Geothermal Research Project “Algäu 2.0”
Research Concepts, Laboratory Investigations and Planning Operations

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ABSTRACT: Planning the utilization of geothermal systems requires the quantification of rock mechanical properties of reservoir rock to secure safe and sustainable reservoir operation. This article outlines the engineering and geotechnical aspects in terms of reservoir enhanced production from Upper Jurassic carbonate rock in the southwest Bavarian Molasse Basin. Specifically, a well is drilled including sidetrack down to 4,000 m depth at the research site Mauerstetten, close to Kaufbeuren. Cuttings are intensively investigated for biostratigraphy whereas drill cores are not taken from the reservoir. Geomechanical tests were conducted on analogue rock material, sampled extensively on analogue outcrops in the Franconian Alp in the vicinity of Ingolstadt. Laboratory analysis on rock samples cover petrographical, petrophysical and geomechanical tests. In particular, the reservoir rock is located in 3600 m TVD and has an average density of $\rho=2.4 \text{ g/cm}^3$ causing an expected vertical stress $\sigma_v \sim 85 \text{ MPa}$. The methodological combination from hydraulic and structural geological characterisation followed by 3D geological-hydraulical modelling of the reservoir helps to understand the impact of distinct fracture populations during reservoir operation. Results indicate that shear fractures significantly increase the rock permeability hence reservoir production.

1. Introduction

Geothermal energy is a promising renewable source of energy for the growing demand of heat and electricity worldwide. As a base load energy source with a modest environmental footprint it is able to mitigate climate change and improve energy security. Two main applications exist for deep geothermal energy. Heat can be used most efficiently for direct heating purposes and in case the temperature is high enough ($>100 \degree \text{C}$) thermal energy can also be converted into electricity. In context with the energy supply reforms, the public acceptance for the use of deep geothermal resources must be increased. In Germany and especially in the region of Munich, numerous successful projects, both on the heat and electricity market, underline the importance of the geothermal energy among the renewable energy sources.

In conventional hydrothermal systems hot water is extracted from deep, hot, water saturated and permeable formations. At the surface heat is extracted from the water. The cooled water may be re-injected into the subsurface to maintain reservoir pressure conditions. However, hydrothermal reservoirs are only those hot and permeable aquifers which contain merely about 1% of the geothermal power generation potential in Germany. The majority of the deep subsurface is hot enough, but not permeable enough at required depth to extract heat economically. The permeability of those reservoirs needs to be enhanced actively to achieve larger production rates. Such systems are commonly referred to as enhanced (or engineered) geothermal systems – EGS.
In Germany hydrothermal systems are the main source of geothermal energy today. The Northern German Basin, the Upper Rhine Graben and the South German Molasse Basin are the three regions in Germany with the highest hydrothermal energy potential. In the South German Molasse Basin low-enthalpy geothermal energy is extracted from open fracture systems and karst in the southern and central part of the carbonate rocks of the Malm formation. Economically successful geothermal electricity generation projects in this area extract water at temperatures above 100 °C (for direct use lower temperatures are used) at a production rate between 50 and 100 l/s with an associated pressure drawdown of 1.5–3.0 MPa. The productivity index (flow rate divided by pressure drawdown at steady state conditions) resulting from these parameters lies between 17 and 34 l/s/MPa. In some parts of the central basin even significantly higher values were observed. In the western part of the basin permeability in the Malm limestones is too low (<1 mD) to produce hot water economically. A geothermal system in this area would have to achieve similar productivity indices as known from the permeable central part of the basin in order to become economically viable. Thus the permeability of the Malm formation in the western Molasse basin needs to be enhanced artificially to develop the geothermal potential in this region. The desired temperatures of more than 100 °C can be reached below 2500 m TVDSS (true vertical depth subsea).

Figure 1: Location of the project area Mauerstetten in the Molasse basin and structural position of the geothermal well Mauerstetten (red comb) [combined from Reinecker et al., 2010 and Bayerischer Geothermieatlas 2012].
2. The “Allgäu 2.0” Research Project

A research project supported by BMU deals with questions in connection with the utilization of hydrothermal energy based on Enhanced Geothermal Systems (EGS) in Malm limestone in the western part of the Molasse Basin westward to Munich city. The orientated deep borehole GT1 in Mauerstetten has been drilled into a fault zone with an ENE-WSW strike direction and southward dip direction (Figure 1). The sidetrack ends at a total vertical depth of 3673m (TVD). The bottom 332m of the borehole has no casing. The borehole GT1 crosses the fault zone near the fault core, suffering a layer defect in the Tithon and a layer repetition in the Kimmeridge regions. The borehole GT1 hadn’t yield the expected 80L/sec flow rate, as the sidetrack near the fault zone was nearly completely dry. In this well, the Malm formation has been reached within a depth of approximately 3430–3630 m below the surface. The temperatures between 110 and 130 °C at this depth are sufficient for electricity generation. An airlift test of the Malm formation conducted in this well showed only an initial productivity index of about 0.5 l/s/MPa which is unfortunately below the minimum desired value. In order to enhance this natural productivity, thermal, chemical and hydraulic stimulation methods are the three main key technologies. A second research project phase will exactly clear the permeability structure at the Mauerstetten site and the measures to be taken in order to increase the reservoir productivity. The concept bases on the use of an artificially generated heat exchanger in a relatively impermeable depth region accessed from existing deep boreholes.

2. Geological and hydrogeological setting

The South German Molasse Basin is a sedimentary basin north of the Alps. It is one of the regions with the highest hydrothermal energy potential in Germany. The German Molasse Basin formed in the Tertiary as an asymmetrical foreland basin of the Alps with NE-SW orientated troughs. On the basis of the lithology, paleogeographical and tectonical development two levels can be differentiated. The basement is built of the Variscan foundation with the Mesozoic rocks of the Triassic, the Jurassic and the Lower and Upper Cretaceous. Above follow after an unconformity the Molasse sediments. The up to more than 500 m thick Malm formation crops out in the Swabian Alps and the Franconian Mountains in the north of the river Danube and dips from north to south under the Alps to increasing depths and temperatures.

In the Upper Jurassic the Vindelizic landmass was flooded entirely and connected the Franconian shelf sea with the deep Tethys. In the north of the Franconian Mountains the seafloor was subdivided into a marl-rich Swabian facies in the NW and the lime-rich Franconian facies in the SE by the Wiesent reef barrier. This is especially shown in the marl rich horizons of the Malm alpha to the Lower Malm delta. Later in the Upper Malm delta wide spreaded sponge reef complexes and reef domes were built. In the Malm delta/epsilon a smooth reef platform developed close to the sea surface. The reef limestones and platy limestones of the Upper Malm were then dolomitized in the shallow highly saline water. The Malm is the hot water aquifer with the highest geothermal potential within the South German Molasse basin. The movement of groundwater is mainly through karst caverns, fractures and bedding planes. Physical and chemical properties of the limestones are often controlled by facies. The interpretation of the diagenetic development of the Malm carbonates shows primarily facial controls. So the formation permeability depends for example strongly on the karstification susceptibility. The dolomitized and dedolomitized “reef facies” has relatively high permeabilities, because recrystallization leads to an increase in porosity and karstification. Besides the stratigraphy, the structural geology is of major importance. According to the world stress map, the direction of the maximum horizontal stress is approximately North-South in the western part of the basin. Since hydraulically induced fractures tend to grow parallel to the maximum horizontal stress these fractures would develop.
Figure 2: Sampling by Hilti-drilling and core boxes

Figure 3: Form of failures after uniaxial loading tests, Kehlheim Limestone B. 3-1-A, PK 79

Figure 4: Overview compression strength values in different facies complexes
The heaped up Molasse sediments from the Alps as well as the alpine formations lead to an applied load which results in an ongoing subsidence of the basin. This is the cause for normal faults with vertical shifts of up to 200 m which are aligned parallel to the Alps. In the western part of the basin faults have been active until the Miocene even 40–50 km north of the alpine formations. Due to the current stress field these E-W striking major faults are under compression and might be low conductive. However, highly conductive fracture systems might be found in the vicinity of these major faults. These systems are potential targets for geothermal development. The well we used in this study is drilled through such a major fault zone but failed to achieve a hydraulic connection to a permeable fracture system.

Table 1: Shear strength, deformation and permeability properties of the “Neuburger Bankkalk” (Neuburg Bank Limestone), Treuchtlinger Marmor (Treuchtling Marble), Layers of Upper Malm and Layers of Lower Malm

<table>
<thead>
<tr>
<th>Layer</th>
<th>Friction angle ϕ [°]</th>
<th>Cohesion c (MPa)</th>
<th>Young modulus E_v,40-60 (GN/m²)</th>
<th>Poisson ratio ν_{40-60} [1]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purbeck Neuburger Bankkalk (Purbeck Neuburg Bank Limestone)</td>
<td>22 - 24 (3 Samples)</td>
<td>34 - 50 (3 Samples)</td>
<td>24.15 to 43.15 (3 Samples)</td>
<td>0.36 – 0.44 (3 Samples)</td>
</tr>
<tr>
<td>Treuchtlinger Marmor (Treuchtling Marble)</td>
<td>38 - 41 (5 Samples)</td>
<td>20 - 43 (5 Samples)</td>
<td>28.39 to 56.86 (5 Samples)</td>
<td>0.13 – 0.45 (2 Samples)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Layer</th>
<th>Permeability (mD)</th>
<th>Porosity (%)</th>
<th>Young modulus E_{v,40-60} (GN/m²)</th>
<th>Poisson ratio ν_{40-60} [1]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper Malm</td>
<td>0.0005 – 4.5</td>
<td>1.2 – 34.4</td>
<td>16.3 – 27.8</td>
<td>0.2 – 0.3</td>
</tr>
<tr>
<td>Lower Malm</td>
<td>0.0001 – 5.0</td>
<td>2.2 – 8.7</td>
<td>25.1 – 33.2</td>
<td>0.2 – 0.3</td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th>Porosity (%)</th>
<th>Mercury porisimetry</th>
<th>Pycnometer</th>
<th>Weighing</th>
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</thead>
<tbody>
<tr>
<td>Purbeck Neuburger Bankkalk (Purbeck Neuburg Bank Limestone)</td>
<td>6.9 ± 3.0 (2 Samples)</td>
<td>21.9 ± 10.6 (2 Samples)</td>
<td>18.1 ± 6.1 (5 Samples)</td>
</tr>
<tr>
<td>Riffkalk (Riff Limestone)</td>
<td>4.4 ± 3.5 (3 Samples)</td>
<td>6.5 ± 3.7 (2 Samples)</td>
<td>5.3 ± 2.7 (12 Samples)</td>
</tr>
<tr>
<td>Treuchtlinger Marmor (Treuchtling Marble)</td>
<td>2.6 ± 1.4 (4 Samples)</td>
<td>3.9 ± 1.0 (2 Samples)</td>
<td>5.4 ± 1.3 (16 Samples)</td>
</tr>
</tbody>
</table>
4. Geotechnical investigations on the Malm limestone

Literature data and laboratory tests on analogue outcrop samples as well as borehole measurements and hydraulic field tests were used to quantify the properties of a typical geothermal system in the western part of the Molasse Basin. Outcrop analogue samples of limestone from the Malm delta (banked limestones with sponges), from the Malm epsilon (reef limestones) and from the Malm zeta 6 (banked limestones) were collected and analyzed. The Figure 2 on the left shows the sampling procedure that produced high quality samples as they appear in the core boxes on the right. The values of the samples from “Neuburger Bankkkalk” and “Kelheimer Riffkalk” were used for the “Reef Facies” (“Upper Malm”), the values from “Treuchtlinger Marmor” represent the lower “Normal Facies” (“Lower Malm”). A brief description of laboratory experiments conducted to obtain porosity, permeability, deformation and shear strength parameters is given below. The overview of the results obtained from the geotechnical experiments are presented in Table 1.

4.1 Hydraulic parameters

Permeabilities of the outcrop analogues were measured at the GFZ on 27 specimens with an argon gas permeameter using cylindrical plugs with a diameter of 2.5 cm and a length of 5 cm. Specimens were dried before at 60 °C in the oven for at least 24 h. To eliminate lateral flow during tests the specimens were jacketed by a neoprene tube. The experiments were performed at room temperature with confining pressures of up to 5 MPa for samples with a minimal flow of about 1 cm3/min. Samples which experienced a lower flow are measured with a higher confining pressure of about 7 MPa because higher pressure stages are required for flow through. For each specimen four to five pressure stages were realized in between 1 MPa and 6 MPa. To calculate the intrinsic permeability the Klinkenberg correction has been performed. Two additional samples were analyzed with a triaxial cell (MTS) at different stress levels. An external project partner (TU Bergakademie Freiberg) measured the permeability of 18 specimens with a flow through method. The results of the laboratory experiments are similar to the permeability range calculated from an airlift test which was done earlier in the well (0.1–2.7 mD). The porosities were measured at the GFZ with three different approaches: (1) Helium pycnometer, (2) Mercury porosimetry and (3) weighing. The measurements involved 94 specimens. For the gas displacement pycnometer AccuPyc 1330 measurements cylindrical specimens with a diameter of 2.5 cm and a length of 5 cm were used. Specimens were dried before at 60 °C in the oven for at least 24 h. Later the mass and the dimensions were accurately described. The AccuPyc 1330 pycnometer determines density and volume of the solid phase of a specimen by measuring the pressure change of helium in a calibrated volume (Micromeritics Instrument Corporation, 2001). Because of the accurate description of the cylindrical specimen the bulk volume can be calculated.

The total porosity can then be derived from the bulk volume and the volume of the solid phase. The measured total permeability and porosity ranges are given in Table 1. The Upper Malm has a higher porosity and permeability compared to the Lower Malm and is therefore our target formation. The values for the Upper Malm come from tests of “Neuburger Bankkalke” and “Treuchtlinger Marmor” analogues. The “Treuchtlinger Marmor” is a transition zone between the high porosity/permeability “Neuburger Bankkalke” of the Upper Malm and the low porosity/permeability “Treuchtlinger Marmor” of the Lower Malm. The high porosity/permeability “Neuburger Bankkalke” and the transition zone were summarized to the Upper Malm.
Figure 5: Mohr-Coulomb limit state sample 1 – “Neuburger Bankkalk”

Figure 6: Shear failure PK 1 – “Neuburger Bankkalk”
Figure 7: Weakly developed wedges of homogeneous test specimens with micritic structure PK 74 (B. 2-5) and PK 66 (B. 2-4)

Figure 8: Overview of Brazilian test results of the “Kehlheimer Bankkalk and Neuburger Bankkalk” (Kehlheim and Neuburg Bank Limestone)
4.2 Mechanical parameters

In order to estimate the geothermic potential of the site, it is essential to determine the uni-axial compression strength of the material. The equivalent samples taken from the layer outcrops by drilling have been tested with an unconfined compression test according to the code DIN-EN-1926(1999). The test specimens had 50mm diameter and a length of 80mm to 100mm. The axial load has been applied with a constant stress rate of 10MPa/min in all tests. The specimens of the layer “Treuchtlinger Marmor” (Treuchtling Marble) have shown the highest uni-axial compression strength values. In numerous samples, a yield on parallel shear planes in load direction has been observed as shown in Figure 3. Figure 4 presents the uni-axial compression strength ranges that have been measured in the test series on different tested material types. The Young modulus has taken higher values in specimens with a normal orientation of the layer boundaries than specimens with parallel orientation.

In triaxial test series, the deformation and shear strength characteristics of different layers have been examined, taking potential anisotropy, granular matrix characteristics, stress loading conditions, fault joint structures and failure modes systematically into account. From the test results, both deformation and shear strength parameters have been determined. The triaxial test have been carried out in multistage loading regime following the code TP BF-StB Teil C 12(1987). The samples had a length of 100mm and a diameter of 50mm. An example for the development of the friction angle and cohesion as parameters of the Mohr-Coulomb failure criterion can be seen in Figure 5. The highest shear strength and Young modulus values have been observed on the “Treuchtlinger Marmor” (Treuchtling Marble) samples. The “Neuburger Bankkalk” (Neuburg Bank Limestone) samples have shown the highest cohesion values. Higher strain rates have lead to a significant increase of the measured shear strength. Cracks have developed along fissures and fault joints in the samples. Figure 6 shows a picture of a tested triaxial sample of “Neuburger Bankkalk” (Neuburg Bank Limestone), denoting damage cracks and the failure plane that have developed.
The grain adhesion of the minerals in the rock matrix has been observed in Brazilian uniaxial tension tests on specimens with 50mm diameter and 25mm width following the code DIN22024 as shown in Figure 7. The test duration has been about 5 to 9 minutes for a single test, controlling the strain rate between individual experiments. The uniaxial tensile strength lays typically at about 1/30th to 1/10th of the uniaxial compression strength, being strongly influenced by anisotropy effects and rock grain matrix characteristics. The coarseness of the rock matrix grain surface positively influences the tensile strength due to a frictional particle locking and better cementation. In order to observe the anisotropy influence, the samples have been differently orientated in the individual test series. The largest interval for the tensile stress has been obtained for the “Kehlheimer Kalk” (Kehlheim Limestone) due to lithological differences and inhomogeneity within the layer. The highest tensile strength values have been measured in the “Treichtlinger Marmor” (Treuhtling Marble) samples with approximately 15MPa. The tensile strength has increased with higher strain rates and reached the highest values in homogeneous samples with loading direction normal to layer boundaries. The Figures 8 and 9 show the result intervals for different materials examined with the Brazilian test.

5. Geothermal reservoir characteristics

The investigation results for the Mauerstetten geothermal site lead to the conclusion, that hydraulic fracturing has the potential to generate fluid pathways between an unproductive well and a permeable fracture system and to develop artificial subsurface heat exchanger areas in the low permeability Malm formation in the western part of the Molasse Basin. The sensitivity analysis of the reservoir parameters of the Malm formation shows the importance of a detailed knowledge of permeability, porosity, Young modulus and stress state. Therefore it is necessary to obtain at least these parameters with an acceptable accuracy before planning and performing a stimulation treatment. Most importantly, zones with high fluid leak-off and stress barriers need to be identified to place treatments within a confined zone to prevent significant fracture height growth out of the target formation.

The sensitivity analysis of the treatment parameters shows that an increase in flow rate increases especially the fracture width and height. An increase in injection volume mainly increases the fracture half-length. Low flow rates may lead to better confined fractures and the probability for the fracture to develop outside of the target formation decreases. Hence, intermediate to low flow rates (50–100 l/s) and large fluid volumes (>10,000 m³) seem to be most appropriate to stimulate the Malm formation in the western part of the Molasse Basin.

Overall, unfavorable rock properties can be handled with an adequate adoption of the stimulation parameters if the reservoir properties and fracturing mechanisms are understood well enough. The fracture height growth is confined within the Upper Malm formation for most reservoir parameter combinations. The development of large hydraulic fractures by hydraulic fracturing treatments with or without proppants in the Malm formation is possible. However, the potential to develop an enhanced geothermal system by hydraulic fracturing in the western part of the South German Molasse Basin with similar production rates to economic hydrothermal projects in the central part of the basin is questionable because too many fractures need to be developed (>15) if there is no much higher permeability zone close by that can be connected to the well. But there are two potential possibilities to stimulate the considered well sufficiently: (1) if a higher permeability damage zone is present and (2) if an injection well is drilled into the damage zone. In these cases only about 4–14 hydraulic fractures need to be developed to achieve the economic target productivities. In order to develop multiple fractures, treatment wells need to be deviated or drilled horizontally. The evaluation of other stimulation technologies like shear stimulation or acid fracturing and a comparison with the results of tensile fracturing treatments could be a beneficial future work.
5. Summary

Geothermal energy is a promising renewable source of energy for the growing demand of heat and electricity worldwide. As a base load energy source with a modest environmental footprint it is able to mitigate climate change and improve energy security. Two main applications exist for deep geothermal energy. Heat can be used most efficiently for direct heating purposes and in case the temperature is high enough (>100 °C) thermal energy can also be converted into electricity. In context with the energy supply reforms, the public acceptance for the use of deep geothermal resources must be increased. In Germany and especially in the region of Munich, numerous successful projects, both on the heat and electricity market, underline the importance of the geothermal energy among the renewable energy sources.

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Acknowledgement

The financial support of this work by the Federal Environment Ministry of Germany (BMU) under Grant 0325267B is herewith gratefully acknowledged.

References


