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Thermo-hydro-mechanical-chemical coupled modeling of a geothermally used fractured limestone

Wolfram Rühaak[a,b,c,*], Claus-Dieter Heldmann[a], Liang Pei[a,d], Ingo Sass[a,b]

[a] *Technische Universität Darmstadt, Geothermal Science and Technology, Schnittspahnstrasse 9, D-64287 Darmstadt, Germany*
[b] *Technische Universität Darmstadt, Darmstadt Graduate School of Excellence Energy Science and Engineering, Jovanka-Bontschits-Straße 2, D-64287 Darmstadt, Germany*
[c] *Federal Institute for Geosciences and Natural Resources (BGR), Stilleweg 2, 30655 Hannover, Germany*
[d] *Helmholtz Centre Potsdam - GFZ German Research Centre for Geosciences, Telegrafenberg, D-14473 Potsdam, Germany*

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1. Introduction

A geothermal doublet is the simplest type of an open system for getting hot water from the subsurface. Earths' heat is subsequently taken from the fluid pumped from one borehole and considerably cooled water is then reinjected in another borehole.

The injection is typically performed in the same geological unit as the extraction. The reason for using such an additional and accordingly expensive deep well is mainly to maintain the original water pressure in the reservoir. Furthermore it is possible to interchange extraction and injection wells; another important reason is, that the chemistry of the injected fluid is close to be in equilibrium with the groundwater in the injection aquifer. In case of disequilibrium reservoir scaling is possible and the resulting decrease of injectivity could jeopardize a project.

In the South German Molasse Basin limestone aquifers have been used within the last decade very successfully for geothermal heating and to a lesser extent for power generation. The Molasse Basin is a sedimentary basin located north of the Alps (Fig. 1). The basin contains mostly Tertiary clastic sediments from the Alpine orogenesis, and Mesozoic clastic and carbonate sediments covering the crystalline basement; the basin has a wedge structure with a moderate dip towards the SSE.

For geothermal application mainly the upper part of the Upper Jurassic (Malm) limestone formation is used due to its large transmissivity.[1] These limestones have an overall thickness of approximately 300 m. At the Swabian and Franconian Alb in the north of the Molasse Basin outcrops of this limestone can be studied. Within the basin the unit dips into greater depth towards the Alps in the South (Fig. 2). Below Munich the Malm aquifer is approximately at a depth of 3500 m and has a temperature around 130 °C.

Especially the region around Munich has been extensively explored. While the usage of this reservoir is increasing, there is also an increased interest in better understanding the reservoir properties (e.g.[2,3]). This study is motivated because observed pumping rates and injection pressures are partly hard to explain. It focusses on available techniques and current limitations in modeling of a fracture in a limestone. Other recent studies dealing with the effect of an increase of injectivity have focused on uncoupled modeling with more detailed chemical reactions and without considering mechanical effects (Baumann et al.[3]).

The THMC modeling is performed intentionally comparably simplified and only in 2D. Previous studies[4,5] have shown that the accumulated complexity of a 3D THMC study makes it very hard to judge the quality of the achieved results. The aim to reduce complexity is also the reason for the application of rectangular quadrilateral elements in this study. Generally 2D and 3D unstructured (triangular or tetrahedral) meshes are available (e.g.[6]).

For a few hydrogeothermal wells tapping the Upper Jurassic reservoir of the Bavarian Molasse Basin both measured injectivity and productivity data are available Fig. 3. A comparison of these data could provide a hint that pressure dependence of hydraulic conductivity in the vicinity of the wells is a significant feature in the parameter range where these geothermal wells are operated.

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* Corresponding author at: Technische Universität Darmstadt, Geothermal Science and Technology, Schnittspahnstrasse 9, D-64287 Darmstadt, Germany.
E-mail address: ruehaak@geo.tu-darmstadt.de (W. Rühaak).

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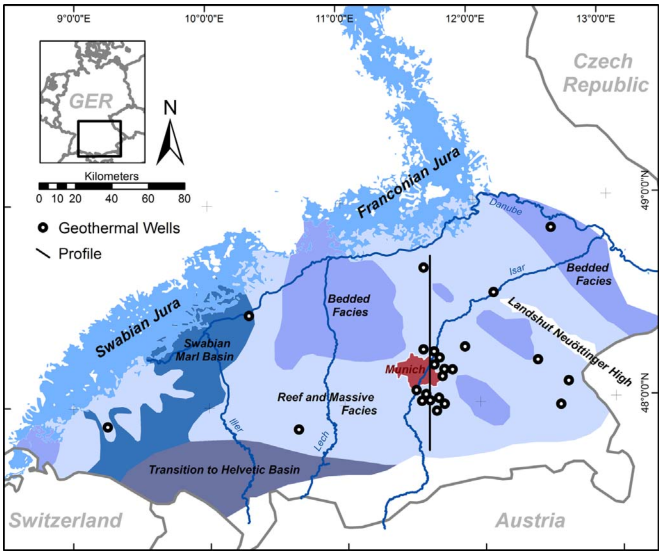

Fig. 1. Study area with location of studied outcrops of the analogues Swabian and Franconian Alb and drillings within the Molasse Basin. The location of the cross section shown in Fig. 2 is marked with a green line. Zones after,[66] Malm contour based on.[67]

Generally, this aquifer is of fractured – porous type. The main inflow sections of the wells are usually in connection with fractured fault zones. A considerable amount of additional karstification in combination with the fractures is likely.

Well productivity (productivity index PI = production rate/bottom hole drawdown) and injectivity (injectivity index II = injection rate/ bottom hole pressure increase) are influenced by a series of processes as listed in Table 1, which shows the II-PI-ratio of six hydraulic test results. They all fulfil the criteria above. All measurements are from downhole pressure gauges. This excludes influences from temperature dependent density of the water column and friction losses in the well.

The main result is that no ratio smaller than 1 is observed (compare Fig. 3), i.e. injectivity has been larger than productivity in all available test data sets. Based on these data the injectivity is only higher than productivity at low to medium PI values. The two very productive wells (PI > 5) do not show this effect. Total difference between downhole well pressure at injection and production is smallest for the two wells with II/PI = 1. The highest II/PI-ratio (1.3) is obtained from data of a short term test.

As explained relatively cold water is injected into the fractured limestone aquifer. Temperature differences are an important source of stress and deformation in solid bodies; only direct strain and no shear strain is produced by the temperature differences.[7] Thermal expansion of a fracture causes a spatially and temporally varying aperture. Direct and shear strain can additionally occur due to an increased pressure resulting from pumping. An increased fluid pressure due to injection can increase fracture apertures.

In addition chemical dissolution as a function of pressure and temperature of the aquifer may occur.

2. Data and methods

For studying the possible effects due to the injection of cold water into the limestone reservoir rocks, similar rocks from analogue outcrops were collected and respective values for the thermal expansion were measured in the laboratory.

Using the thermo-triaxial device in Darmstadt[8], the linear coefficients of thermal expansion of different rock specimens of different sublithotypes of limestone (Malm) were measured under defined stress conditions.[9]

2.1. Chemical model

Changes in mineral volume due to solution and dissolution reactions can significantly affect permeability in porous rocks.[10] The chemical reactions of the model were limited on the fastest reaction kinetics. In case of carbonate rocks this is dissolution and precipitation of calcite and dolomite.

Although only calcite dissolution is considered, other species can affect the reaction rates and should be similar to natural conditions therefore. For this purpose in a first step a reservoir fluid and its CO_2 partial pressure is calculated to reservoir conditions in equilibrium with calcite, using reported real fluid and gas composition data from a geothermal well in the Malm aquifer.[11] This reservoir fluid is the initial injection fluid, and enters the model with lower temperature and less $CaCO_3$.

Within the model physical and chemical processes change the fluid parameters, e.g. temperature by heating or Ca concentration by dissolution, and likewise influence calcite dissolution rates. Reaction rates were calculated for sets of different parameters with the hydro-chemical software PhreeqC 3.[12] The rates are converted in aperture growth rates and put in matrices. During the numerical simulation the code calls the matrices for the conditions in every node and receives a reaction rate, which consequently increases or decreases locally the aperture of the fracture.

2.1.1. Constraints of calcite dissolution

Solubility of a mineral is represented by its solution index. It is dependent on temperature and pressure which are therefore necessary variables of the matrices. The leading reactions (Eq. (1)–4) for calcite dissolution are given by[13]. The precipitation and dissolution of calcite in aqueous systems is

$$CaCO_3 + H_2O \longleftrightarrow Ca^{++} + HCO_3^- + OH^- \tag{1}$$

and the reaction constant (product of the ion activity) is depending on the ion concentrations. Because the dissolution of calcite is a proton

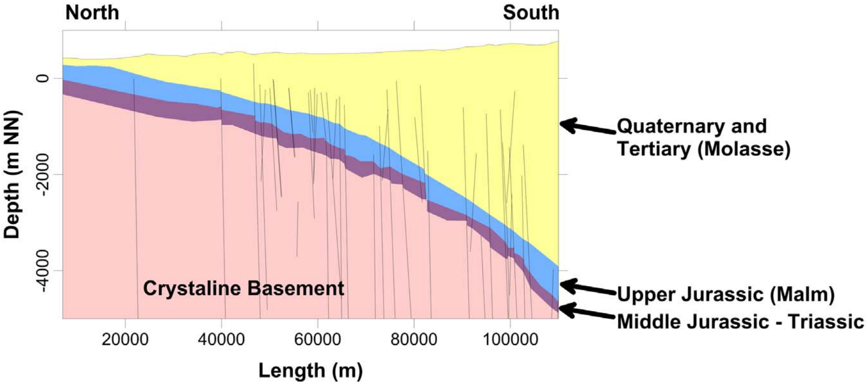

Fig. 2. Simplified cross section of the Molasse Basin (based on https://www.geomol.lfu.bayern.de, accessed April 1st, 2016). The location of the cross section is shown in Fig. 1.