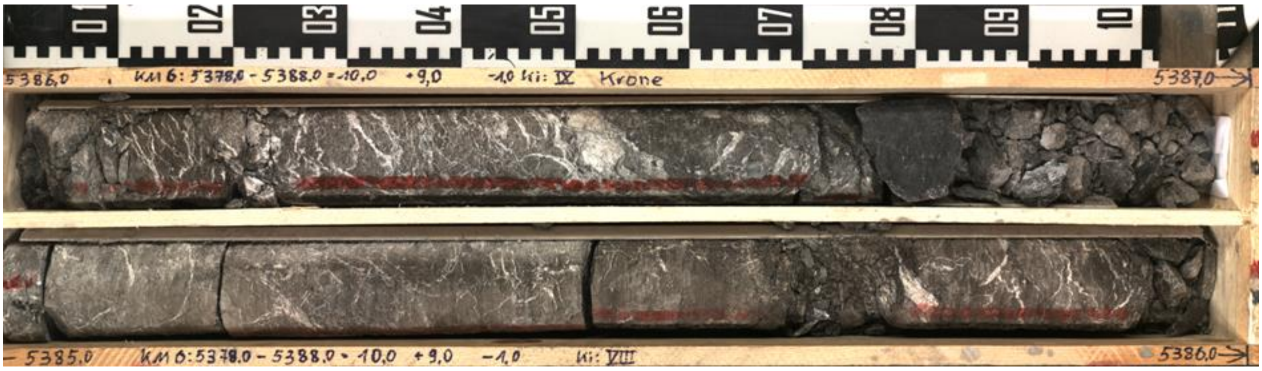

Figure 4: Photo-scan of drilling cores from depths between 5385.0 and 5387.0 m MD.

Because of the planned geomechanical and hydraulic tests on cores also 360°-photo-scans were made from 57 convenient core pieces for possible former structural investigations (Fig. 5).

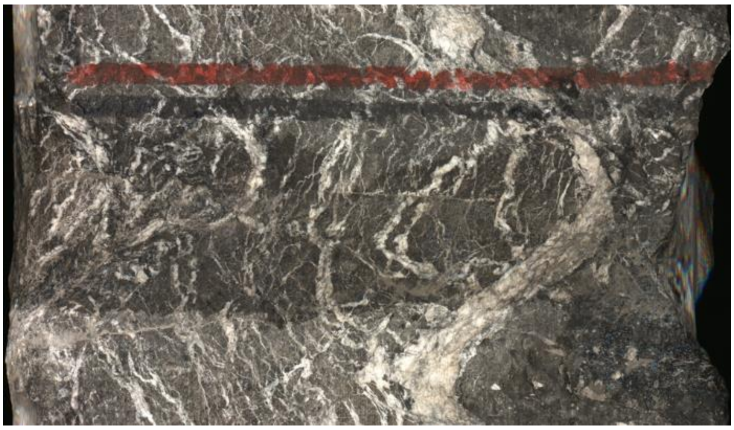

Figure 5: 360°-photo–scan of core piece 5,386.2 – 5,386.69 m MD.

4. HYDRAULICS AND HYDROTECTONICS

In direct connection to the drilling work, a cleaning lift was carried out, which could not be completed due to dry falling of the lift line. Therefore, the acidification measures were started in the incompletely cleaned well. The acidification was carried out in 3 phases with the drill stem at a depth of 5,097 m MD with 15% HCl and the new biodegradable retarding acting acid SSB-007. This was followed by a step test with packer and nitrogen injection via coiled tubing. On the pipe section of the 4th section, a pressure cell was installed during the step test, during which only a small amount of production could be achieved.

Resulting from mud losses, borehole measurements and hydraulic tests, the permeability structure of the Gartenberg fault zone is characterized by the permeability of the damage zone of the first Gartenberg branch fault, at which the main mud losses occurred during the sidetracking (Fig. 6). Pores and joints of the approx. 100 ° N striking and approx. 70 ° inclining syn- and antithetical faults of the Gartenberg fault zone in approx. 4.5 km depth are partially mineralized by calcite or dolomite. The permeability of the fault zone is much higher than the rock permeability of the intact core. Accordingly, it is a purely joint-controlled reservoir system with hydraulically conductive fractures in dense, hydraulically low conducting matrix rock. The shear tendency analysis (Morris et al., 1996) of the existing fault system in the recent stress field is important on the one hand for groundwater flow estimations (hydrotectonics after Larsson, 1972) and on the other hand for the estimation of the fault reactivation potential of the Gartenberg fault zone. It shows, on the one hand, that the low transmissivity of the fault zone of $3.2 * 10^{-7}$ m^2/s (0.03 m^2/day) and on the other hand the low reactivation potential (Dussel et al., 2019a) with respect to the N-S directed main stress reflects the expected compressive character of the fault zone with approx. 100 ° N strike.

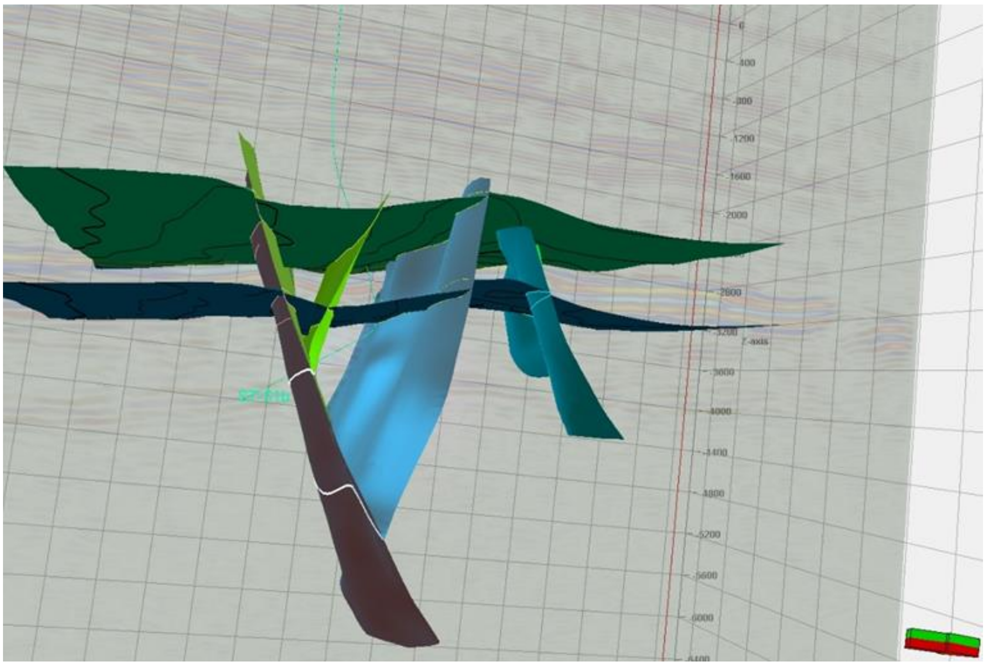

Figure 4: Hydraulic active damage zone of the first branch fault (light blue) of the Gartenberg fault system (Top Malm: dark blue, dark green reflector: Lithothamnion limestone (Eocene), fine light blue-green: one of the previous planned but later neglected sidetrack-versions.

The main inflow zone is located in the area of total mud loss at 5116 m to 5118 m depth (about 4630 m TVD). The evaluation of the mud losses and the logging measurements, in particular temperature and sonic log, revealed a width of the main loss (damage) zone of about 70 m (Dussel et al., 2019a). Other potentially small permeable fracture zones were interpreted based on downhole measurements and lower mud losses in the environment of further intersected faults (Table 1).

Table 1: Inflow/ mud loss zones determined by different methods.

Inflow zone	*depth (m MD)*	*Method/ Observation*	*Note/ Interpretation*
1	**5054 (to 5120)**	**From 5054 beginning of sneaking mud losses**	**Mud loss zone**
2	**5116-5118**	**Total mud loss** **Resistivity: ca. 5 Ohmm**	**Main inflow/ loss zone** **after GTN (2017) at 5116 MD Gartenberg branch fault**
(2b)	**5115-5120**	**Sonic: Low-velocity zone**	**Main inflow/ loss zone**
3	5149-5153	Resistivity: ca. 5 Ohmm	Inflow zone
(3b)	5100-5175	Sonic: relative Low-velocity zone	Inflow zone, damage zone of the first Gartenberg branch fault
4	**5658 – 5680**	**Drilling break and rising of mud loss at 5658 m MD to 8 m_3/ h (GTN, 2017)**	**Fault (en echelon segment) to Gartenberg main fault (GTN, 2017)**

Diagenetic development, which increases with depth and whose prediction will be one of the greatest challenges in geothermal exploration in the future, has a decisive influence on the permeability structure of the encountered Upper Jurassic carbonates (Koch, 2018, Mraz, 2019, Mraz et al., 2019, Steiger, 2018). While isolated reef debris indicates a nearby reef in otherwise quiet still water facies, dolomitization has stopped at an early stage. The findings of the sidetrack GEN-1ST-A1 indicate a petrothermal system with natural, hydraulically conductive fracture zones in the direct vicinity of faults in dense rock (Fig. 5).

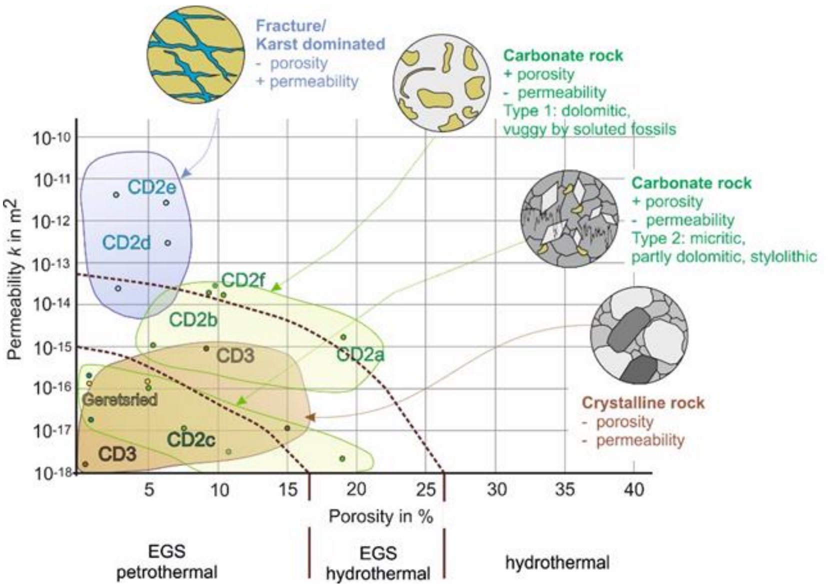

Figure 5: Porosity and reservoir permeability relation of Geretsried GEN-1ST-A1 in comparison with different carbonate and crystalline rock that represents enhanced geothermal systems. The labels CD2a-e and CD3 correspond to conduction dominated play type labeling from Moeck (2014), CD2f is new and is from Böhm (2012) and Birner (2013). CD2a, c, d, f are Upper Jurassic of the South German Molasse basin, CD2b and e are carbonate from the Alberta Basin. The yellow dots are from the deep geothermal well Geretsried (Dussel and Moeck, 2019).

5. DISCUSSION

The 5 times higher injectivity of GEN-1ST-A1 might be caused by poroelastic effects. This is in contrast to other wells drilled in the Upper Jurassic formation in the Munich region north of Geretsried where the ratio injectivity/ productivity lies between ca. 1 and 1.3 ls-1bar-1 (Rühaak et al 2017). With the possibility of developing a dense reservoir and applying EGS technologies, it was anticipated at the start of the project that the corresponding EGS potential would be geomechanically investigated. The finding of natural hydraulically conductive damage zones of faults in otherwise tight rock, however, occurs unexpectedly in its clarity: So far, total mud losses is general are equivalent to the drilling success of the wellbore, but this correlation is not valid in Geretsried. The reasons for this finding can not be conclusively determined with the available research results. However, similar findings have been reported in the granitic fossil system in the Cooper Basin in Australia (Betina Bendal, DMITRE, Australia, person. Comment).

Plausible reasons can be:

•In order to combat the flushing losses, highly viscous pills were used. The cleaning lifts after completion of the drilling work have not cleaned the tightened fractures in the loss zones.

•The acidification measures in the long Open Hole range of about 1700 m did not work in the places where the mud loss occured, the fissures are still sealed.

•The partially cleared fractures are kept open by the pore fluid pressure of about 450 bar. Under production conditions and reduced pore fluid pressure, the fractures close and explain the significant difference between productivity and injectivity. Since the fractures can not keep open, the connection of the wellbore to the reservoir deteriorates with increasing subsidence in the borehole.

Hydraulic test interpretation revealed a skin factor of -5. This means that the well is good attached to the formation, but what if the remaining damage sticks deeper in the internal filter cake? After Harris and Mckay (2014) "… uniform, effective cleanup can be very hard to achieve in low permeability or variable permeability formations. Uniform cleanup is even more difficult to achieve in horizontal wells." So they conclude "When using HCL it is difficult to achieve uniform damage removal over long openhole horizontal producing intervals which can result in disappointing well productivity." To overcome this the authors cited other studies which used reacting breakers like enzymes and oxidizers along with two-step treatments. Really another option of Cleansorb is the in-situ acid production, which might be tested in the future in Geretsried. Especially Acidgen HA or Acidgen LG might be used in the temperature range 90-160 °C (Harris and Mackay 2014). Another ability of the organic acid lies in the degrading of polymers which were also used whilst drilling as fluid loss additives (Xanthan, PAC). Concerning environmental aspects by using these organic acids there should be no problem to get an allowence from the local environment state agency. Was acidzing sufficient to break the filter cake, especially the internal filter cake, or did as in some studies about drilling in carbonate formations mentioned by Harris and Mckáy (2014) develop a very low permeable crush zone behind the filter cake ? Or would it be necessary to use also starch and cellulose breaking enzymes (two-stage treatment or Cleansorb's solution in a single treatment fluid). Oxidizers also can break polymers, but together with acids some problems arise, like the possibility to develop toxic gases. After Harris and Mckáy (2014) "effective filter cake cleanup has been achieved at temperatures ranging between about 20 °C and 150° C. So there are still som questionmarks for the processes above this temperature range.

6. CONCLUSION

The hydrothermal development concept, which focuses on fault cutting zones, can be carried out with pinpoint precision using 3D seismic and VSP. However, a good permeabilioty of the borehole is not given. The question remains unanswered of the reasons for the total mud losses and subsequent lack of a sufficient production rate. It is possible that the acidification in the steeply inclined well bore did not work at the zones where the mud losses occurred.

The VSP measurement could continue until the cement bridge of the old borehole GEN-1 at 4287 m depth. Temperatures of 144 ° C were feasible, but challenging for the measuring tool (4-levels Slim Wave 3-components hydrophones in the frequency range 12-95 Hz).The residence time of the measuring tool at these temperatures should be kept as short as possible, repeated measurements should be avoided. To save operating times, a geophone chain is recommended as described.

Economic viability of the coring depends of the use of synergies between coring and drilling progress. Core sequences deeper 5000 m MD should therefore not planned for a few meters, but rather to a few decameter ranges. Please note a roundtrip time of about 35 hours at depths below 5000 m MD.

For the first time in the Molasse Basin, the hydraulic characteristics of deep Malm Carbonates also took into account the geological structure and the stress field. Corresponding analyzes of the cores allow a precise characterization of the disturbed and undisturbed dolomite and limestone with proven and verified methods, which have not yet been used at the lower Malm for geothermal reservoir characterization. For the first time in Germany the use of biodegradable acid has been used to stimulate the Upper Jurassic carbonates. Hydraulic tests were typically carried out in the Molasse basin as Casing lift tests (nitrogen, airlift or with a deep pump). For the first time a stem test was carried out for this project. This was especially important for the quality of the data, but also for the safety of the borehole. Other scientific and technical relevant results are in terms of reinterpretation and optimization of a 3D seismic survey and numerical simulations. With the analysis and interpretations of the sidetrack data, it was also possible to verify the suitability of the deep dolomite reservoir for proppant use (petrothermal use).

Due to the failure of the GEN-1ST-A1 sidetrack, which was established between April and October 2017, and the structurally controlled petrothermal character of the reservoir, further research is needed on geophysical reconnaissance methods and reservoir-adapted retrofitting measures in the future. The matrix permeability of the limestones and dolomites of the Upper Jurassic at the Geretsried site is low and does not support an economic flow rate from the low transmissive damage zones of the fault. With a length of about 1300 m of the up to 70-85 ° inclined open hole section, the transmissibility of approx. 7 mDm is very low. The results of the hydraulic core analyzes carried out at the TU Munich show a low matrix porosity of the Jura carbonates in the sidetrack GEN-1ST-A1, which together with partly calcite and dolomite-healed joints and faults of the drilled approx. 100 ° striking fault zone, which is nearly perpendicular to the maximum horizontal stress leads to no economic flow rate. The productivity of 5 l/s of the sidetrack Geretsried GEN-1ST-A1 is 5 times lower than the injectivity. With pressure reduction, the joints will close. In order to maintain productivity at the level of injectivity, the open cracks drilled in the fault zones would need to be kept open by suitable proppants. As a result of the non-productivity of the sidetrack GEN-1ST-A1, alternative geothermal utilization options were investigated at the Geretsried site. The most promising, among several alternative measures considered, is the zonal acidification and keeping open of the inflow areas identified in the sidetrack with suitable proppants.

The project Dolomitkluft was assigned to the Federal Government's 6th Energy Research Program, which aims to make the transformation of Germany's energy supply environmentally friendly, safe and cost-effective through innovative energy technologies. Deep geothermal energy plays an important role in this because of its independence from climate factors and its base load capacity within renewable technologies. An important focus of BMWi's research funding is to further develop the exploration strategies in such a way that suitable sites can be selected, investigated and ultimately developed for heat generation and power generation. This is where the dolomite joint project contributes: The cost recovery and use of heat and electricity from deep geothermal reservoirs was performed in an energetically interesting area of the Southern Molasse (south of the area Sauerlach) exemplified at the Geretsried site in the concession field Wolfratshausen. The work of this research project was intended to increase the production rate and thus the later commissioning of a power plant for generating electricity from deep geothermal energy in a region which, despite its high potential, could not be successfully developed with temperatures > 160 ° C. With the extensive data gained from the reservoir and the experience gained from the development, the changes in the storage can be understood during a later operation by a comprehensive process understanding. The findings are transferable to fault-controlled reservoirs and are exemplary for the entire southern Molasse Basin. The project results at the example site show that economic power generation from deep geothermal energy in the southern Molasse basin is unlikely. The project results indicate a petrothermal location that can be used to generate heat instead of electricity. For this purpose, it must be shown in the future that the fractures in the deep lying carbonates can be kept open under production conditions.

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