PROCEEDINGS, 41st Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 22-24, 2016
SGP-TR-209

Processes in the Vicinity of an Injection Well of a Geothermal Facility in the Malm Aquifer

M. Lafogler [a], F. Wenderoth [b], J. Bartels [b], G. Somogyi [a], T. Hinkofer [a], K. Hess [a], T. Baumann [a]

[a] Technische Universität München, Institute of Hydrochemistry, Marchioninistrasse 17, D-81377 München

[b] Aquasoil GmbH, Joachim-Friedrich-Str. 48, D-10711 Berlin

tbaumann@tum.de

Keywords: Hydrogeothermal, Tracertest, Geothermal doublet, Dissolution of carbonates

ABSTRACT

With high temperatures, high transmissivities, and low salinities the Malm Aquifer in the Bavarian Molasse Basin offers ideal conditions for the exploitation of hydrogeothermal energy. In 2011 the Pullach geothermal facility was extended with a third geothermal well to account for the increasing heat demand. In the course of this extension an injection well was converted to a production well. Hence, for the first time in the history of geothermal exploration of the Malm Aquifer, production data became accessible from the surrounding of an injection well which has been in operation for more than 5 years. This data, together with data from a push-pull tracer test started 9 months before the conversion, allows unique access to the processes at the injection well and sets the baseline for an assessment of the long term behavior of geothermal heat and power plants in the Molasse Basin. The development of the production temperatures went faster than expected, after 4 years of production the initial temperatures have almost been reached. This can only be explained with a vertically heterogeneous distribution of the transmissivity. In this setting, the cold water forms a thin disc which extends much further from the injection well. Thus, the effective area of the heat exchange with the matrix of the aquifer is larger than in a homogeneous setting. The breakthrough of the tracers was affected by an unexpected delay of the start of the production. The regional flow led to a shift of the injected tracer pulses with the innermost tracer pulse being entirely transposed downstream of the injection well. The recovery rates mirror the sorption coefficients of the individual tracers as determined in batch tests and column tests. It became apparent, that the stagnation phase led to a bias towards sorption with slow kinetics and diffusion-limited matrix interactions. The hydrochemical data showed a significant increase of the concentrations of calcium, magnesium, and bicarbonate indicating a dissolution of dolomite. The dissolution overcompensates the effects of the increased viscosity of the injected cold water. Modeling results indicate that lower temperatures and different lithostratigraphy are contributing to the dissolution. These processes would also occur if the water would be produced from a dolomite and injected into a limestone, which explains why most facilities in the Molasse Basin have recorded decreasing injection pressures.

1. INTRODUCTION

Geothermal energy is a key technology for the transition from fossil resources to renewable energy. The Malm aquifer in the Bavarian Molasse Basin offers unique hydrogeological conditions for district heating and power generation. With 15 plants operating and another dozen in construction or planning, exploration is highly successful. However, detailed knowledge about the processes occurring in the aquifer which is crucial to run geothermal facilities is scarce. After more than 10 years of operation there is a good record of the hydraulics and the hydrochemistry at the production wells, including extensive data from pump failures and the development of precipitates (Mayrhofer et al. 2014). The injection well and its surrounding, however, is usually a black box which is not readily accessible. Here, not even the temperatures in the immediate vicinity have been measured. Nevertheless, the performance of the aquifer near the injection well controls the long-term operation of the geothermal system. Thanks to an extension of the Pullach geothermal facility with a third well in 2011 there was a unique opportunity to produce water from a former injection well after 5 years of operation. Since the start of the production from this well in 2012, an extensive data set of hydraulic, thermal and hydrochemical data was collected.

2. MATERIAL AND METHODS

2.1 Site description

The Bavarian Molasse Basin is a sedimentary foreland basin located in South Germany. One hundred and fifty million years ago in the Late Jurassic a large sea-level rise flooded the southern region of Germany. In this marine environment, different types of carbonates were deposited. Compact and layered carbonates were formed in lagoons and flat settings, whereas reef or compacted limestones were built of reef debris. At the end of the Jurassic, the sea level fell and the carbonate sediments where partly exposed at the land surface during the Cretaceous leading to karstification. In the Tertiary, the Molasse Basin was formed as a result of the Alpine orogenesis and the eroded debris was deposited there. The western part of the Molasse Basin is dominated by terrestrial sedimentation, whereas the eastern part has a mainly marine character (Bayer. Geol. Landesamt 1996). From the northern margin of the Molasse basin to the central basin at the edge of the Alps, the depth of the basin reaches a depth of up to 6,000 m b. s. l. The main target for geothermal exploration in the Bavarian Molasse Basin is the upper Malm formation. It is a carbonate-karstified deep groundwater aquifer which dips to the south and attains a vertical thickness up to 600 m in the Southern Franconian Alb and beneath the Southern Molasse sediments (Prestel et al. 1991). In the central Molasse Basin the temperatures in the Malm aquifer reach from 80 °C north of Munich to over 140 °C south of Munich. Together with a high productivity of up to 150 L/s this makes the Malm aquifer an ideal target for hydrogeothermal exploration. Fig. 1 shows a schematic of the Pullach geothermal facility, located south of Munich. This facility is used for district heating. The geothermal wells Th1a (production) and Th2 (injection) were drilled in 2005 and started production in 2006. In 2011 a third well (Th3) was drilled. It was decided to use the highly productive Th3 as an injection well and to convert the existing injection well Th2 to a production well. The disadvantage of the expectedly low temperatures produced from the former injection well was accepted in favor of a fail-safe system production from the wells Th1a and Th2 in parallel.

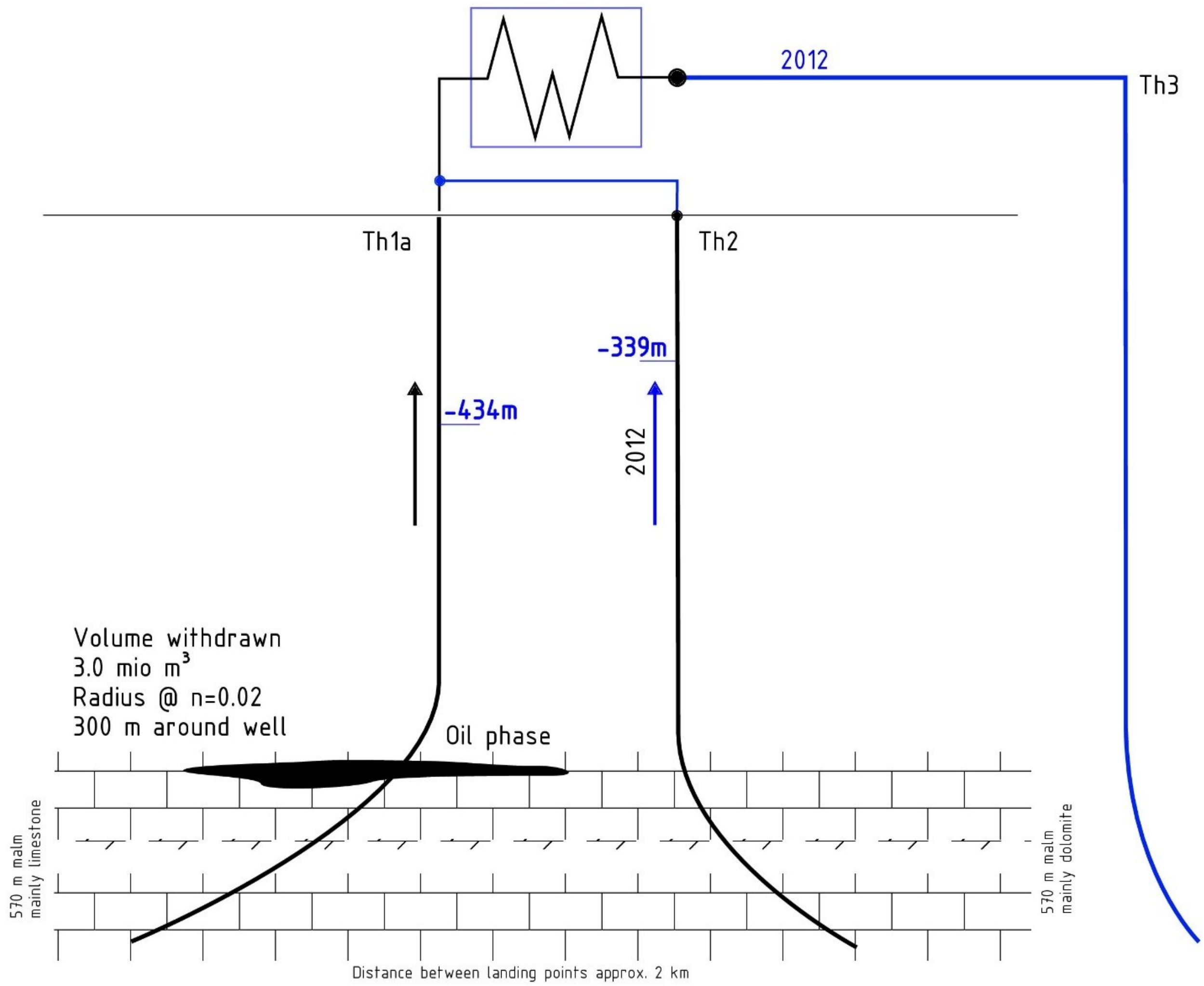

Figure 1: Schematic of the Pullach geothermal facility

The cuttings from Th1a and the long-term hydrochemical data show that this well explores mainly limestone in a banked facies. On the other hand, the cuttings and the very few hydrochemical analyses from the exploration phase of Th2 indicate that this well is likely exploring dolomitic reef facies. The landing points of the two wells are roughly 2 km apart. Therefore, a breakthrough of the injected water was not to be expected during the operation phase until 2011.

2.2 Monitoring

Temperatures and flow rates were recorded at the well head and stored in a database. Samples for hydrochemical analyses were taken at the well head. When the temperatures were above 98 °C, the samples were taken using a cooler, or after the heat exchanger if available. The water temperature, pH, redox potential (Eh), and electrical conductivity (EC) were measured with pH 330 (WTW), Redox SenTix ORP chain (Ag/AgCl 3.5 mmol KCl), and LF 92 (WTW) on-site. Chloride was measured using ion chromatography with EC detector (IC 25, IonPac AS9-HC column, Dionex). Sodium and potassium were measured using atomic emission spectrometry (ELEX 6361, Eppendorf). Calcium was titrated with EDTA, and magnesium was measured using flame atomic absorption spectrometry (AAS 3300, Perkin Elmer). Dissolved sulfides in water (S^{2-} , HS^- and H_2S) were precipitated on-site with 10 mL zinc acetate (2 %). The concentration of the precipitated zinc sulfide was measured with the methylene blue colorimetric method (Deutsches Institut für Normung 1995) using a spectrophotometer (Double Beam UV-190, Shimadzu). Analytical errors were determined using six samples taken at site 4 collected within 20 min. For cations and anions the analytical error is between 2 and 11 %.

2.3 Tracer test

Nine months before the scheduled conversion of the well Th2 a tracer test was started in a push-pull setting. Five tracer pulses, each consisting of a tracer with low matrix interactions (Na-Fluoresecein/URA, Na-Naphthionate/NAP) and a tracer with higher sorption properties (Eosine yellow/EO, Sulforhodamine B/SRB) were injected. Due to some technical issues production did not commence immediately after the injection phase, but with a time lag of almost 11 months. During that time a few tests with the pumps in Th2 were run with a total volume of less than 3000 m³.

3. RESULTS

3.1 Development of the temperatures

Fig. 2 shows a timeline of the temperatures and volumetric flow rates before and after the conversion of the well Th2. The production temperature of Th1a is increasing from 95 °C to 102 °C and varies slightly with the production rate reflecting decreasing heat losses in the production pipes (Tilley and Baumann, 2014). The injection temperatures mirror the ambient conditions, with low injection temperatures and high flow rates in winter and vice versa. After the start of the production in late 2012 the temperatures at the well head of the Th2 increase steadily from 65 °C to almost 95 °C in early 2014. The seasonal variation of the injection temperatures has fully vanished. For the first million m³ of thermal water produced from well Th2 the difference between injected and produced thermal energy amounts to roughly 60E9 kJ which is attributed to heat exchange between rock matrix and injected water.

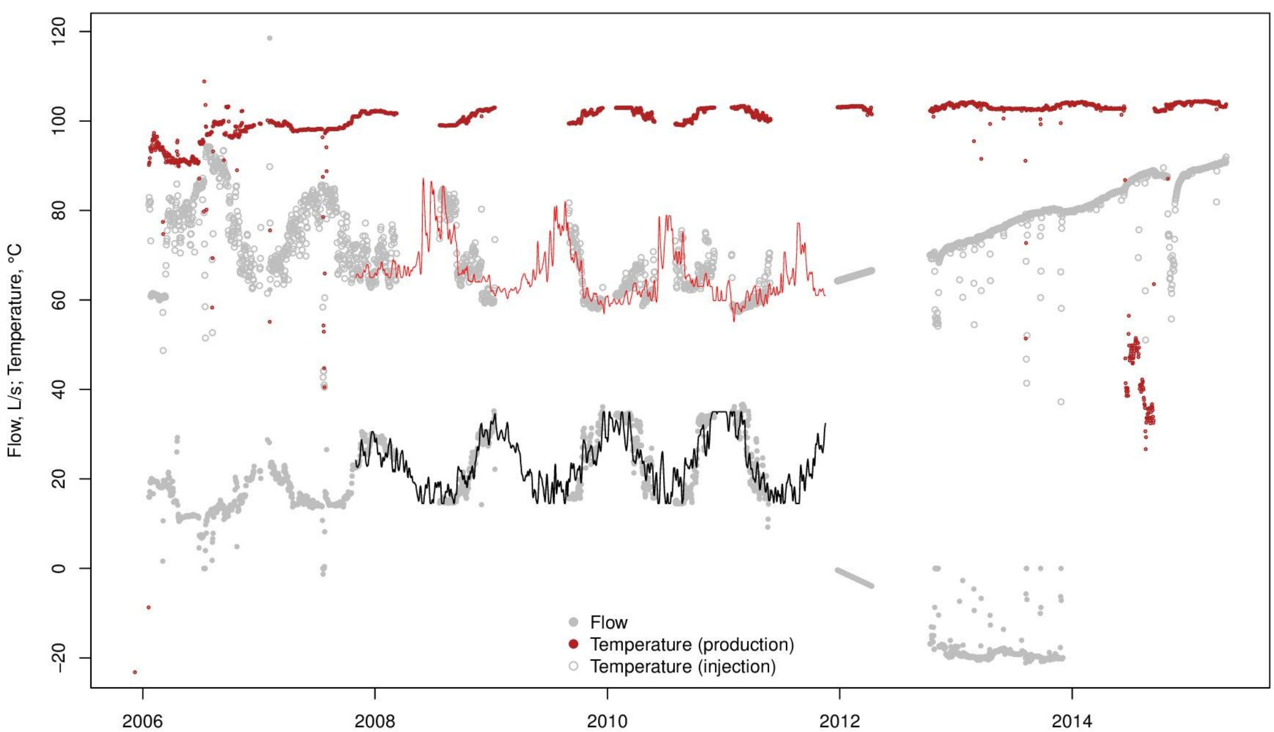

Figure 2: Monitoring of the Pullach geothermal facility

The fast increase of the temperatures and the lack of seasonal variations indicate a large area where the injected water can exchange thermal energy with the rock matrix. Model simulations show, that this can only be accomplished if thin layers with high transmissivity interchange with thick layers of low transmissivity, thus indicating a highly heterogeneous flow pattern in the Malm aquifer. The model of the temperature development is supported by earlier assumptions of a highly conductive stratum which were based on the hydraulic interaction of the wells Th1a and Th2.

3.2 Tracer test

While the water produced with the first test run of the pump in well Th2 did not contain any tracer further tests of the pumps, each with a very low produced volume on the order of a few thousand m³, revealed a surprisingly high concentration of the tracers. Fig. 3 shows the breakthrough curve of Na-Naphthionate as an example.

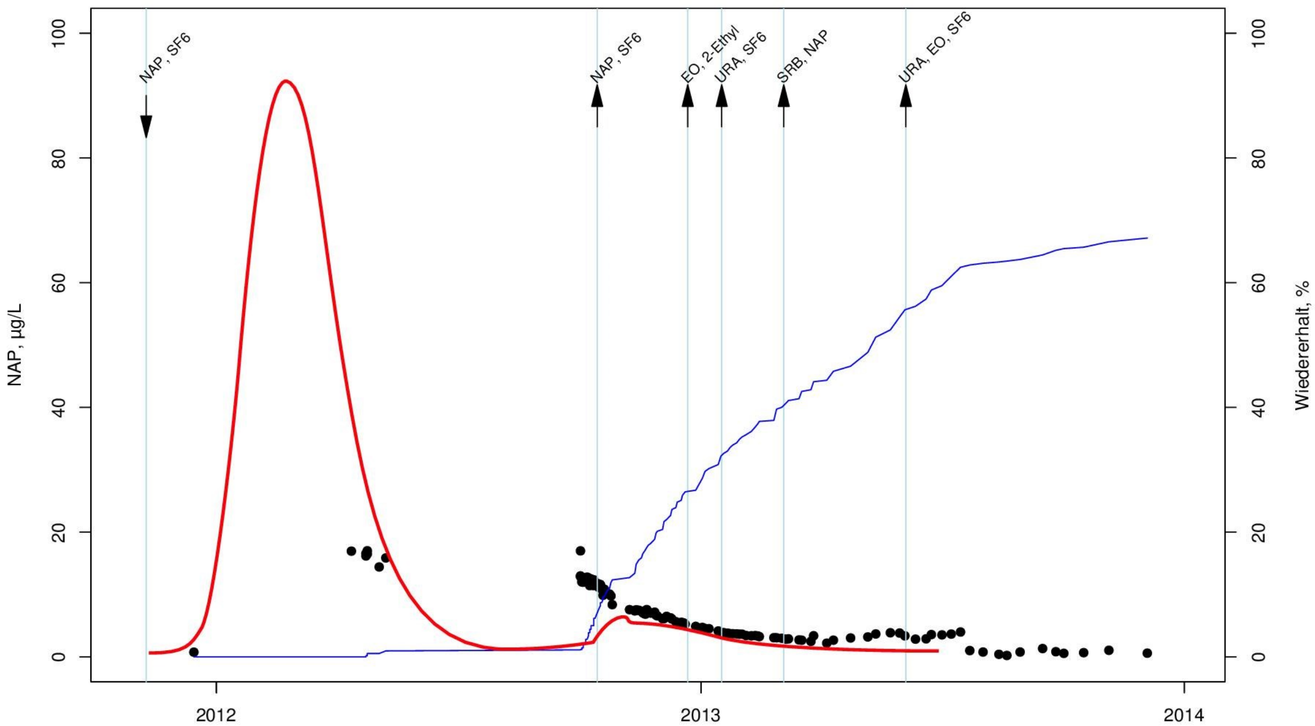

Figure 3: Measured (black dots) and simulated (red line) breakthrough, and cumulative recovery of Na-Naphthionate

This early breakthrough seems to contradict the push-pull setup, but can be nicely explained by a regional flow, transposing the whole injected tracers downstream of the well. In this case, the tracers detected during the later tests of pumps can be interpreted as the tracer front passing through the well by regional flow. With the start of production the tracer pulses, which are now located downstream of the well, are pulled backwards into the well. This assumption is supported by the recovery rates for the tracers, which are in a range of 14 % (SRB) to 67 % (NAP). The recovery rates are lower for tracers with higher sorption coefficients, which makes sense because of higher matrix interaction. Eosine, which has the highest k_{OW} -value of all applied tracers, was not detected at all. This indicates a partitioning into an oil phase and supports the hypothesis, that the oil phase produced from well Th1a is distributed along the main flow paths in well Th2.

3.3 Hydrochemistry

The hydrochemical characteristics of the waters in the Pullach geothermal system are plotted in a Schoeller diagram in Fig. 4. The hydrochemical analyses of Th2 from 2005 have to be taken carefully because the samples were taken not too long after chemical stimulation of the aquifer with HCl. Therefore, the concentrations of calcium, magnesium, bicarbonate and chloride are still expected to be higher than natural. The effects also show up in a high variance of the concentrations. The difference between the injected water and the produced water are evident and above all initial expectations. There is a significant increase of magnesium, calcium, and bicarbonate whereas the concentrations of sodium and chloride are almost identical and the concentration of sulfate decreases sharply. The latter goes along with a sharp increase of the sulfide concentrations pointing to microbial reduction of sulfate as the temperature conditions are more favorable for sulfate reducing bacteria in the cold injection well. The change of the magnesium, calcium, and bicarbonate indicates a dissolution of the dolomite matrix. While the water from Th1a is in equilibrium with limestone it is far from equilibrium with regard to dolomite. The difference is approx. 0.6 mmol/L dolomite which is lose to the theoretical values calculated with PhreeqC (Parkhurst & Appelo, 2013) for this system. The dissolution amounts to a dissolved mass of 120 tons of dolomite for the first million m³ of produced water. This is equivalent to 40-50 m³ of dissolved dolomite in the surrounding of the injection well.

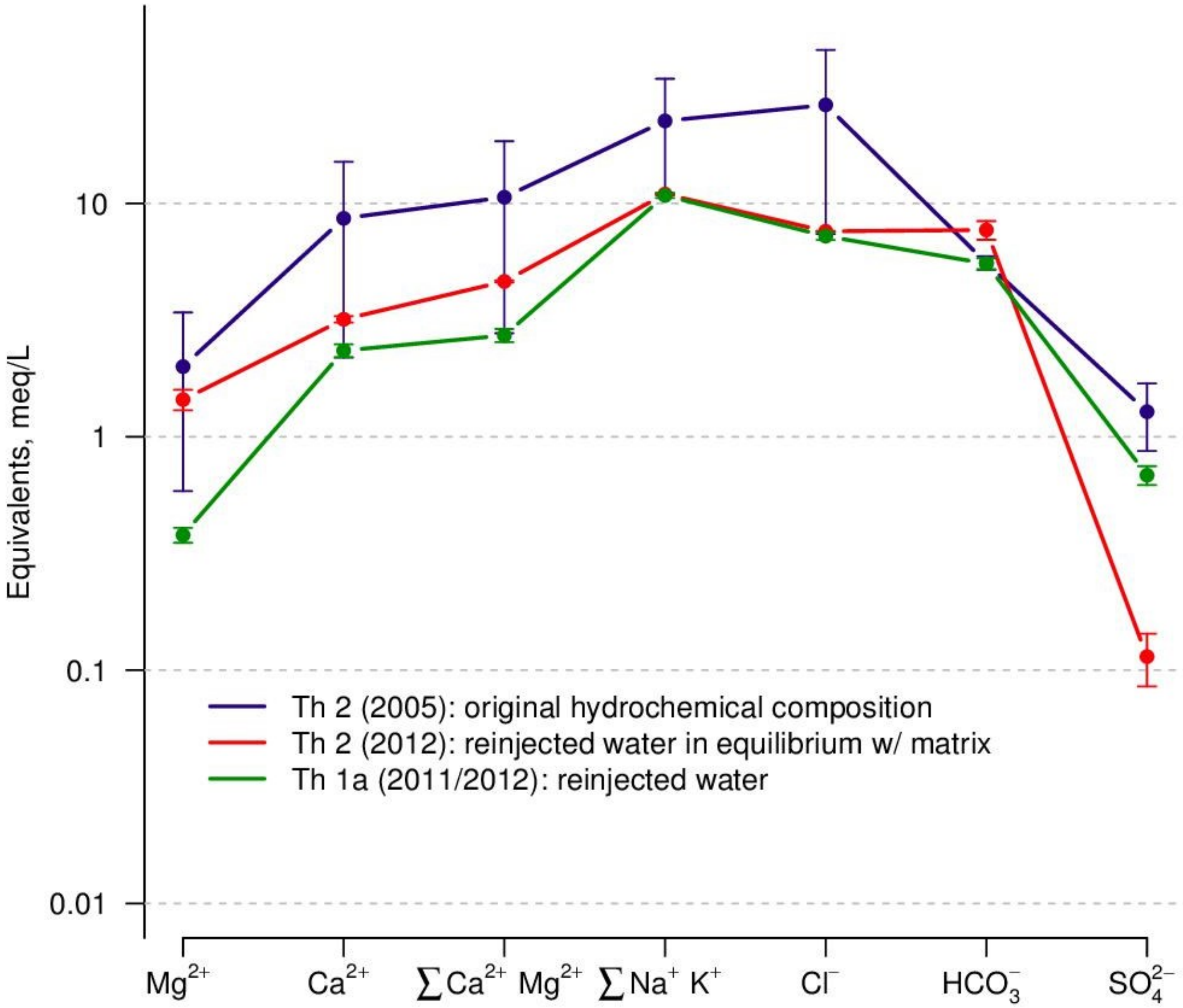

Figure 4: Schoeller diagramm of the injected and produced water for well Th2

The dissolution of dolomite takes place along the main flow paths. The reaction kinetics indicates that an equilibrium is not reached within the first 10-20 meters from the borehole. This is supported by the hydraulic data which indicates an increase of the transmissivity for the first 50 meters from the borehole. The effects of the dissolution of the rock matrix overcompensate the effects of the increased viscosity of the injected cold water and are responsible for decreasing pressure heads. Simulations and hydraulic data show, that this effect also takes place in settings producing from dolomitic reef facies into banked limestone.

4. CONCLUSION

The conversion of a former injection well into a production well provided unique access to the processes in the surrounding of the injection well. The results have shown, that hydraulics and temperatures are sensitive to the heterogeneity of the transmissivity in the aquifer. Due to the low porosity and the small widths of the flow paths the effects of dissolution of the rock matrix are high. This leads to an increase of the injectivity, which can also be set for other lithostratiphic settings in the Malm aquifer. The tracer test provided data for the regional flow component and a possible pressure dependency of the flow to the well, i.e., an activation of flow paths at high pressure. It also indicates that the oil phase is distributed along the main flow paths which are likely different to the regions where the oil was trapped initially.

ACKNOWLEDGMENT

This project was funded by the Federal Ministry for Economic Affairs and Energy (contract 0325469) based on a decision of the German Bundestag. We gratefully acknowledge support by IEP GmbH, Pullach, and our project partner Erdwerk GmbH, Munich.

REFERENCES

Bayer. Geol. Landesamt: Erläuterungen zur Geologischen Karte von Bayern 1:500000 [Explanation to the geological map of Bavaria 1:500000]. *Bayer. Geol. Landesamt*, Munich, Germany (1996).

Prestel, R., Stier, P., Jobmann, M., Schulz, R., Strayle, G., Wendebourg, J., Werner, J., Wolf, M., Eichinger, L., Salvamoser, J., Weise, S., and Fritz, P.: Hydrogeothermische Energiebilanz und Grundwasserhaushalt des Malmkarstes im süddeutschen Molassebecken [Hydrogeothermal energy balance and groundwater balance of the Malm karst in the South German Molasse Basin]. *Bayer. LfW und LGRB*, Munich, Germany (1991).

Tilley, B., and Baumann, T.: On temperature attenuation in open-loop wells, *Renew. Energy,* **48**, (2012), 416-423.

Mayrhofer, C., Niessner, R., and Baumann, T.: Hydrochemistry and hydrogen sulfide generating processes in the Malm aquifer, Bavarian Molasse Basin, Germany, *Hydrogeol J*. **22**, (2014), 151-162.

Parkhurst, D., and Appelo, C. A. J.: Description of Input and Examples for PHREEQC Version 3—A Computer Program for Speciation, Batch-Reaction, One-Dimensional Transport, and Inverse Geochemical Calculations, U.S. Geological Survey, Techniques and Methods 6--A43 (2013).