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Development of a thermo-hydraulic 3D model of the deep carbonatic Malm aquifer in the Munich region (Germany) with special emphasis on a 3D seismic survey

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ABSTRACT

The mutual interference of several geothermal doublets and the relationship of seismic and hydraulic parameters were the focus of the joint research project "Geothermal characterization of karstic-fractured aquifers in Greater Munich, Germany (2008-2011)". Thirteen doublets and triplets in production or under construction in the Munich region (Germany) provided important data for the development of a hydrogeological model (HGM). On the basis of the HGM a numerical thermo-hydraulic 3D model was generated in order to describe the hydraulic and thermal situation at the end of 2011 and to forecast the effects for the proposed lifetime of the geothermal power plants. The processing and interpretation of the 3D seismic survey in the area of Unterhaching (27 km^2) could provide indications of potential hydraulic conductive zones, especially tectonic structures and different facies. After 50 years of operation thermal effects will be limited to the near surrounding area of the injection wells. In this period hydraulic influences on neighbouring doublets will be in most cases of small significance. Sometimes higher interferences will occur when injection wells are situated very close together or high injection rates or low hydraulic conductivities prevail. The numerical model represents a decision support for the optimized and sustainable hydrogeothermal usage of the Malm aquifer for the region of Munich.

1. INTRODUCTION

For the near future geothermal exploration in the South German Molasse Basin is the most promising deep geothermal activity in Germany. In the next years some more wells are expected to be drilled in the munich region. Also in nearby regions the Malm aquifer contains a big geothermal potential depending on regional temperature variations, tectonic framework, facies, dolomitization and karst degree.

2. RESERVOIR

The high productive deep buried Upper Jurassic (Malm) aquifer of the Molasse basin represents the most important hydro-geothermal reservoir in Central Europe (fig.1).

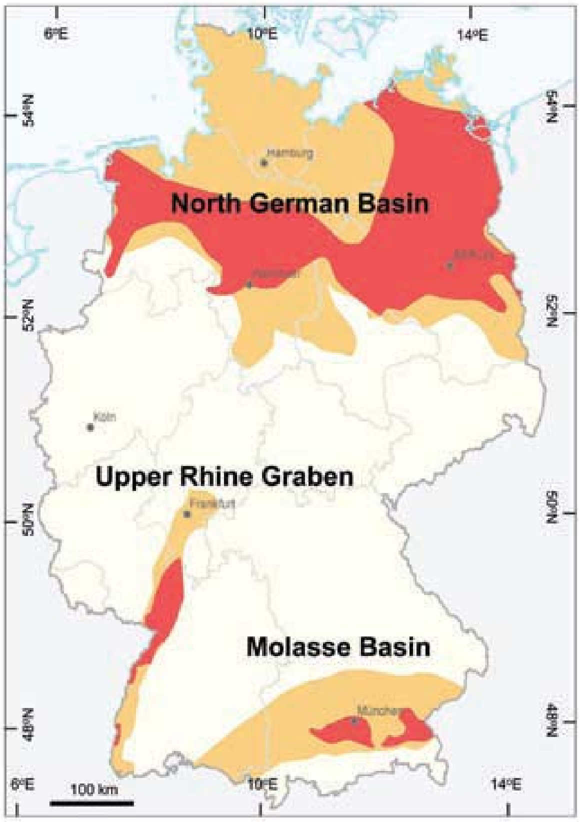

Figure 1: Areas of geothermal interest in Germany, red areas indicate temperatures of more than 100°C (Lüschen et al. 2011 after http://www.geotis.de).

From the outcrop in the Swabian and Franconian Alb, downbending to the South towards the Alps, the aquifer consists in the munich region (see fig. 2) of

600 to 650 m thick massive and bedded limestones and dolomites, which are successively covered by small cretaceous and more than 1 km thick tertiary molasse sediments.

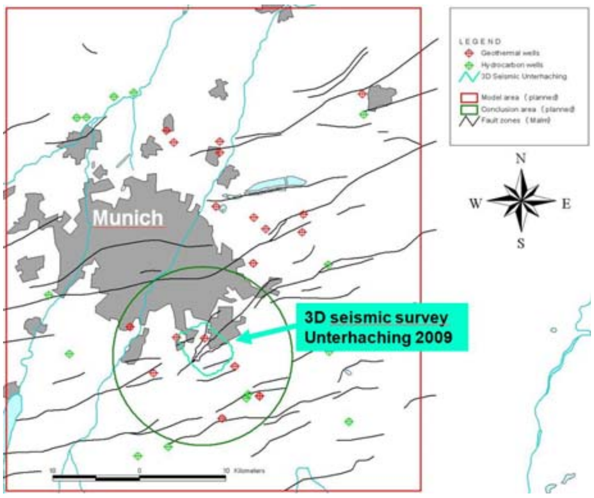

Figure 2: Model area with main features (red dots: geothermal wells, green dots: hydrocarbon wells, black lines: main fault zones (Top Malm), green circle: conclusion area of the numerical model, status quo end of 2010).

In the model area (ca. 2700 km^2) groundwater temperatures of the fractured and karstified Malm aquifer are rising from about 50°C (NW) to 150°C (SW). Until now geothermal wells in the munich region are drilled to depths between 1500 and 4500 m encountering hot thermal water which is reinjected with temperatures of about 60°C. Production and injection rates range from 12 to 120 l/s. At the end of 2011 geothermal power plants in the Munich region pumped and reinjected water of about 400 l/s totally.

3. 3D SEISMIC SURVEY UNTERHACHING

In 2009 a 3D seismic survey was launched in the surrounding of the geothermal well Unterhaching Gt 2, south of Munich (fig. 2). Field measurements were undertaken by Deutsche Montan Technologie GmbH (DMT). Processing and interpretation was done by LIAG (Lüschen et al. 2011, 2013). The most important tectonic feature in the survey area, a 45°N striking fault zone with a throw of about 250 m previously interpreted from 2D seismic measurements was affirmed by the 3D seismic survey. Furthermore it turned out to be that the new 3D measurements showed a more complex tectonic framework (en echelon pattern of normal faults connected with relay ramps or accommodation zones) with two other orientations of main fault systems (25°N and 70°N, where the latter is consistent with the general striking of the main fault zones parallel to the border of the Alps (Bachmann et al. 1987). Besides a detailed geological interpretation and attribute analyses (coherence) one of the most exciting and promising features concerning the relationship between seismic and hydraulic parameters was found in the seismic interval velocities: Low velocity zones, although ambiguous, which point to shattered zones in the surrounding of fault zones, were interpreted as hydraulic conductive zones (fig. 3 and 4).

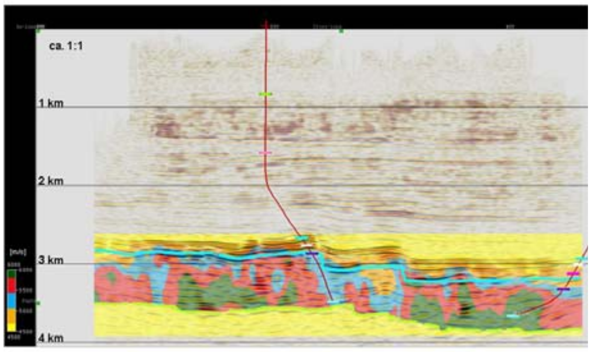

Figure 3: Inline (NW-SE) with overlain seismic interval velocities (only interval Lithothamnion limestone to base Malm), in the centre: geothermal well Unterhaching Gt 2, colour scale: from 4500 (yellow) to 6000 m/s (green) (Lüschen et al. 2013, submitted).

Low seismic velocities occur in the vicinity of the geothermal well Unterhaching Gt 2 (fig. 3: centre) whereas high velocities occur near the well path at the right border of fig. 3, which could most probably ascribed to compact bedded limestones. This finding coincides very well with the analysis of pump tests (see also chapter 5: numerical model) and cutting analysis (Wolfgramm et al. 2012).

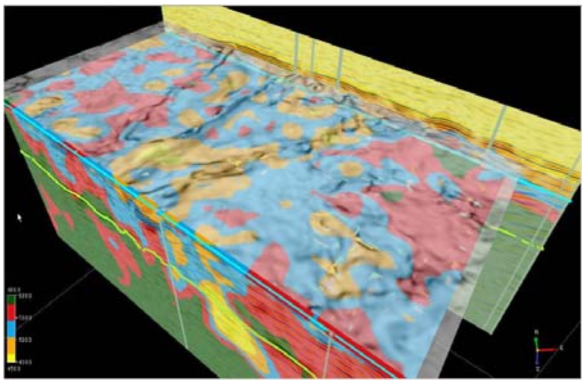

Figure 4: Seismic interval velocities after further analysis-iteration with refinement of the analysis interval from 150 m to 75 m. Overlain is a depth slice with the fault system on Top Malm. Top Malm was flattened, colour scale see fig. 3 (Lüschen et al. 2013, submitted).

Besides evidence for potential waterbearing zones in the Malm aquifer, fig. 4 shows clearly low-velocity zones in the variscian basement. However there is up to now no hydrochemical hint for a vertical hydraulic connection from the Malm carbonates to the granites and gneisses underlying the sedimentary cover.

Another key question for groundwater flux, which kept for long times geologists occupied is the potential karstification of the carbonatic layers. In depth slices showing similarity or coherence attribute, circular structures, interpreted as karstic collapse structures, are very often present (Lüschen et al. 2011).

4. GEOLOGICAL 3D-MODEL

In the beginning of the project, with the hydraulic importance of fault zones kept in mind, a 3D structural model for the munich region was planned. With ongoing development of the geological model another geological parameter seemed to play an important role to determine the hydraulic behavior of the aquifer:

facies

In the munich region the Malm occurs in the so-called Franconian facies: In Upper Jurassic time a carbonatic platform developed on which reefs, mounds and other organic build-ups alternated the tributary bedded or basin facies (Meyer and Schmidt-Kaler 1996). Böhm et al. (2012) analysed the relationship between facies and productivity of geothermal wells in the munich region and identified the reef facies as the most productive facies in the Malm. Detailed determinations of different rock facies derived from cuttings from 4 boreholes in the surrounding of Unterhaching 2 (Wolfgramm et al. 2012), the interpretation of the 3D seismic survey Unterhaching and the interpretation of 2D seismic profiles in the Munich region yield a distribution map of borderlands (reefs or mass facies) with potential favorable porosities and basin areas (basin or bedded facies) with potential poor porosities (Fritzer et al. 2012).

3D Structural model

A 3D structural model (GOCAD) and a 2,5D structural model (ArcGis) were developed by the Bavarian Environment Agency (LfU). Fig. 5 gives a bird's eye view of the surface of the tertiary Lithothamnion limestone (green) and the important hydrostratigraphic boundaries beneath in the conclusion area (see fig. 2).

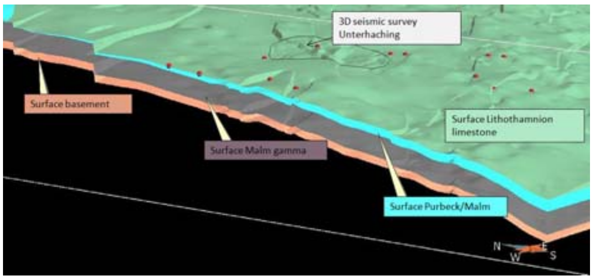

Figure 5: Section of the 2,5D structural model ("flying curtains") with view on the surface of the tertiary Lithothamnion limestone, contour of the area of the 3D seismic survey Unterhaching with high resolution and geothermal wells (red dots).

5. HYDROGEOLOGY

5.1 Hydrodynamics

Hydraulic potentials in the munich region point in general to a NNW to SSE groundwater flow direction in the northern model area (370 m asl to 340 m asl), whereas measurements in the southern part reveal an unclear trend, most possible to SE or E. In comparison to the artificial changes in hydraulic potentials the natural gradient is negligible especially in the southern part of the study area, where hydraulic conductivities decrease.

5.2 Hydraulics

After Birner et al. (2012) hydraulic conductivity in the Malm aquifer ranges between 1 x 10-7 and 1 x 10-4 in the munich region with an increasing trend from SW to NE.

5.3 Hydrogeological model

Considering partly or total loss of the drilling fluid and borehole measurements in 30 geothermal wells and 23 oil drillings in the munich region and other significant wells in adjacent areas a simplified hydrogeologic "standard profile" of the Malm aquifer was developed (fig. 6).

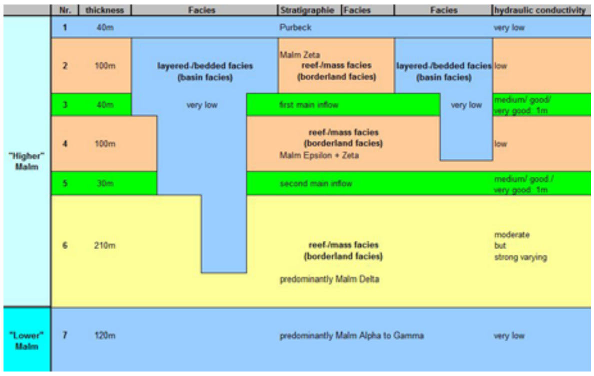

Figure 6: Hydrogeologic "standard profile" for the Malmaquifer in the munich region (after Dussel et al. 2011).

The main result was the division into "Higher Malm" (Malm δ to Purbeck) with good hydraulic conductivities especially in the reef-facies and "Lower Malm" (Malm α to γ) with very low hydraulic conductivities in general.

Beyond that hydrostratigraphic units from the low permeable basement to the high permeable quaternary rubble of the river Isar were parametrized.

5.4 Hydrochemistry

The Malm groundwater bears an astonishing low mineralisation for these depths (660 mg/l median value) and belongs to the Na-Ca-HCO3-Cl-Type (Birner et al. 2011).

6. NUMERICAL 3D-MODEL

Considering the multidisziplinary results as already described a 3D-FEM Model (FEFLOW) was conducted. The model area covers 57 x 47 km (fig. 2 and 7).

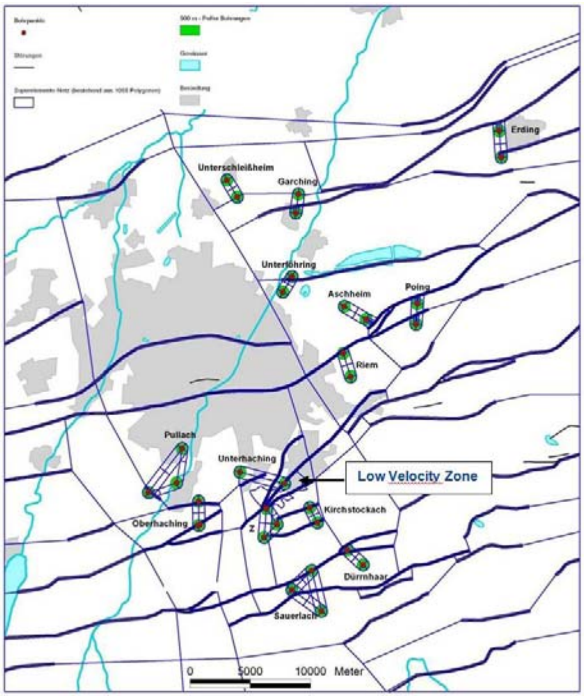

Figure 7: Superelement net with doublets and triplets and the low-velocity zone derived from the 3D seismic survey Unterhaching in the southern centre, thick black lines: main fault zones on Top Malm (Bartels and Wenderoth 2012).

The model comprises 34 model slices with 8 mio. elements and ca 1,5 mio knots (fig. 8). Mainly because of the relative low hydraulic permeability of the tertiary overburden in general, the whole model covering all strata in the model region was reduced to 25 layers ranging from the Lithothamnion limestone (Top Eocene) to the Variscian basement.

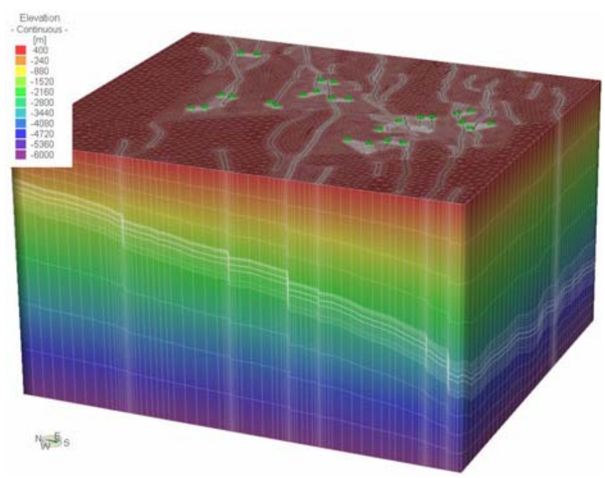

Figure 8: 3D-FE-Model, bird's eye view from Southwest (exaggeration: 5 times).

Previously mentioned lateral and vertical distribution of geological facies (reef and basin facies) was incorporated and blended within the model shape (see for example fig. 9: dark blue = distribution of low permeable basin facies in the upper main inflow zone).

In the southern centre of the model area a numerical conclusion area was choosen, which comprises the 3D seismic survey Unterhaching and neighbouring doublets and triplets of the geothermal energy plant Unterhaching (see fig. 2). Because of inconsistent hydraulic potential data in the southern part of the model area (see ch. 5) no groundwater gradient was used. In the conclusion area the model was hydraulically calibrated with the interaction of wells during several pump tests. For the interpretation of the interaction curves the operation modes of all geothermal wells in the region had to be taken into account. Starting with a very detailed calibration of the two Unterhaching wells, based on flowlog measurement amongst others, a first vertical conductivity distribution was derived which had to be slightly varyied in other zones (fig. 9). In accordance with the interpretation of the 3D seismic survey (see ch. 3) it was mandatory to create a low permeable zone between Unterhaching and Kirchstockach. ("Uha-Kst" in fig. 9).

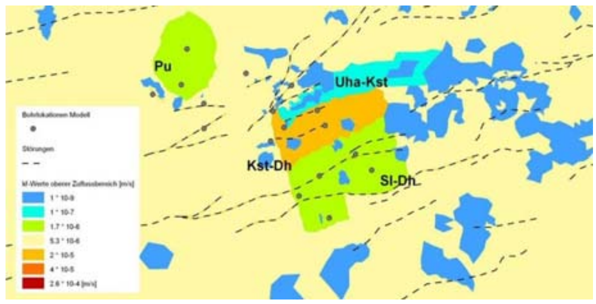

Figure 9: Detail of the conductivity distribution in the southern model area: Upper main inflow zone after calibration showing different "calibration zones", hydraulic conductivities: 1 x 10^{-7} m/s (light blue), 1,7 x 10^{-6} m/s (green), 5,3 x 10^{-6} m/s (yellow), 2 x 10^{-5} m/s (orange), (PU = Pullach, Uha-Kst = Unterhaching-Kirchstockach, Kst-Dh = Kirchstockach – Dürrnhaar, Sl-Dh = Sauerlach – Dürrnhaar).

After stepwise calibration and implementing of extraction and injection rates and temperatures the thermal-hydraulic status quo at the end of 2011 was simulated (fig. 10). This first simulation of the 3D regional model is now available for planners and owners of permission and allowance fields in the munich region in the frame of a user agreement with LIAG (Leibniz Institute for Applied Geophysics).

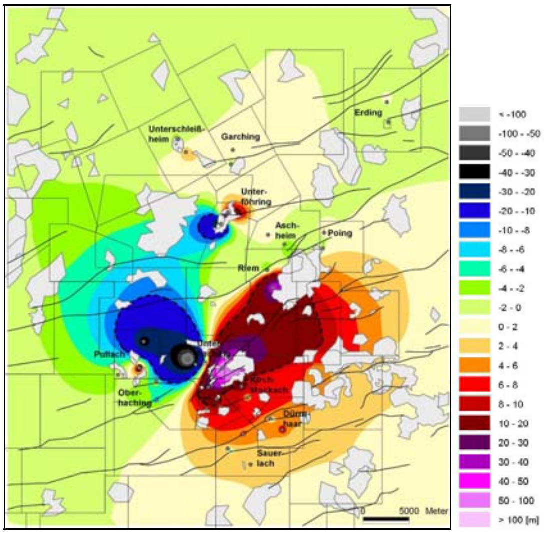

Figure 10: Groundwater potentials at the end of 2011 in the first main inflow zone, light grey areas: basin facies, thin polygones: permission and allowance fields (Bartels and Wenderoth 2012).

At the end of 2011 a groundwater depression cone already developed around the geothermal extraction wells Unterhaching Gt 1/1a and Pullach TH 1a (blue colours in fig. 10). In the eastern center of the conclusion area a raising of the hydraulic potential is caused by the injection wells Unterhaching Gt 2 and Riem TH 2 (red colours).

Two further simulations over 50 years, starting with the situation at the end of 2011, were run:

simulation 2: all drilled wells were taken into account

simulation 3: simulation 2 with an additional triplet "Z" (see fig. 7) which was planned and nowadays is already drilled.

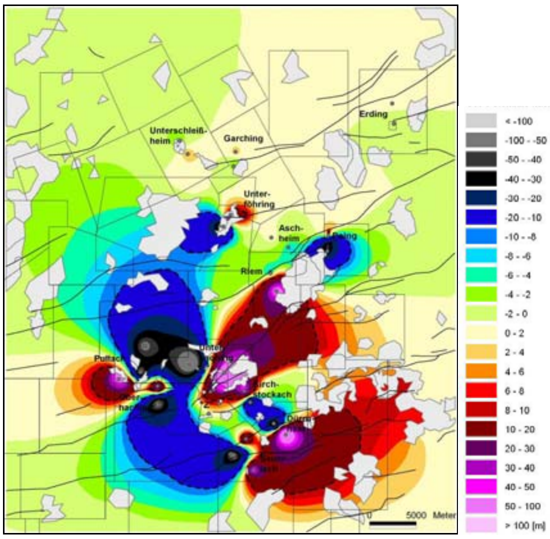

Figure 11: Groundwater potentials after 50 years in the first main inflow zone, without fictive triplet Z, light grey areas: basin facies, thin polygones: permission and allowance fields (Bartels and Wenderoth 2012).

After simulation 2 (without the fictive triplet "Z") the depression cone in the western part of the model area will extent south to the extraction wells Oberhaching Gt 2 and Sauerlach Th 1a, with a small interruption caused by the injection wells Oberhaching Gt 1 and Pullach TH 3 (fig. 11). Conspicuously the Pullach geothermal plant was extended from a doublet array to a triplet array with a reversal of an injection well to an extraction well. To the right the geothermal power plants of Kirchstockach, Dürrnhaar and Sauerlach (from North to South) will go in operation, causing a differentiated image of depression and raising of hydraulic potentials. Simulation 3, taking into account a fictive triplet "Z", will be revised in the near future because of the new array (situation now: doublet is drilled).

The results of the simulations were concentrated in an interference matrix which revealed influences from one well to another larger than 10 m in only a few cases.

The *temperature* field after 50 years will be influenced significantly only in the near surrounding of the injection wells (fig. 12).

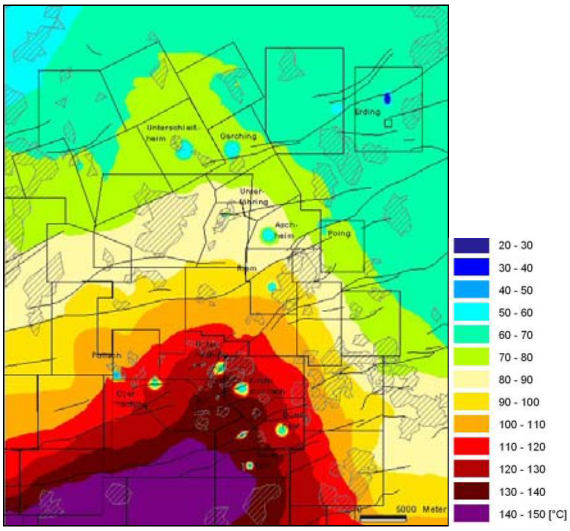

Figure 12: Temperature field after 50 years in the upper main inflow zone, without fictive triplet Z (Bartels and Wenderoth 2012).

Stopping the operation of the geothermal power plants from that time, a nearly complete regeneration of the thermal field will take place after 3000 years.

7. CONCLUSIONS AND FORECAST

In the region of the bavarian capital Munich a high potential low-enthalpy aquifer comes together with a favourable consumer structure. Based on actual geological and thermohydraulic data, simulated hydraulic and temperature effects to neighbouring geothermal permission or allowance fields in the munich region will be negligible for the next 50 years.

The equivalent-porous simulation gives an overview for operators of the geothermal power plants and state offices to manage the geothermal power plants in a sustainable way, also coming together with the neigbours. The regional 3D model (FEFLOW), as at end of November 2011, can be used by field owners and commissioned project companies in the munich region in the frame of a user agreement with LIAG (Leibniz Institute for Applied Geophysics). The further development of the numerical model will be encountered in the project "Science transfer for further development of deep geothermal energy in the South German Molasse Basin", financed by the BMU (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety of Germany). Detailed results of the joint research project "Geothermal characterization of karstic-fractured aquifers in Greater Munich, Germany (2008-2011)" are described in the final report (Schulz and Thomas 2012).

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