PROCEEDINGS, 43rd Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 12-14, 2018
SGP-TR-213

3-D Geothermal Reservoir Modeling of the Upper Jurassic Carbonate Aquifer in the City of Munich (Germany) under the Thermal-Hydraulic Influence of Optimized Geothermal Multi-Well Patterns – Project GeoParaMoL

E. Meneses Rioseco, J. Ziesch, B. Wawerzinek, H. Von Hartmann, R. Thomas and H. Buness

Leibniz Institute for Applied Geophysics, Stilleweg 2, D-30655 Hannover, Germany

Ernesto.MenesesRioseco@liag-hannover.de

Keywords: Geothermal reservoir exploration, characterization and modeling, 3D thermal-hydraulic modeling in porous, fractured, faulted and karstified Upper Jurassic carbonate reservoir, Bavarian Molasse Basin, 3D seismic interpretation, deep geothermal energy utilization in urban regions, optimization of geothermal multi-well patterns, geothermal reservoir management and production optimization, evaluation and assessment of geothermal potential, 3D regional modeling and long-term thermal-hydraulic prediction of reservoir development.

ABSTRACT

Deep geothermal reservoir exploration and characterization are indispensable when it comes to reservoir modeling, reservoir management and reservoir optimization of a multi-well geothermal field. In particular, the Upper Jurassic carbonate aquifer – also known as Malm aquifer - in the Munich region of the South German Molasse Basin has experienced extensive exploration and thermal water use in the last two decades. One of the most prominent geothermal projects set up by the municipal energy supplier of the city of Munich (Stadtwerke München-SWM) and currently in progress is called GRAME - optimized and sustainable reservoir development of deep geothermal plants in the Bavarian Molasse Basin. Following the SWM's district heating vision of turning Munich by 2040 into Germany's first large city to develop its district heating completely from renewable energy, this project aims at exploring, characterizing and optimizing potential reservoir sites for deep geothermal energy utilization in the southern part of the city of Munich. SWM's district heating vision implies the development of 400 MWth for the Munich district heating provided by the optimized placement of around 40 deep geothermal wells by 2040.

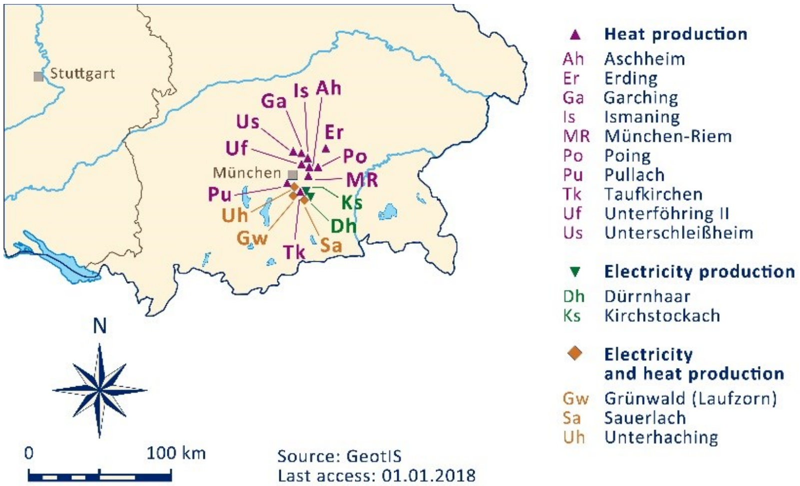
The present work lies within the scope of the GeoParaMoL project, which is part of the GRAME project and focusses on the estimation of geophysical parameters to determine facies of the Malm, structural and stratigraphic geological features and the modeling of the thermal-hydraulic long-term behavior of the Malm affected by geothermal multi-well arrays. This work concentrates on reservoir modeling of the Upper Jurassic carbonate aquifer in the southern part of the city of Munich. The aim is to predict the long-term thermo-hydraulic behavior of such fractured and karstified reservoir affected by different geothermal doublet and triplet arrays as well as smart multi-well patterns under different operational conditions. This includes the entire workflow starting from the seismic interpretation through building the geological and petrophysical model up to flow and heat transport modeling in order to optimize geothermal energy recovery. The optimization of geothermal energy production as well as reservoir management of multi-well patterns involve the study of possible positive and negative thermal-hydraulic interferences that such multi-well systems may have within the system and with neighboring geothermal wells already in operation in the immediate surroundings of the study region. Carbonate sedimentation leads to typical sedimentary patterns, which can be visualized by seismic imaging. Seismic reflections show seismic impedance contrasts and have to be translated into sedimentary and lithologic boundaries by the seismic interpreter. According to the rise and fall of sea level, a carbonate platform grows and calcareous sediments are precipitated or distributed on ramps or within lagoons and faunal activity leads to build-ups of different size. These build-ups themselves control the sedimentation process in their neighborhood. These processes result in a heterogeneous distribution of different carboniferous facies. Seismic sequence stratigraphy is a tool, which helps identify sedimentary environments in a seismic section or a seismic cube. During this workflow, typical seismic patterns are linked to carbonate features, sedimentary sequences are identified and the development of the carbonate platform is reconstructed.

Without borehole information, the determination of geophysical parameters for facies interpretation is challenging. The integration of shear waves could be helpful to limit the range of lithological and petrophysical parameters. For this reason, shear wave measurements were carried out during the regular 3D seismic survey in Munich. Conventional CMP processing shows shear wave reflections from the top of the Upper Jurassic carbonate platform on both horizontal components. An observed travel time ratio of t_S/t_P=1.55 indicates a V_P/V_S ratio of 2.05 for a P-to-S converted wave. Furthermore, the combination of P- and S-waves enables the derivation of geophysical parameters (e.g., V_P/V_S) to support the facies interpretation. Apart from carbonate facies, faults play an essential role in geothermal exploration. The prediction of potential fluid pathways in urban Munich started with the interpretation of a 3D seismic survey (170 km^2) that was acquired during the winter of 2015/2016 in Munich. The stratigraphic horizons, Top Aquitan, Top Chatt, Top Bausteinschichten, Top Lithothamnien limestone (Top Eocene), Top and Base Malm (Upper Jurassic), together with the detailed interpretation of the faults in the study area were used to construct a 3D geological model. The study area is characterized by synthetic normal faults that strike parallel to the alpine front. Most major faults were active from Upper Jurassic up to the Miocene. The Munich Fault, which is the biggest fault in the study area, has a maximum vertical offset of 350 meters in the central part. Increased fluid flow along the faults has led to massive sinkhole structures with up to 60 m displacement.

The long-term thermal-hydraulic behavior (~ 50 years) of the Malm aquifer affected by diverse geothermal doublet arrays and multi-well configurations has been numerically modelled with FEFLOW 7.0. Several scenarios with varying geometrical and operational conditions were implemented and numerically simulated. Preliminary thermal-hydraulic modeling results show that, for the simulation time considered, geothermal doublet arrays with a lattice spacing between 1 and 2 km and flowrates between 80 and 120 l/s are promising scenarios. In addition, model results indicate that geothermal multi-well configurations of 4 to 6 wells are under particular geothermal and hydrogeological conditions more appropriate. This later model result relates to the role of hydraulically active faults. Finally, modeling results suggest thermal and hydraulic advantages and disadvantages of geothermal doublet arrays over a single doublet. For instance, the use of geothermal doublet arrays leads to a significantly slower advancing thermal front (i.e., thermal breakthrough) but once the thermal breakthrough is reached, the temperature in the production well drops more rapidly.

1. INTRODUCTION

Due to the favorable geothermal and hydrogeological conditions as well as the great heat demand and district heating network in the city of Munich (Germany) and surroundings, this region represents an ideal place for geothermal energy utilization. There has been in the last two decades an impressive development in the utilization of geothermal energy in the region of greater Munich, e.g., Dussel et al. (2016). In particular, the Upper Jurassic carbonate aquifer – also known as Malm aquifer - in the greater Munich region of the South German Molasse Basin has experienced extensive exploration and thermal water use in the last two decades. Fig. 1 shows the geothermal plants in the immediate surroundings of the city of Munich already under operation for several years. One of the most prominent geothermal projects set up by the municipal energy supplier of the city of Munich (Stadtwerke München-SWM) and currently in progress is called GRAME - optimized and sustainable reservoir development of deep geothermal plants in the Bavarian Molasse Basin. Following the SWM's district heating vision of turning Munich by 2040 into Germany's first large city to develop its district heating completely from renewable energy, this project aims at exploring, characterizing and optimizing potential reservoir sites for deep geothermal energy utilization in the southern part of the city of Munich. SWM's district heating vision implies the development of 400 MWth for the Munich district heating provided by the optimized placement of around 40 deep geothermal wells by 2040.



Source: GeotIS
Last access: 01.01.2018

Figure 1: Map shows existing geothermal plants already under operation for several years in the so-called greater Munich region. Note that both electricity and heat are being produced. Each geothermal plant consists of a doublet or a triplet.

The present work lies within the scope of the GeoParaMoL project, which is part of the GRAME project and focusses on the estimation of geophysical parameters to determine facies of the Malm, structural and stratigraphic geological features and the modeling of the thermal-hydraulic long-term behavior of the Malm affected by geothermal multi-well arrays (e.g., http://www.liag-hannover.de/en/fsp/ge/geoparamol.html). This work concentrates on geothermal reservoir modeling of the Upper Jurassic carbonate aquifer in the southern part of the city of Munich. The aim is to predict the long-term thermal-hydraulic behavior of such fractured, faulted and karstified reservoir affected by different geothermal doublet and triplet arrays as well as smart multi-well patterns under different operational conditions. This includes the entire workflow, starting from the seismic interpretation through building the geological and petrophysical model up to flow and heat transport modeling, in order to optimize geothermal energy recovery.

It is worth mentioning that the underground model as well as the geothermic and hydrogeological model dealt with in this work builds upon an already existing model for the greater Munich region (Dussel et. al. (2016) and references therein). The Upper Jurassic carbonate reservoir (Fig. 2) and in particular its hydrostratigraphy in the Bavarian Molasse Basin has been extensively examined on a regional scale by the previously mentioned authors. One of the key motivations of this work is to improve and update the existing underground and thermal-hydraulic model in urban Munich, where the previous model lacks precision and is less robust. This is technically done within a workflow that involves the combination of three main software, i.e., SKUA-GOCAD, ArcGIS and FEFLOW 7.0. The geological structures and stratigraphy as well as facies distribution interpreted from the 3D seismic data are being currently implemented in the model. Another important aim of this work is to evaluate the geothermal potential of the Upper Jurassic aquifer in urban Munich by means of thermal-hydraulic modeling the complex interaction of multiple geothermal doublet and triplet arrays under varying operation conditions and geometric parameters. In addition, the long-term (~50 years) spatiotemporal evolution of temperature and pressure caused by several smart geothermal multi-well systems such as hexagon-patterns have been modelled. Especially the influence of geological control factors and the thermal-hydraulic interactions of the injection and extraction wells within the arrays and with neighboring geothermal wells already in operation is examined in terms of the thermal breakthrough or thermal short-circuit as well as the pressure near- and far-field.

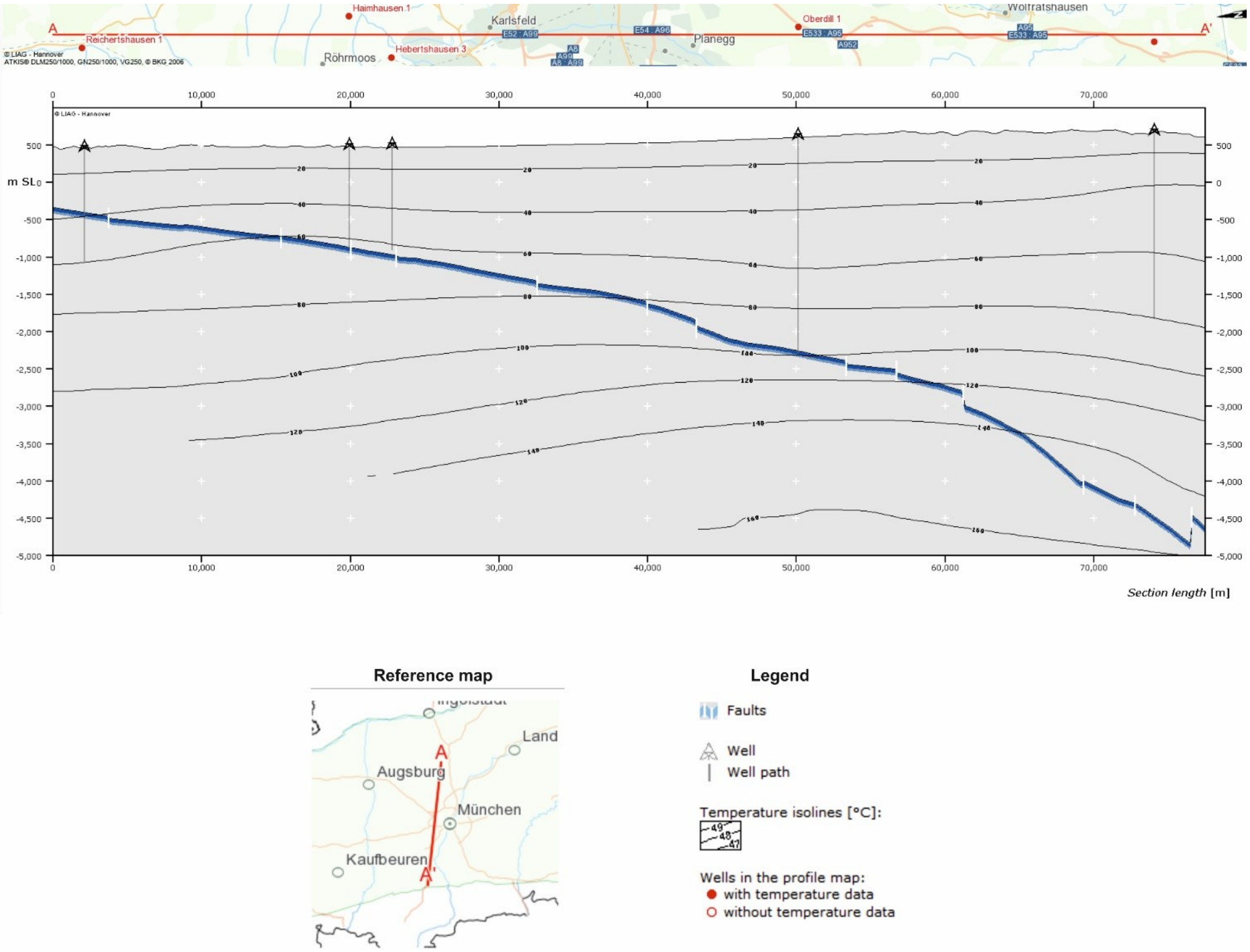


Figure 2: North-South profile (left to right) of the Bavarian Molasse Basin obtained from the freely accessible web-based interactive geothermal information system GeotIS (http://www.geotis.de). The dark blue line displays top of the around 600-650 m thick Upper Jurassic aquifer. The position of the profile and geothermal wells is illustrated in the upper map. Note that vertical exaggeration is 5:1 and a reference map is shown in the lower section of the picture.

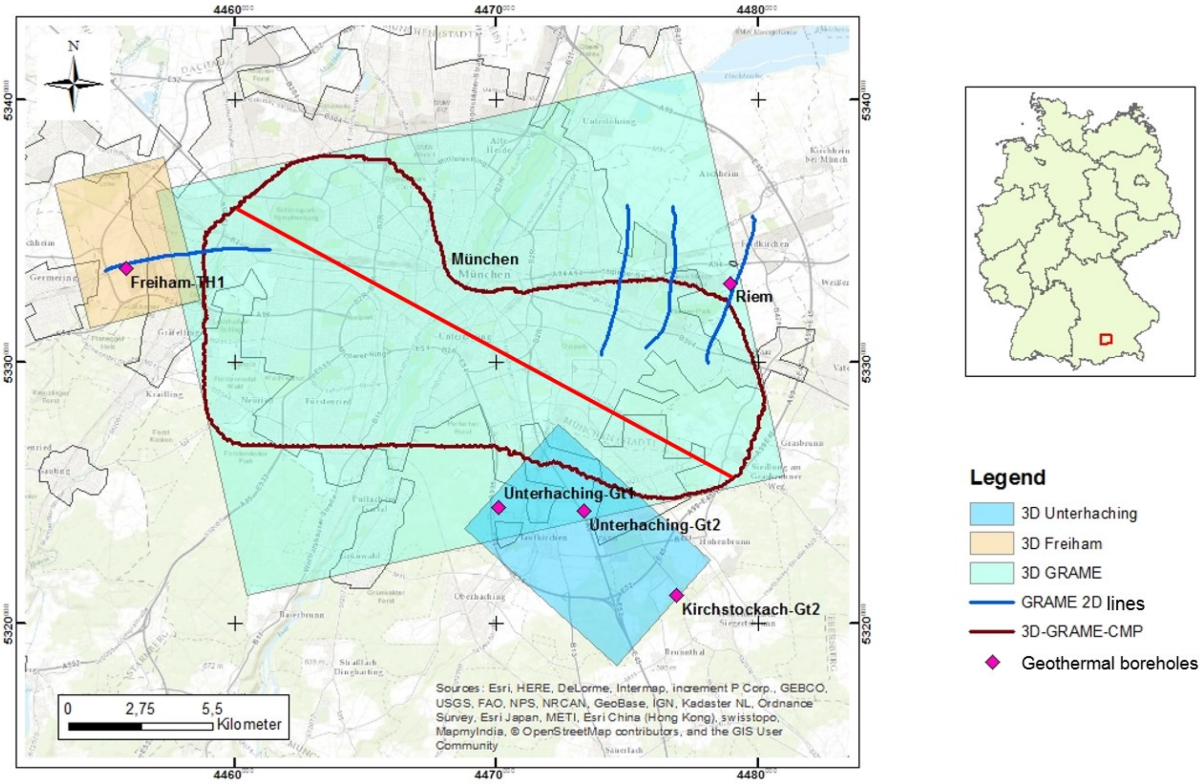
2. GEOTHERMAL RESERVOIR CHARACTERIZATION

It has always been challenging to characterize and model carbonate reservoirs at depth. In the scientific literature, carbonate reservoirs are considered as “just difficult” (Ringrose & Bentley (2015)). The complex porosity and permeability structures that result from depositional and diagenetic processes at different scales makes it difficult to properly implement and model them at a required resolution. In particular, the Upper Jurassic carbonate reservoir in the Bavarian Molasse Basin has been the subject of extensive investigation (e.g., Lüschen et al. (2011); (2014); Dussel et al. (2016) and references therein).

The prediction of potential fluid pathways in urban Munich started with the interpretation of a 3-D seismic survey (~170 km^2) that was acquired during the winter of 2015/2016 in Munich (Germany) within the Bavarian Molasse Basin (Fig. 3). Deformation analysis focusses on the structural interpretation and retro-deformation analysis to detect sub-seismic faults within the geothermal reservoir and overburden. We explore the hydrothermal Malm carbonate reservoir (at a depth of ~3 km) as a source of deep geothermal energy and the overburden of Tertiary Molasse sediments.

The stratigraphic horizons, Top Aquitan, Top Chatt, Top Bausteinschichten, Top Lithothamnien limestone (Top Eocene), Top and Base Malm (Upper Jurassic), together with the detailed interpretation of the faults in the study area were used to construct a 3D geological model. The study area is characterized by synthetic normal faults that strike parallel to the alpine front. Most major faults were active from Upper Jurassic up to the Miocene (Fig. 4). The Munich Fault, which is the biggest fault in the study area, has a maximum vertical offset of 350 meters in the central part.

The fault system that we observe in the new 3D seismic below the southern part of Munich is characterized by different structural features that developed in an extensional regime with a strong strike-slip component. Particularly noticeable are relay ramps and horst/graben structures. Increased fluid flow along the faults lead to massive sinkhole structures with up to 60 m displacement. Major faults terminate in horsetail splays towards the east. All these features potentially increase fluid flow and indicate potential geothermal targets. This detailed understanding of the structural development and regional tectonics of the study area will guide the subsequent determination of potential fluid pathways in the new 3D subsurface model of urban Munich.



Sources: Esri, HERE, DeLorme, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community

Figure 3: Different 3D seismic cubes that result from recent 3D seismic surveys in the city of Munich and its immediate surroundings. The study area, which encompasses an area of approximately 170 m^2 of the city of Munich, is marked with a thick brown polygon. This data set constitutes the basis for the 3D seismic interpretation, structural and stratigraphic analysis as well as facies analysis. The red line marks the location of the cross-section shown in Fig. 4.

Carbonate sedimentation leads to typical sedimentary patterns, which can be visualized by seismic imaging. Seismic reflections show seismic impedance contrasts and have to be translated into sedimentary and lithologic boundaries by the seismic interpreter. According to the rise and fall of sea level a carbonate platform grows and calcareous sediments are precipitated or distributed on ramps or within lagoons and faunal activity lead to buildups of varying size. The build-ups themselves control the sedimentation process in their neighborhood. These processes result in a heterogeneous distribution of different carboniferous facies. Seismic sequence stratigraphy is a tool which helps to identify sedimentary environments in a seismic section or a seismic cube. During this workflow typical seismic patterns are linked to carbonate features, sedimentary sequences are identified and the development of the carbonate platform is reconstructed.

The interpretation process is performed on the seismic section, in the optimal case perpendicular to the main distribution of seismic sediments or in a seismic cube parallel to seismic horizons, which represent sequence boundaries. In this case, one can see the local distribution of sedimentary patterns occurred in a single time interval. On the seismic section, sedimentary patterns can be distinguished by the geometry of the seismic reflections. Lagoons often show fine-layered parallel reflection, dipping elements with top laps or sigmoidal structures characterize prograding ramps and larger buildups have lower impedance contrast and some show a more chaotic pattern.

Seismic classification can be used to parametrize seismic reflections and to visualize the distributions of local sedimentary systems (Fig. 5). This is done with the help of seismic attributes. These attributes are calculated from the seismic traces by different methods. The seismic wavelet can be divided into the phase, the frequency and the amplitude. One approach constitutes the extraction of instantaneous attributes by the Hilbert transformation. It calculates the instantaneous phase, frequency and amplitude. Another method to measure frequency is the spectral decomposition. These attributes are calculated for each seismic trace. The measurement of differences between traces is done by geometric attributes like the variance or texture attributes.

The Upper Jurassic platform in the study area was classified by the use of seismic attributes. The top of the reservoir was defined by choosing the top of the “Lithotamnien Kalk” layer. This Upper Eocene layer covers the entire platform in the area and can be used as a key horizon. Flattening of this horizon restores most of the faults within Upper Jurassic. This is also facilitated by the fact that faults within the carbonate platform dip nearly perpendicular to the surface. After flattening, the lateral succession of buildups, ramps, and lagoons can be studied much better. The base of the reservoir was defined by a strong reflector near the Top of the Middle Jurassic. The reservoir itself with a thickness of approximately 600 m was divided into 8 layers. For the classification the amplitude, dominant frequency and similarity were used. Within each layer the average of each attribute was calculated trace by trace. The classification was built by gathering amplitudes and frequencies into three intervals each. For the similarity, two intervals were used. These add up to 18 classes. The class distribution within each layer can be projected on its top. In this way one can go through the reservoir looking at the successive reservoir layer to obtain an impression how the classes and therefore the seismic reflections change laterally and horizontally.

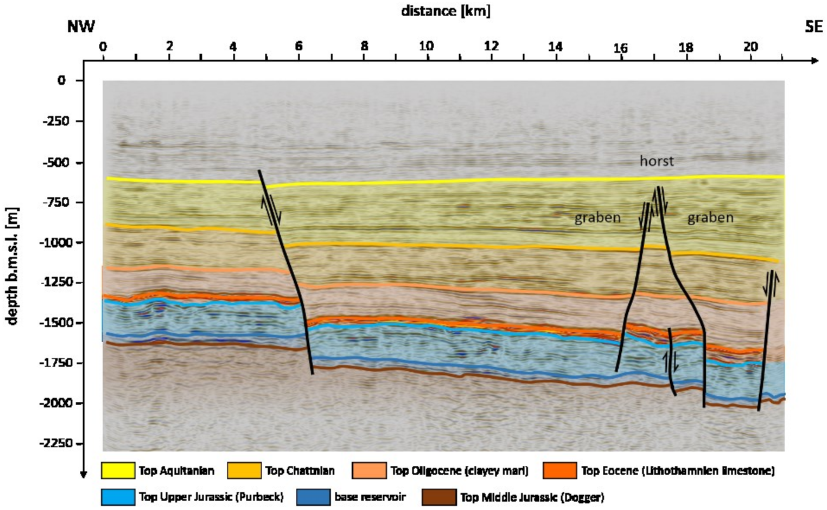


Figure 4: Seismic cross-section and structural geological interpretation along the red line shown in Fig. 3. Mainly 7 horizons were interpreted together with a series of faults from reservoir base until the Molasse sediments.

Based on this classification, the reservoir was divided into different zones, layer by layer. The zones themselves change their area and shifts in their main locations could be recognized from layer to layer. By comparing these zones with parts of the seismic sections, the development of the carbonate platform could be analyzed. In the middle northern part, a low reflectivity area is located which remain locally steady but change its extent over the time. This could be part of an inner platform, which is not structured by buildups, ramps or lagoons. Towards the south an elongated area is occupied by a buildup with clearly recognizable windward and leeward sides. The eastern part is made of a ramp which was structured over time by smaller build ups. The western part consists of a trough with smaller buildups adjacent to the inner platform and shows a clear transgression near the top of the reservoir. The interpretation reflects the high heterogeneity of the Upper Jurassic carbonate platform within the South German Molasse Basin. The advantage of this classification is that the areal extent of features recognized within the volume can be visualized. This facilitates the recognition of dependencies between geological features and this in turn improves the understanding of the development of the carbonate platform.

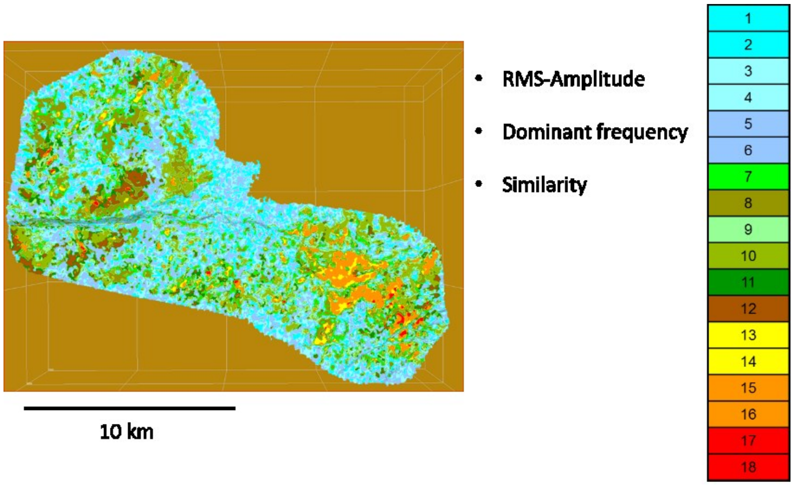


Figure 5: Classification map on a selected plane parallel to Top Carbonate platform. The reservoir (TopMalm-BasisMalm) was subdivided vertically into 8 layers. The classification was made using three seismic attributes. Small amplitudes are shown in blue while large amplitudes are displayed in red. The zonation focused here predominantly on amplitudes. In particular, the lateral division of the domain into reef and trough facies subdomains (blue-green/red) is clearly visible.

Without borehole information the determination of geophysical parameters for facies interpretation is challenging. The integration of shear waves could be helpful to limit the range of lithological and petrophysical parameters. For this reason, shear wave measurements were carried out during the regular 3D seismic survey in Munich. To acquire a 3D S-wave dataset, the regular 3D survey was additionally recorded on 3C sensors. In the eastern part of the survey 467 3C MEMS (micro-electro mechanical system) sensors were deployed as single sensors along one main and two crosslines.

Conventional CMP processing shows shear wave reflections from the top of the Jurassic carbonate platform on both horizontal components. An observed travel time ratio of $t_S/t_P=1.55$ indicates a V_P/V_S ratio of 2.05 for a P-to-S converted wave. This is in good agreement with average V_P/V_S ratios of 1.9-2.1 for Molasse sediments revealed from recently-conducted VSP measurements in the west and south of Munich. The application of asymptotic conversion point binning (ACP, Tessmer & Behle 1988) improves the velocity analysis and the resulting structural image: Reflections from the top of the carbonate platform as well as reflections within the Jurassic Malm reservoir are clearly visible. Furthermore, the combination of P- and S-waves enables the derivation of geophysical parameters (e.g., V_P/V_S) to support the facies interpretation. The derivation of V_P/V_S ratios has been carried out using the two-way travel time (TWT) differences of P and S waves within the reservoir. First comparisons between facies analysis for different layers within the carbonate reservoir and V_P/V_S ratios have been made. Preliminary results show a similar pattern of the distribution of facies classes and V_P/V_S ratios. For example, Fig. 6 displays low V_P/V_S ratios in the area of bluish facies classes. Next steps concern the combination of the distribution of facies classes and V_P/V_S ratios to derive further information of lithology distribution and possibly porosity trends.

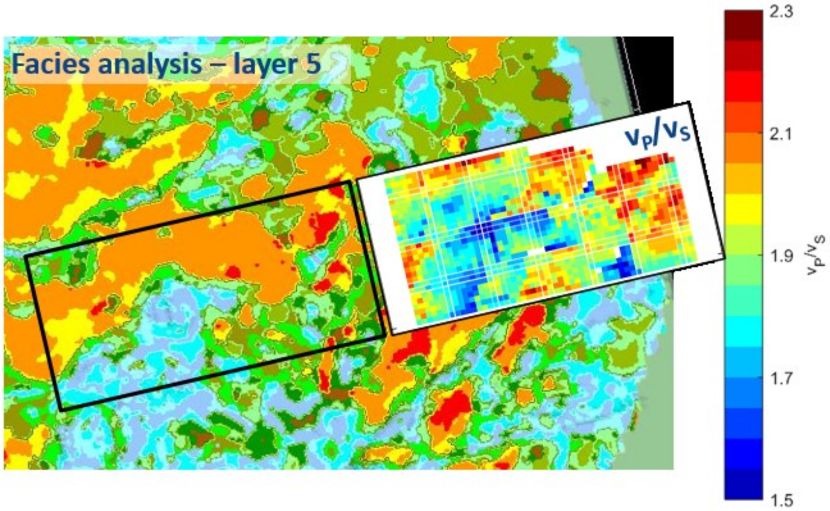


Figure 6: Comparison between facies analysis (in the same layer as displayed in Fig. 5) and V_P/V_S distribution is shown in the outlined area (black rectangular). The derivation of V_P/V_S is done based on the two ways travel time (TWT) difference of the Top Carbonate Platform and intra reservoir horizon. Note that the V_P/V_S ratio is strongly variable laterally, which is also seen in the facies analysis (Fig. 5). The dimensions of the rectangle outlined in black are 3.0 x 1.3 km.

To complement the information obtained from the V_P/V_S ratios on porosity trends as well as the results from the retro-deformation on the permeability structures of fault zones, current work focusses also on the porosity and permeability structures that result from the geological structures interpreted from the 3D seismic data. Hydrotectonic considerations of the main structural features in the study area such as relay ramps, horsetail splays, horst and graben structures as well as collapse structures (karst-related sinkholes - dolines) may also contribute to a better understanding of the overall permeability field related to these geological structures. Moreover, although carefully chosen, porosity-permeability relationships for the different carbonate facies classes are taken from the literature (e.g., Lucia (2007)). Well logging data as well as aquifer tests resulting from geothermal wells planned for May 2018 in the study area will reveal more insight into the porosity and permeability structures. As mentioned earlier, the model presented in this work builds upon an existing geothermal reservoir model (Dussel et al. 2016). An extensive geothermic and hydrogeological dataset concerning the study area has been described by Dussel et al. (2016). One of the main goals in the GeoParaMoL project is to improve and update the underground model in urban Munich (subdomain of the previously mentioned existing reservoir model) with the results of the 3D seismic survey conducted recently in unban Munich. This work also aims at improving geothermal reservoir characterization and modeling in the study region, which involves the adequate adjustment and matching of this subdomain into a bigger, regional geothermal reservoir model for the greater Munich region.

Fig. 7 shows one of the steps in the geothermal reservoir modeling workflow, where the geological structures and stratigraphy interpreted from the recently acquired 3D seismic dataset are embedded and discretized in the region of interest. Fig. 8 displays the temperature distribution in Top Upper Jurassic in the study area. As can be seen, the temperature increases towards the southeastern part of the area under investigation. This implies, from the geothermic viewpoint, that this region plays an important role in the optimization of geothermal multi-wells systems.

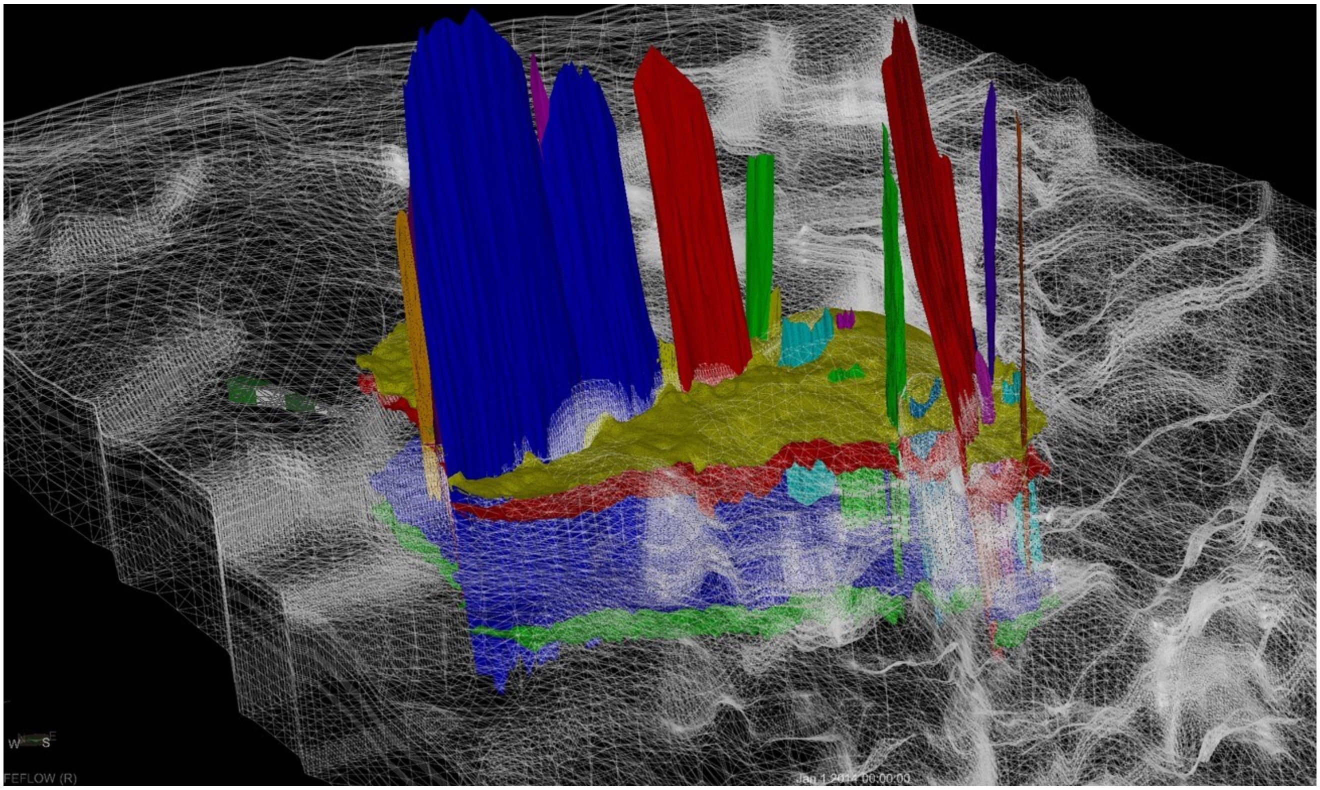


Figure 7: 3D view of the 3D grid with updated geological structures and stratigraphy based on 3D seismic interpretation in the area under investigation. The model consists of more than 3 million grid elements. Currently, a more detailed facies distribution is also being implemented.

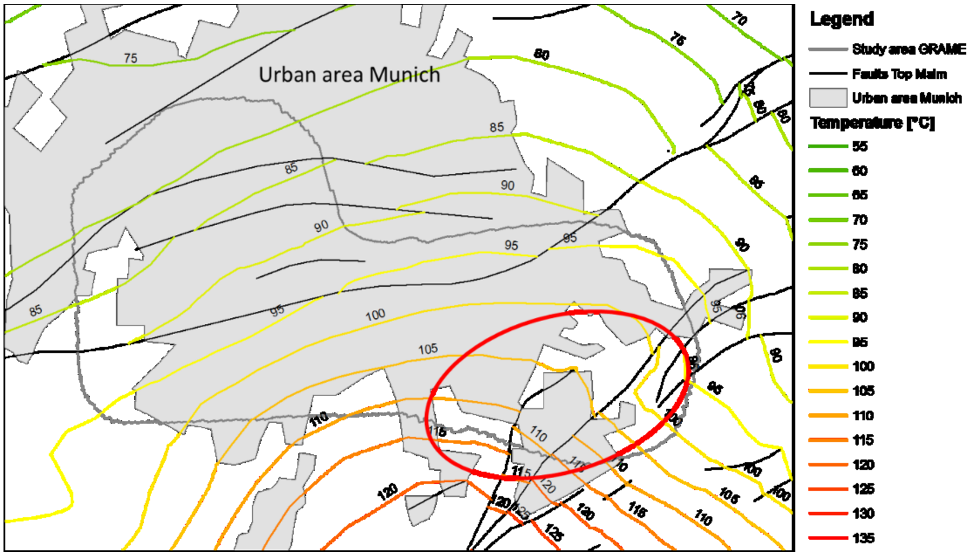


Figure 8: Temperature distribution in Top Malm from GeotIS (status 10/2017). The area marked with thick red line indicates the domain in the study area of highest temperature.

3. THERMAL-HYDRAULIC NUMERICAL MODEL IN POROUS, FRACTURED AND FAULTED RESERVOIR

FEFLOW 7.0 ® is the finite-element software that was used to model the long-term (~50 years) coupled thermal-hydraulic evolution of the Upper Jurassic aquifer affected by different geothermal doublet and triplet arrays as well as smart multi-well systems. In particular, the 2D analytical model introduced by Jobmann and Schulz (1989), which addresses the long-term thermal-hydraulic interaction of geothermal doublet arrays, is numerically, more realistically implemented in the 3D model. The fundamental equations describing the coupled thermal-hydraulic model in porous, fractured and faulted reservoir are based on the momentum (Darcy flow for porous medium and plane parallel Hagen-Poiseuille flow for fractured and faulted medium), mass or so-called continuity and energy balance equations (e.g., Diersch (2014) and references therein).

The transient groundwater flow equation results from the combination of the momentum and mass conservation equations and is given by:

$$S_0 \frac{\partial h}{\partial t} = \nabla \cdot \mathbf{q} + \mathbf{Q} \tag{1}$$

where S_0, h, t, $\boldsymbol{q}$ and Q are the specific storage due to fluid and medium compressibility (m^{-1}), the hydraulic head (m), the time (s), the fluid flux or Darcy velocity ($m\ s^{-1}$), and the fluid sources and sinks (s^{-1}).

The energy or so-called "temperature" equation is given by the diffusion-advection equation:

$$c_V \frac{\partial T}{\partial t} = \nabla \cdot \left(\boldsymbol{\lambda} \cdot \nabla \boldsymbol{T} - \boldsymbol{\rho}^f \boldsymbol{c}^f \boldsymbol{q} \boldsymbol{T} \right) + \mathbf{H} \tag{2}$$

where c_V, T, t, λ, ρ^f,c^f, $\boldsymbol{q}$, and H are the bulk volumetric heat capacity ($J\ m^{-3}\ K^{-1}$), the temperature (K), the time (s), the heat conductivity tensor ($J\ m^{-1}\ K^{-1} s^{-1}$), the fluid density ($kg\ m^{-3}$), the fluid heat capacity ($J\ m^{-3}\ K^{-1}$), the fluid flux or Darcy velocity ($m\ s^{-1}$) and the heat sources and sinks ($J\ m^{-3} s^{-1}$). Thermal, hydraulic boundary and initial conditions as well as parameters have been set according to the specific conditions in the region and are described in detail by Dussel et al. (2016).

4. MODELING RESULTS

Several scenarios of geothermal doublet arrays and different multi-well patterns have been modelled to evaluate the geothermal potential of the study area in urban Munich. Different patterns of doublet and triplet arrays were implemented and geometrical parameters as well as operational conditions (injection and production rate as well as injection temperature) were varied over a technically and site-specific reasonable range.

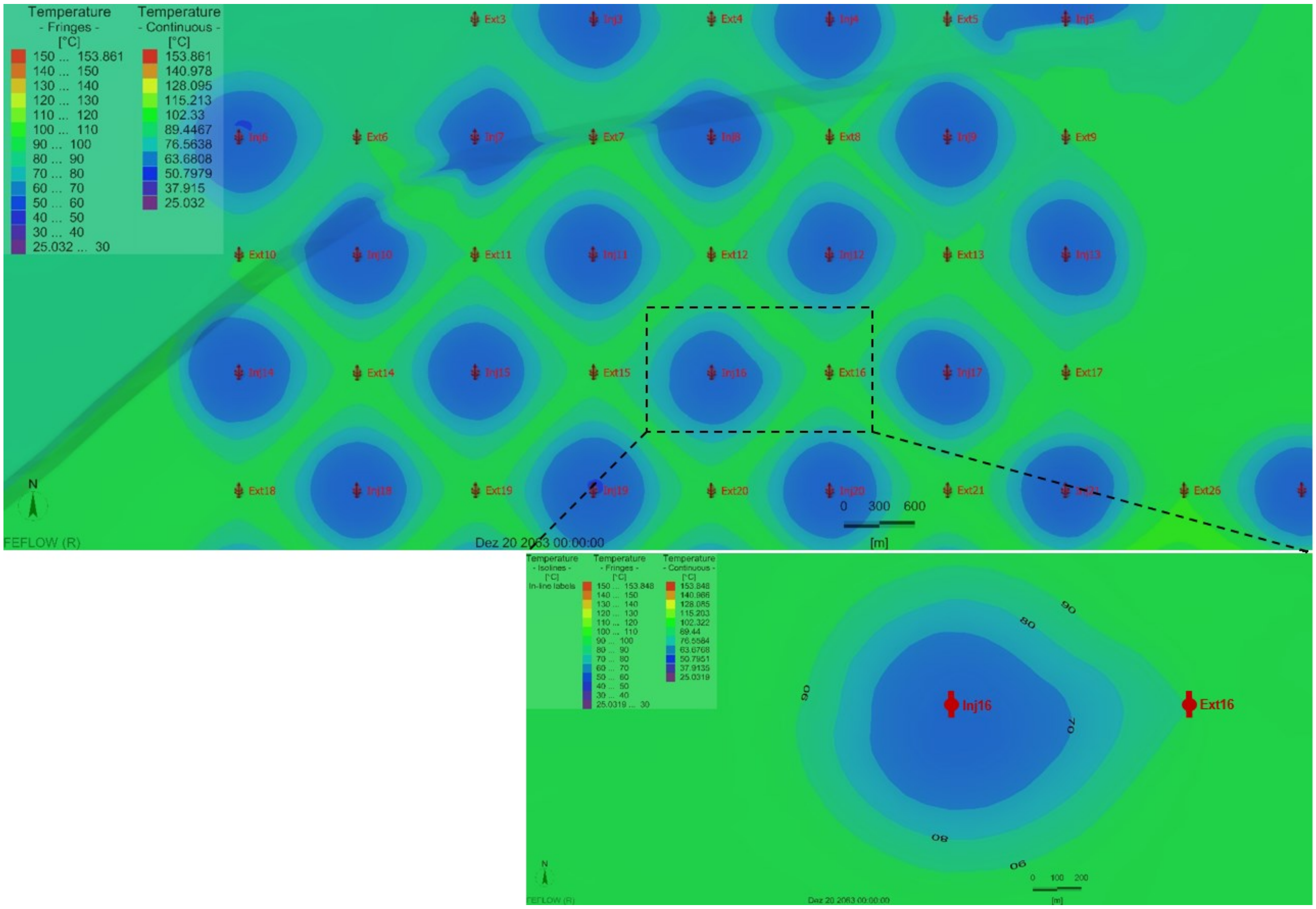


Figure 9: Temperature distribution in the first main influx zone after 50 years modeling time for a geothermal doublet array of 1 km lattice spacing, 80 l/s permanent injection and production rates and 60 °C water injection temperature. Note that in the case of a doublet array the thermal breakthrough is slowed compared to a single doublet (lower picture). Ext stands for extraction well (production well) and Inj stands for injection well.

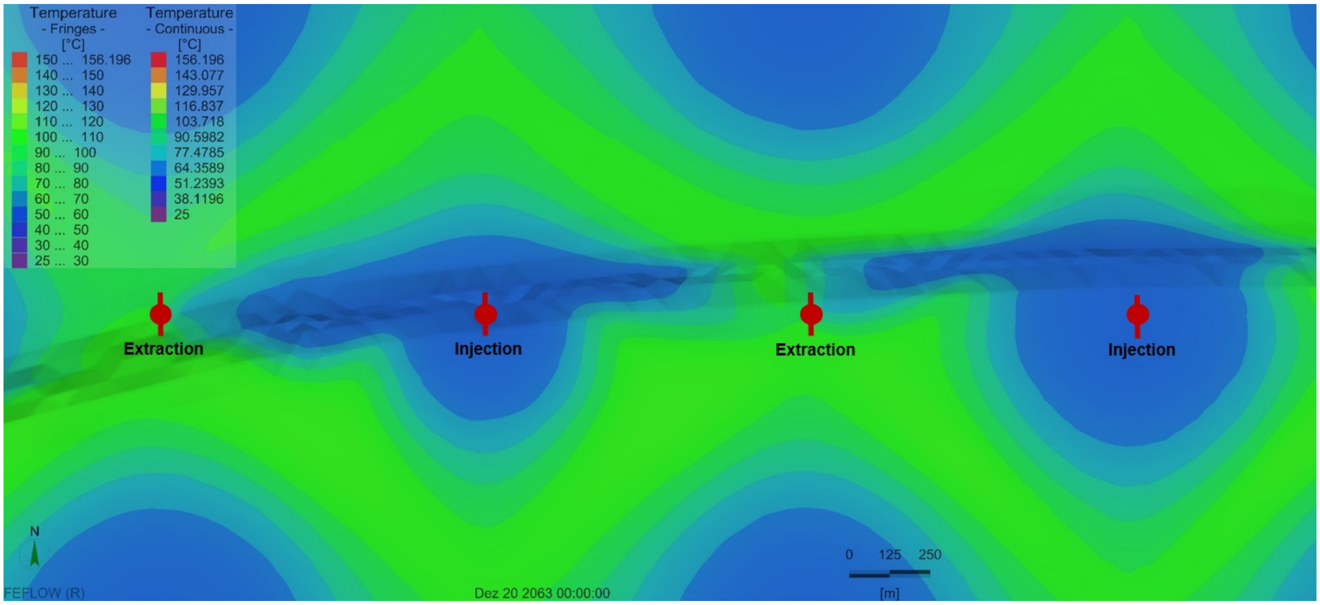


Figure 10: Temperature distribution in the first main influx zone along and across a major hydraulically active fault after 50 years of simulation time. 80 l/s of injection and production rates have been circulated for a geothermal doublet array of 1 km lattice spacing.

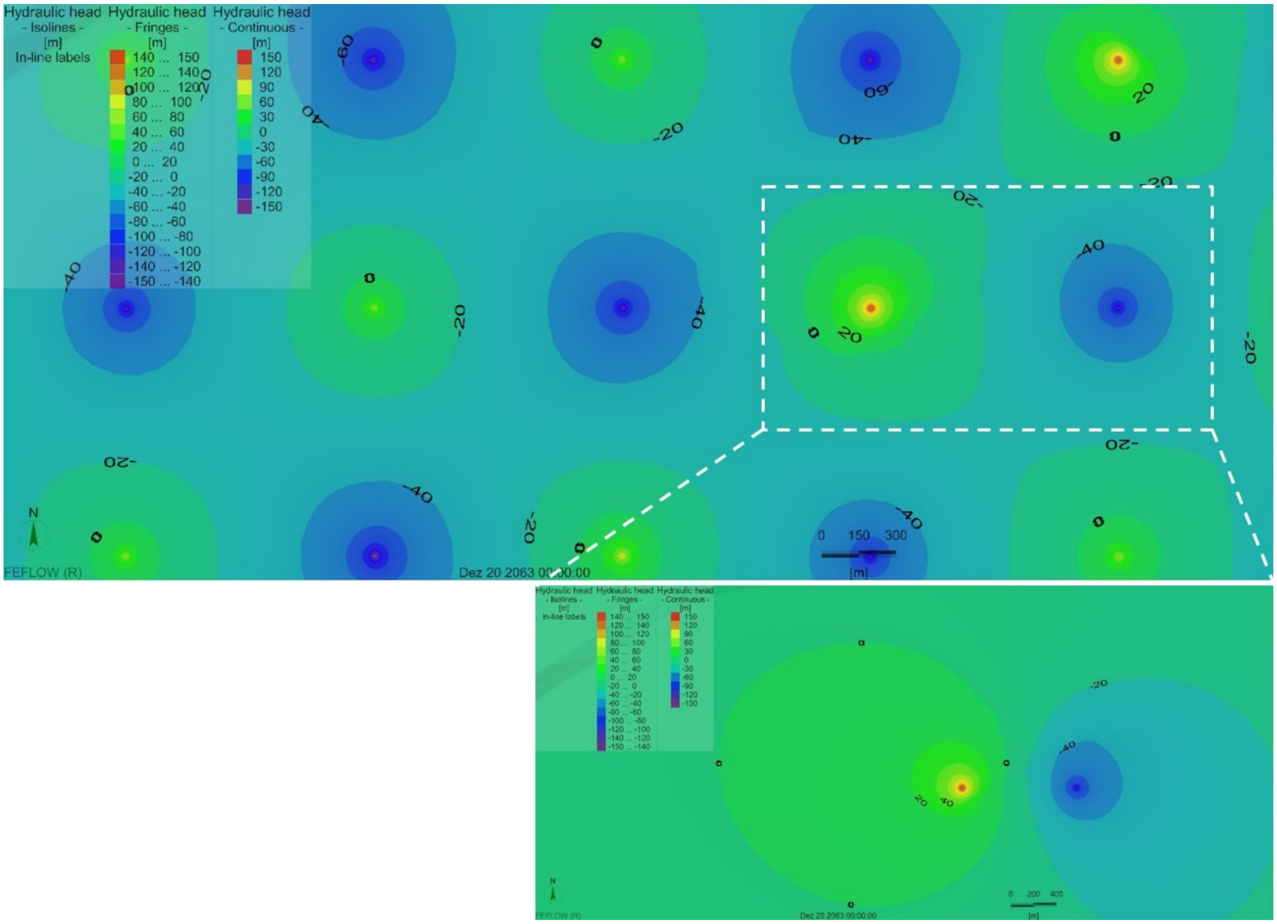


Figure 11: Pressure field (hydraulic head) in the first main influx zone after 50 years modeling time for a geothermal doublet array of 1 km lattice spacing, 80 l/s permanent injection and production rates and 60 °C water injection temperature. Note that in the case of a doublet array the pressure field shows advantages in case of a doublet array compared to a single doublet (lower picture) in terms of the extent of the pressure drawdown and buildup.

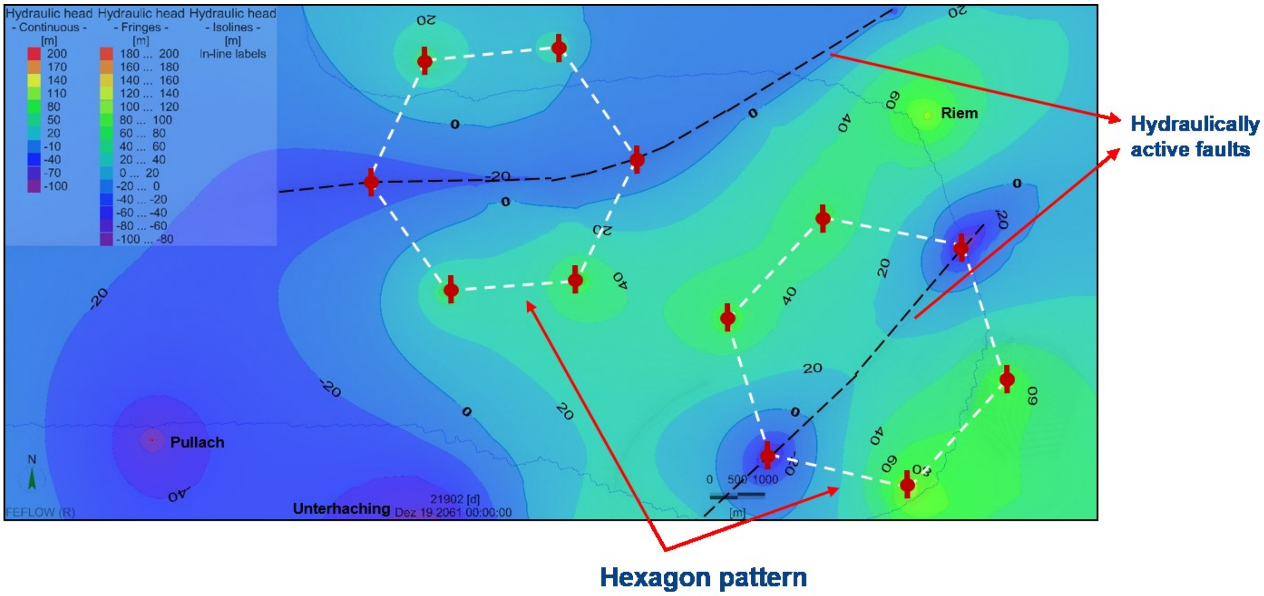
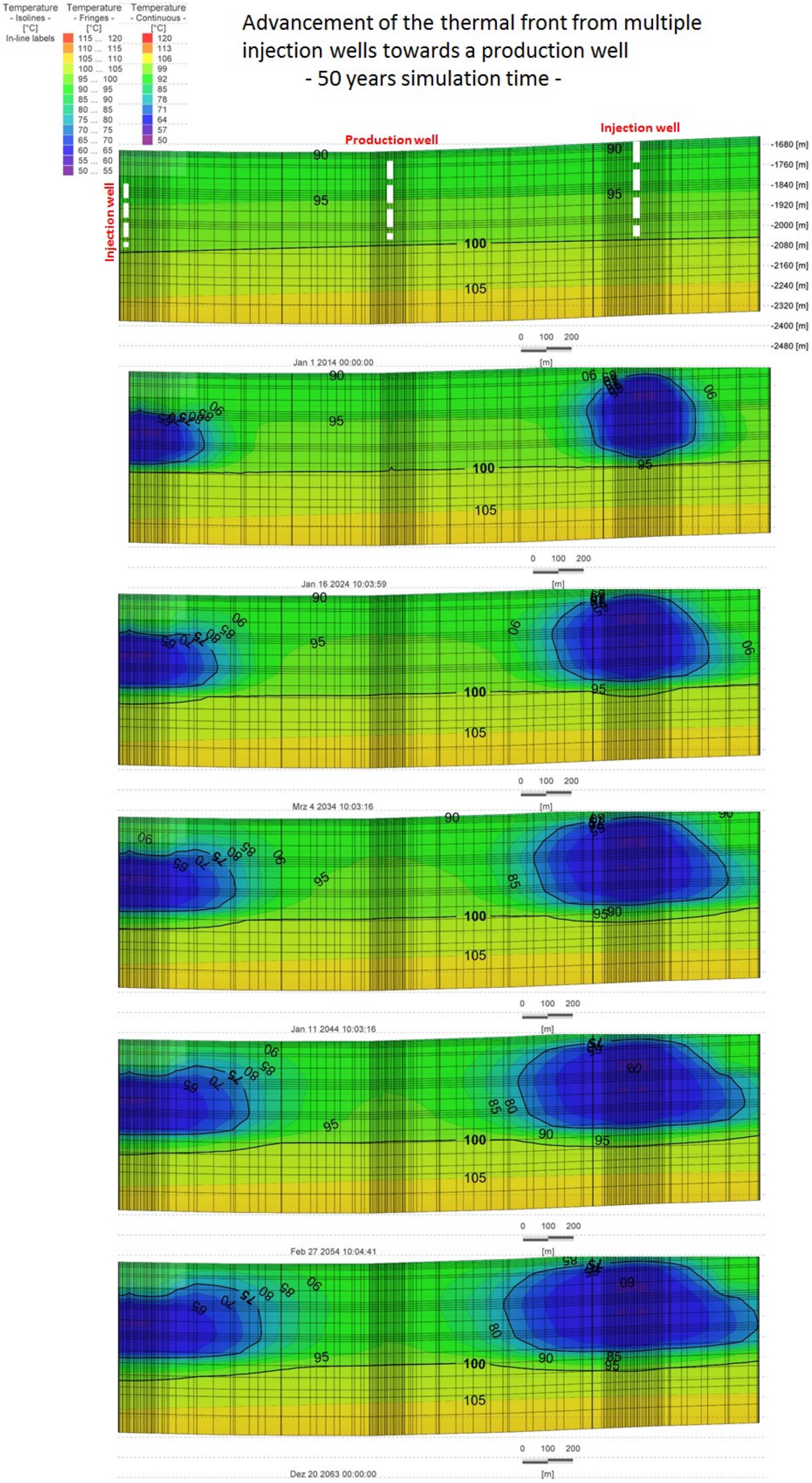


Figure 12: Pressure field (hydraulic head) in the first main influx zone for multi-well configurations (hexagon-configuration of 6 geothermal wells) after 50 years simulation time. Red symbols display injection and production wells. Different hydraulically-active faults are shown with black dashed lines. Note that production wells are placed in the fault zones while injection wells are placed around the faults. 150 l/s of thermal water has been constantly produced in each production well and 75 l/s of cooled thermal water has been permanently injected in the injection wells.

As can be seen in Fig. 9, 3D numerical results of long-term (~50 years) thermal-hydraulic interaction between injection and production wells in a doublet array confirm the positive influence concerning the thermal breakthrough of such geothermal doublet array compared to a single geothermal doublet, firstly addressed by means of a 2D analytical model developed by Jobmann and Schulz (1989). In contrast to a single doublet, where there is a preferential direction of flow velocity between injection and extraction well, in the case of such geothermal doublet array the four directions of flow velocity from the injection towards the production wells – the straight line connecting them - are equally (non-preferentially) distributed. Thermal-hydraulic numerical modeling also corroborates a delay of around 5% in the establishment of the thermal breakthrough in the case of a doublet array compared to a single doublet. This positive impact that results from such doublet array constellation makes at first glance the thermal lifespan of geothermal plants longer. However, as previously pointed out by Jobmann and Schulz (1989), modeling results show that once the thermal breakthrough is established, the temperature at the production well drops more rapidly than in the case of a single geothermal doublet. This is due to the contribution of the cold front from the four neighboring injection wells.

When it comes to optimizing a multi-well array, several thermal, hydrogeological, economic and technical aspects compete against each other resulting in a multi-variable optimization problem (e.g., Vörös et al. (2007) and Llanos et al. (2015)). In particular, the pressure difference between production and injection well should be minimized as well as the temperature drop at the production well. Fig. 10 shows the thermal impact of a hydraulically active fault in the study area on the lifespan of a randomly placed doublet array when the multi-well array is not properly placed around hydraulically active faults. It is clearly visible that the thermal breakthrough in this case is reached much faster, leading, in the worst case, to a thermal short-circuit. How much faster the thermal breakthrough is reached obviously depends on the permeability structure of the fault complex (fault core and damage zone), assuming that all other parameters are the same. The combination of such specific multi-well arrangements and realistic geological, hydrogeological and thermal conditions in highly heterogeneous reservoirs show how geological control factors and resulting permeability structures severely influence the optimization of multi-well patterns.

Another important aspect constitutes the near- and far-field pressure distribution that result from the constant injection and production of fluid in such geothermal doublet and triplet arrays as well as other multi-well systems such as hexagon patterns. Figs. 11 and 12 show the pressure field (hydraulic head) after 50 years modeling time caused by a geothermal doublet array and hexagon multi-well systems, respectively. Modeling results displayed in Fig. 11 illustrate the advantage of a geothermal doublet array over a single doublet. The pressure drawdown and build up caused by a single doublet is more widespread than the pressure field caused by a doublet array. In the case of a doublet array the pressure drawdown and build up caused by the production and injection wells counteract each other, resulting in a more spatially constrained pressure field. This, in turn, has a positive effect on existing neighboring geothermal wells already in operation for several years. A successful optimization of multi-well patterns in highly heterogeneous carbonate reservoirs not only depends on a fine characterization of the reservoir but also on the complex long-term thermal-hydraulic interactions of the multi-well array with existing neighboring geothermal wells already in operation. Moreover, the well spacing density plays a major role in the generated pressure far-field. Model results indicate that fluid flow regime in the entire region of greater Munich is highly controlled by such highly densely spaced doublet array.



Advancement of the thermal front from multiple injection wells towards a production well
- 50 years simulation time -

Figure 13: Vertical cross-sectional of the spatiotemporal evolution of the thermal front from two injection wells towards a production well (see Fig. 9, Inj15-Ext16-Inj16). The subsurface temperature disturbance due to the injection of 60 °C cooled water and hot water extraction is shown in 6 snapshots starting from 2014 (upper picture) up to 2063 (lower picture). As can be seen from the images, after 50 years of 80 l/s permanent water injection and extraction, the thermal breakthrough has not been reached for 1 km distance between injection and extraction wells.

A stationary flow regime is established a couple of years later after the onset of injection and production. Site-specific thermal and hydrogeological conditions make special multi-well design systems more appropriate than regular geothermal doublet arrays (Fig. 12). Fig. 13 shows a cross section of a typical spatiotemporal evolution of the cold front from one injection well towards two production wells along an imaginary straight line connecting them (Ext15-Inj16-Ext16 in Fig. 9). Especially the effect of the hydraulically stratified Upper Jurassic (Malm) aquifer in main influx zones is clearly visible. The shape of the advancing thermal plume (cold front) is controlled to a significant extent by the main influx zones within the Malm aquifer.

5. CONCLUSIONS

The optimization of geothermal multi-well patterns in a highly heterogeneous carbonate reservoir is a multi-variable optimization problem. A fine characterization of such reservoir is required to successfully optimize the spacing of geothermal doublet and triplet arrays. A recently conducted 3D seismic survey in urban Munich and the subsequent interpretation of the 3D seismic data substantially contribute to a better characterization of the geological structures, stratigraphy and facies distribution in the Upper Jurassic carbonate reservoir. This 3D seismic survey in urban Munich shows that this geophysical exploration tool constitutes an indispensable geophysical prospecting method for the foreland-basin geothermal play-type. Major stratigraphic horizons together with the detailed interpretation of the faults in the study area were used to construct a 3D geological model. Seismic classification is used with the help of seismic attributes to parametrize seismic reflections and to visualize the distributions of local sedimentary systems resulting in different carboniferous facies classes. The integration of shear waves was used to limit the range of lithological and petrophysical parameters. Preliminary results show a similar pattern of the distribution of facies classes and V_P/V_S ratios. The long-term thermal-hydraulic behavior (~ 50 years) of the Upper Jurassic aquifer affected by different geothermal doublet arrays and multi-well patterns has been numerically modelled with FEFLOW 7.0. Several scenarios with varying geometrical and operational conditions were implemented and numerically simulated. Preliminary thermal-hydraulic modeling results show that, for the considered simulation time, geothermal doublet arrays with a lattice spacing between 1 and 2 km and flowrates between 80 and 120 l/s are promising scenarios. In addition, model results indicate that geothermal multi-well configurations of 4 to 6 wells are under particular geothermal and hydrogeological conditions more appropriate. This later model result relates to hydraulically-active faults. Finally, modeling results suggest thermal and hydraulic advantages and disadvantages of geothermal doublet arrays over a single doublet. For instance, the use of geothermal doublet arrays leads to a significantly slower progressing thermal front (i.e., thermal breakthrough), but once the thermal breakthrough is reached the temperature in the production well drops more rapidly.

6. ACKNOWLEDGMENT

The GeoParaMoL project wouldn‘t have been possible without the financial support of the German Federal Ministry for Economic Affairs and Energy (BMWi). We thank specially the municipal energy supplier of the city of Munich (Stadtwerke München-SWM) for the active support as well as the firms DMT GmbH and Erdwerk GmbH for the fruitful collaboration.

REFERENCES

Diersch, H.-J.: FEFLOW: Finite Element Modeling of Flow, Mass and Heat Transport in Porous and Fractured Media, *Springer-Verlag* Berlin Heidelberg, (2014).

Dussel, M., Lüschen, E., Thomas, R., Agemar, T., Fritzer, T., Sieblitz, S., Huber, B., Birner, J. and Schulz, R.: Forecast for Thermal Water Use from Upper Jurassic Carbonates in the Munich Region (South German Molasse Basin), *Geothermics*, **60**, (2016), 13-30.

Jobmann, M. and Schulz, R.: Hydrogeothermische Energiebilanz und Grundwasserhaushalt des Malmkarstes im süddeutschen Molassebecken, *Abschlussbericht,* Band I, Archive Nr.: 105040, Niedersächsisches Landesamt für Bodenforschung, Hannover, Germany, (1989).

Llanos, E. M., Zarrouk, S. J. and Hogarth, A.: Simulation of the Habanero Enhanced Geothermal System (EGS), Australia, *Proceedings,* World Geothermal Congress, Melbourne, Australia, (2007).

Lucia, F. J.: Carbonate Reservoir Characterization: An Integrated Approach, 2nd edition, *Springer-Verlag* Berlin Heidelberg, (2007).

Lüschen, E., Dussel, M., Thomas, R., and Schulz, R.: 3D Seismic Survey for Geothermal Exploration at Unterhaching, Munich, Germany, *First Break*, **29**, (2011), 45-54.

Lüschen, E., Wolfgramm, M., Fritzer, T., Dussel, M., Thomas, R. and Schulz, R.: 3D Seismic Survey Explores Geothermal Targets for Reservoir Characterization at Unterhaching, Munich, Germany, *Geothermics*, **50**, (2014), 167-179.

Ringrose, P. and Bentley, M.: Reservoir Model Design: A Practitioner’s Guide, *Springer-Verlag* Dordrecht Heidelberg New York, (2015).

Tessmer, G. and Behle, A.: Common reflection point data-stacking technique for converted waves, *Geophysical Prospecting*, **36**, (1988), 661-688.

Vörös, R., Weidler, R., de Graaf, L. and Wyborn, D.: Thermal Modelling of Long Term Circulation of Multi-Well Development at the Cooper Basin Hot Fractured Rock (HFR) Project and Current Proposed Scale-Up Program, *Proceedings,* 32nd Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA (2007).