Geothermal reservoir modeling and simulation of the Upper Jurassic aquifer for district heating in the city of Munich (Germany)

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ABSTRACT

Geothermal district heating development has been gaining considerable relevance in Europe with a significant installed capacity and numerous projects currently under development. This work focusses on the Greater Munich region in Germany, which shows one of the most dynamic developments. Geothermal reservoir modeling, simulation and optimization of highly heterogeneous carbonate aquifers, thermo-hydraulically influenced by diverse multi-well configurations and well patterns, have received considerable attention in the last decades. In this study, the Upper Jurassic carbonates of the Bavarian Molasse Basin (Germany), which constitutes a porous, fractured and karstified geothermal reservoir that has been successfully exploited for geothermal energy in recent history, is modelled (static) and simulated (dynamic) in terms of the recoverable geothermal energy under different exploitation schemes for southern urban Munich (Germany). By means of analytical and numerical thermo-hydraulic modeling and simulation, current and future reservoir performance under diverse recovery strategies is examined.

1. INTRODUCTION

Geothermal district heating development has been gaining momentum in Europe with a significant installed capacity and numerous projects currently under development. In particular, the Greater Munich region in Germany shows one of the most dynamic developments (e.g., Bertani et al. 2017). Geothermal projects such as GRAME and GeoMaRE in the city of Munich are prominent examples of efforts taken to facilitate the German energy transition by substantially contributing to the decarbonisation of district heating networks in mega cities. The successful example of the geothermal energy development in the Greater Munich region (Fig. 1) makes it clear that considerable heat demand together with significant accessible geothermal resources and an economic, technological and political commitment to the transition to renewal energy are key ingredients for a sustainable and decarbonized district heating development. To this development, large companies such as the municipal energy supplier of Munich (Stadtwerke München - SWM) as well as large financial institutions substantially contributed. According to the SWM's district heating vision, the heat demand of the city of Munich should be met by 2040 completely by renewable energy. To accomplish this, geothermal energy extracted from the Upper Jurassic carbonate formation should contribute most to the heat transition in the city of Munich. Numerous geothermal extraction and production wells are planned by 2040 in the city of Munich.

Geothermal reservoir modeling, simulation and optimization of highly heterogeneous carbonate aquifers, thermo-hydraulically influenced by diverse multi-well configurations and well patterns, have received considerable attention in the last decades. The Upper Jurassic carbonate reservoir of the Bavarian Molasse Basin (Germany) constitutes a karstified, faulted and fractured reservoir that has been successfully exploited for geothermal energy in recent history. Both aspects are addressed in this work.

As new static and dynamic data becomes available, the geothermal reservoir has to be updated and further refined. In this work, the structural and facies models that result from the 3D seismic interpretation of the subsurface below the GRAME region in southern urban Munich together with data on petrophysical properties is integrated and assimilated in a reservoir model. To create a robust 3D tetrahedral mesh capable of handling numerical dynamic reservoir simulations, great efforts are taken to properly mesh complex geological structures containing a relatively large number of intersections (fault-fault and fault-horizon intersections). Furthermore, the recoverable geothermal energy is estimated by implementing diverse grid-shaped arrangements of geothermal doublets in the Upper Jurassic aquifer in southern urban Munich. In addition, optimized exploitation concepts and sustainable reservoir management are analysed using 3D numerical thermo-hydraulic modeling and simulation.

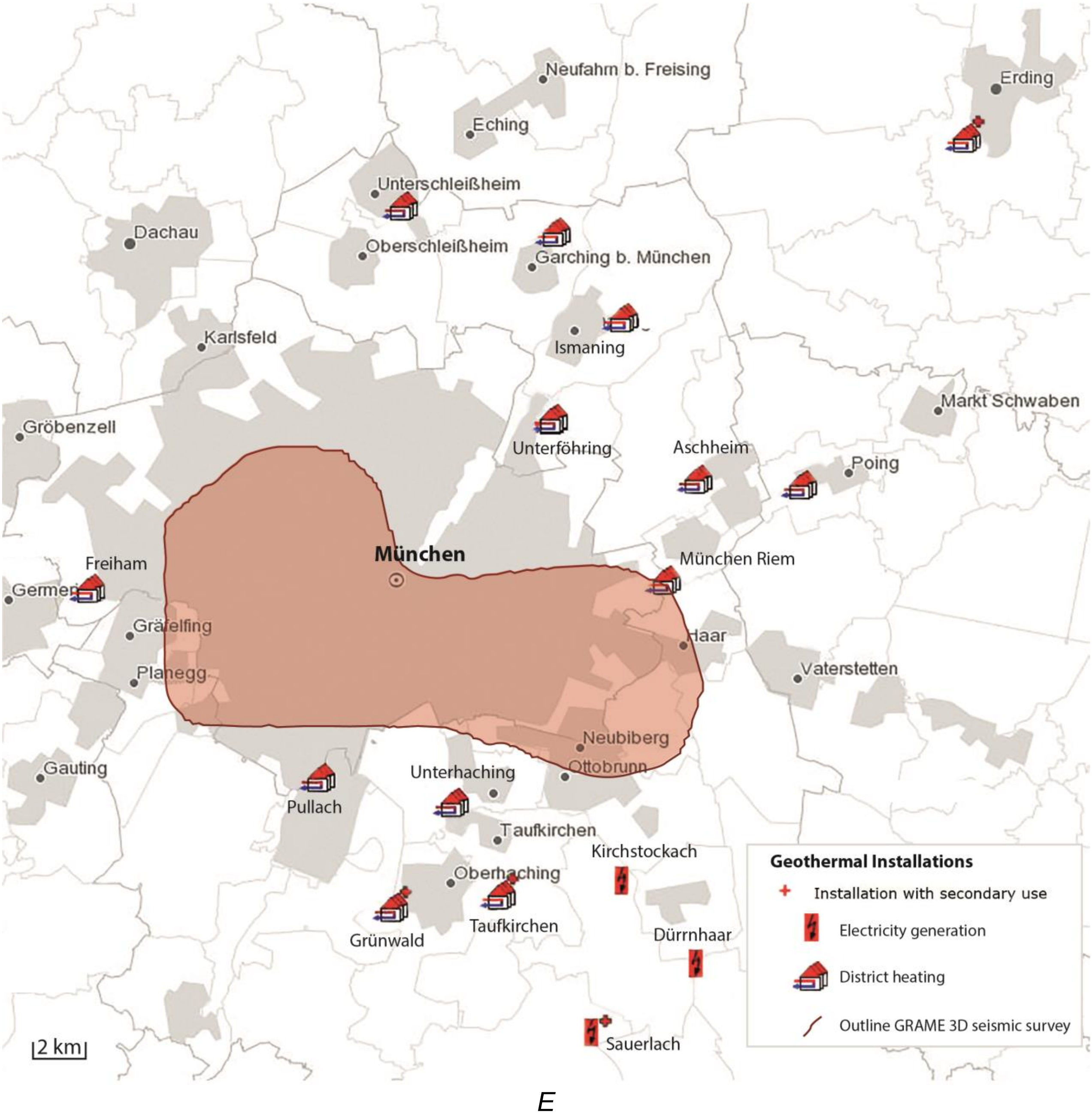

Figure 1: **Map displays existing deep geothermal facilities under operation for several years in the Greater Munich region. Note that both electricity and heat are being produced. Each geothermal plant consists of a doublet or a triplet. In the case of Unterföhring geothermal plan, two doublets are implemented. The study area, which encompasses an area of approximately 170 m^2 of the city of Munich, is marked with a thick reddish polygon and constitutes the exploration field of a recent 3D seismic survey (GRAME region). The dataset obtained in this 3D seismic campaign constitutes the basis for the 3D seismic interpretation: Structural and stratigraphic analysis as well as facies analysis. This picture is obtained from the freely accessible web-based interactive geothermal information system GeotIS (http://www.geotis.de) and subsequently modified.**

2. BUILDING THE RESERVOIR MODEL

Key geological controls on fluid flow and heat transport in general in geothermal reservoirs are a major focus of analysis when it comes to capturing the major geological features contributing to reservoir compartmentalization. The segregation of recoverable fluid/heat accumulation into several single fluid/pressure compartments is caused by the prevention of flow across sealed boundaries in the reservoir (e.g., Jolley et al. 2010). In the last decades it has become increasingly evident that reservoir compartmentalization is a consequence of a combination of multiple geologic factors such as hydrostratification, sealed faults or hydraulically active faults, facies distribution and diagenesis to mention a few. Rough tectonic interpretation and understanding the rough depositional environment are key ingredients for the construction of reservoir models and represent an important part of this work. Capturing key heterogeneities at different scales that affect reservoir connectivity is fundamental for the assessment of reservoir performance. As mentioned before, sealing faults, facies boundaries and internal sedimentological layering act as baffles to flow when the permeability contrast is considerable (e.g., Aminzadeh and Dasgupta 2013, Cannon 2018).

Another important aspect in the context of building a reservoir model relates to the data availability during the entire life cycle of a reservoir. As new data becomes available, the reservoir model has to be updated. As can be seen in section 3.2, the integration of diverse structural, stratigraphic, hydrogeological and geothermal data together with dynamic reservoir simulation has led to a 3D geothermal reservoir model of the Upper Jurassic aquifer in the Greater Munich region (Dussel et al. 2016, and references therein). The 3D seismic campaign conducted during the wintertime 2016/2017 in southern urban Munich, which is a subdomain of the Greater Munich model, provides valuable data for building a more resolved stratigraphic, structural and facies model in that subdomain (e.g., Buness et al. 2019, von Hartmann et al. 2019). An important part of this work focusses on the construction of a static geothermal reservoir model, going through the entire workflow of building a stratigraphic and structural model, a facies model, a 3D water-tight robust mesh capable of handling dynamic reservoir simulations, and a property model (see also chapter 4). It is noteworthy that at this stage of data availability in the GRAME region in the city of Munich, a relatively simple 3D reservoir model is built.

Since normal faults and reef-/mass facies (swell facies) constitute preferential geothermal reservoir targets in the Upper Jurassic aquifer in the Bavarian Molasse basin, the following subsections briefly describe the geological structures that play a considerable role in controlling fluid flow in the Upper Jurassic formation in the GRAME region (urban southern Munich).

2.1 Structural and stratigraphic interpretation based on 3D seismic data

Structural and stratigraphic controls on the permeability structure of the Upper Jurassic geothermal reservoir in the GRAME region need to be elucidated. According to Siler et al. 2019, it is critically important to adequately characterize the structural and stratigraphic geometries of geothermal reservoirs in complex geological settings (e.g., Ziesch et al. 2018). Especially in blind geothermal systems such as those present in foreland geothermal play types, where fault intersections and fault terminations may represent important geothermal targets, the 3D geological representation and precise characterization of subsurface information is of great importance.

As for the structural and stratigraphic part, a geological 3D model was created with the software SKUA-GOCAD based on a 3D seismic interpretation with the software Petrel, containing seven stratigraphic horizons and about twenty-four faults (Fig. 2). The structural inventory consists of synthetic and antithetic normal faults with offsets up to 350 m. One of the main faults constitutes the Munich fault (part of the Markt-Schwabener Lineament), which splits towards the east into smaller and smaller segments. This observation, as well as the interpretation of horsetail structures and relay ramps, leads to the conclusion that most major faults in the study area have strong strike-slip kinematics (e.g., Buness et al. 2019).

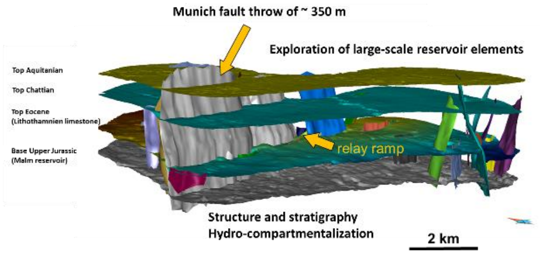

Figure 2: 3D geological model based on 3D seismic data interpretation in southern Munich (GRAME region, see Fig. 1). Only four out of seven interpreted stratigraphic horizons and around 24 faults are displayed.

Further structural elements such as sinkholes, hook and horst/graben structures show the complexity of the study area and suggest that increased deformation is also to be expected on the sub-seismic scale. All these structures potentially facilitate fluid flow and may represent important geothermal drilling targets.

2.2 Facies interpretation based on 3D seismic data

There exist extensive literature and abundant knowledge on facies and diagenesis of the Upper Jurassic carbonates from petrofacial investigations with cuttings, borehole measurements and reservoir outcrop characterization in the Frankonian and Swabian Alp (e.g. Dussel et al. 2016, Buness et al. 2019, von Hartmann et al. 2019 and references therein).

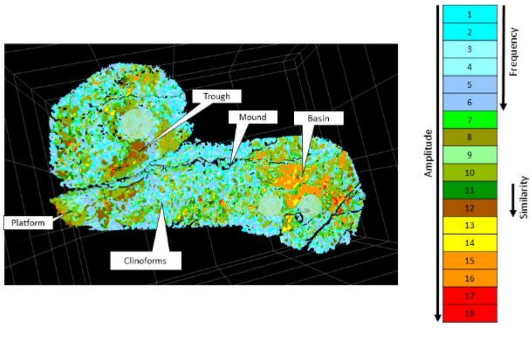

Figure 3: Seismic attribute classes of the fifth layer (out of 8 layers) inside the Upper Jurassic.

The colour code used is displayed on the right hand side. Frequency and similarity attributes repeat along the colour bar.

Based primarily on 3D seismic data interpretation in the GRAME region, the following approach is adopted for the seismic facies analysis: The Upper Jurassic units were divided vertically into 8 layers, each of them with a thickness of around 70 m. Within every layer and for every bin the following three seismic attributes were computed: (1) dominant frequency, (2) amplitude and (3) similarity. The range of dominant frequencies and amplitudes were divided into three intervals and the similarity into two intervals. A careful scrutiny of the results indicated a strong correlation between amplitudes and similarity values, i.e. small amplitudes show less similarity and vice versa. In this case, a further division of amplitude values according to similarity was performed. Taken together, this led to 18 independent combinations (Fig. 3), which are subsequently colour coded and projected on top of each layer.

3. ANALYTICAL AND NUMERICAL METHODS USED

For the assessment of the recoverable geothermal energy as well as for the long-term sustainable reservoir management, basically two approaches are chosen. The analytical principle model proposed by Jobmann and Schulz 1989 is used to examine the advantages and disadvantages in terms of positive and negative thermo-hydraulic interferences that grid-shaped arrangements and multi-well configurations of geothermal doublets may have within such configurations an with adjacent geothermal wells already in operation for several years. Besides, covering an exploration field such as the GRAME study region in the city of Munich with such multiple arrays of geothermal doublets enables to estimate the recoverable geothermal energy and the optimized reservoir management. Such geothermal well patterns are implemented in a 3D geothermal reservoir model that has been built for the Greater Munich region (Dussel et al. 2016, and references therein). This 3D reservoir model integrates and reconciles data from diverse measurements with differing resolution and accuracy. During the life cycle of a reservoir, as new static and dynamic data become available as is the case of the newly acquired 3D seismic data related to the Upper Jurassic carbonate reservoir in the GRAME region in southern Munich, the reservoir model is refined in terms of incorporating key reservoir heterogeneities such as vertical zonation, lateral compartmentalization and anisotropy or directional fluid flow.

3.1 Analytical principal model

When it comes to assessing the recoverable geothermal energy in hot sedimentary aquifers at regional scale by geothermal doublet operational schemes, one of the first and most relevant works applied to the Upper Jurassic aquifer in the South German Molasse Basin was carried out by Jobmann and Schulz 1989. Fundamentally, this analytical and physically-based work provided the prerequisites for a comprehensive, economically relevant realization of the geothermal energy supply for the area of the southern German Molasse Basin. The main goal of Jobmann and Schulz 1989 was to determine as accurately as possible the recoverable geothermal energy from the deep groundwater of the Upper Jurassic aquifer in the above mentioned area. To accomplish this, the study area was covered with an array of geothermal doublets (Fig. 4). For the longest possible life time of such doublet arrays and in general multi-well systems, the distance between the boreholes should be as large as possible, however keeping the hydraulic connection between injector and producer.

Inspired by their district heating vision of turning Munich by 2040 into Germany’s first large city to develop its district heating completely from renewable energy, the municipal energy supplier of the city of Munich (Stadtwerke München – SWM) considered the principle model of geothermal doublet arrays developed by Jobmann and Schulz 1989 to evaluate and optimize 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 numerous deep geothermal wells by 2040.

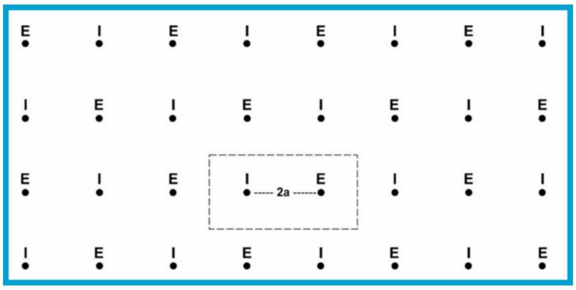

Figure 4: Principle model for a geothermal doublet array, modified after Jobmann and Schulz 1989. I and E stand for injection and extraction well, respectively. 2a denotes the distance between injection and extraction wells.

Alternatively, other reasonable well pattern and multi-well configurations can be implemented depending on the geothermal and hydrogeological settings as well as recovery concepts (Fig. 5). In particular, in the oil and gas field development, the use of different well pattern is widely spread for an optimized reservoir management (Onwunalu and Durlofsky 2011, Wendong et at. 2014, Wang et al. 2015, Zhang et. al 2015, Liu and Sun 2017, Qin et al. 2018). It is noteworthy that, in contrast to geothermal exploitation concepts, these geometric well configurations are intended to optimize the oil and gas recovery from hydrocarbon-bearing formations by sweeping the hydrocarbons towards the production wells through injection of fluid or gas.

In a geothermal context, in addition to the pioneering analytical work done by Jobmann & Schulz 1989, other numerical computations of multi-well configurations have been considered for different geothermal reservoirs (e.g., Vörös et al. 2007, Llanos et al. 2015, Willems et al. 2017a,b, Zhang et al. 2019).

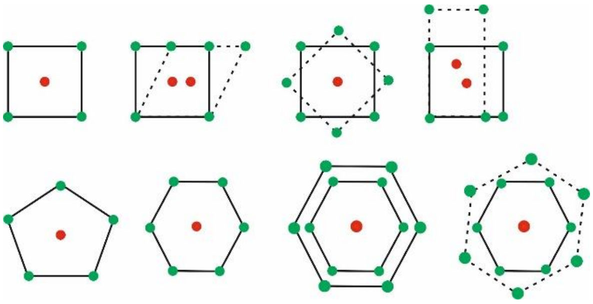

Figure 5: Different scenarios of multi-well configurations widely used in the oil and gas field development (modified after Zhang et. al 2015 and Onwunalu and Durlofsky 2011). Green points represent possible injection or production wells. Red points situated in the middle of such configurations also depict production or injection wells depending on the exploitation strategy or a common site from which multilateral well configurations of injection and production wells deviate.

Optimal geothermal field development strategies, in particular smart well locations and production strategies require a quantitative understanding of heat and fluid transport that result from relatively closely deployed multi-well patterns. To prove the exploitation concept of such wells arrangement, the long-term performance of hexagon and square pattern of geothermal wells have been computed for the habanero geothermal site in the Cooper Basin, Australia (Vörös et al. 2007, Llanos et al. 2015). Moreover, to evaluate the influence that the separation between the injectors and producers on the dimensions of geothermal concession fields, different geothermal doublet constellations have been numerically modelled for hot sedimentary aquifers in Holland (Willems et al. 2017a,b).

3.2 3D numerical thermo-hydraulic model of the Greater Munich region

Numerical dynamic reservoir modeling and simulation enable the investigation of geohydraulic and heat transport coupled processes in geothermal reservoirs. The geothermal potential, the optimized placement of geothermal wells and the search for sustainable and optimized reservoir exploitation concepts require numerically modeling phenomena of fluid flow and transport in heterogeneous porous and fractured geologic media. In particular, main objectives of numerical reservoir modeling and simulation constitute model calibration, history matching and forecasting future scenarios.

The broadly used groundwater modeling and simulation software FEFLOW 7.1 ® (e.g., Diersch 2014) is employed as finite-element software to model the long-term (~50 years) coupled thermo-hydraulic performance of the Upper Jurassic aquifer affected by different geothermal doublet and triplet arrays as well as smart multi-well patterns. In particular, the 2D analytical model introduced by Jobmann and Schulz (1989), which addresses the long-term thermo-hydraulic performance of multiple geothermal doublet arrays, is numerically, more realistically implemented in the so-called 3D Greater Munich model (Dussel et al. 2016). The latter consists of a numerical thermo-hydraulic 3D model of the geothermal Upper Jurassic aquifer (Malm) in the Munich region that has been developed based on interdisciplinary reservoir characterization (Fig. 6). At the time of development, this geothermal reservoir model included 13 deep geothermal plants with 28 wells. An important feature of this reservoir model is that it is hydraulically calibrated and history matched. Therefore, the predictive power of this geothermal reservoir model is highly valuable. Pressure and temperature changes caused by the continued operation of existing geothermal wells together with the assessment of the total geothermal potential of the reservoir are the main goals of this geothermal reservoir model. This 3D geothermal reservoir model of the Upper Jurassic in the Munich region incorporates regional geological elements such as structural geological elements, facies distribution, temperature distribution, hydrogeological and geothermal properties based on diverse 2D and 3D seismic interpretations, a considerable number of well logging analyses, borehole geophysical measurements, and measurements on plugs and cores from the Upper Jurassic aquifer. Data on aquifer tests and interference pumping tests were used to calibrate the reservoir model and this represents one of the most important parts of this 3D geothermal reservoir model. The model encompasses an area of about 57 km x 47 km (2679 km^2). In particular, carbonate sedimentological considerations as well as the fault and facies distribution led to vertical and lateral variations in the porosity and permeability distribution of the Upper Jurassic aquifer. After implementing well patterns, the 3D mesh contains more than 3.0 million elements and almost 2.0 million nodes. The 3D mesh exhibits high resolution around geothermal wells and in throws of the main fault zones to properly capture high hydraulic gradients. This work also includes the further development and improvement of this existing reservoir model on many levels. Recently acquired 3D seismic data in the GRAME region as well as yearly operational data of the geothermal wells in operation (pressure, injection and production rates and temperatures) contribute to the update and refinement of the static and dynamic reservoir model.

The fundamental equations describing the coupled thermo-hydraulic processes involved in the porous, fractured and karstified Upper Jurassic geothermal 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 laws (e.g., Diersch 2014 and references therein).

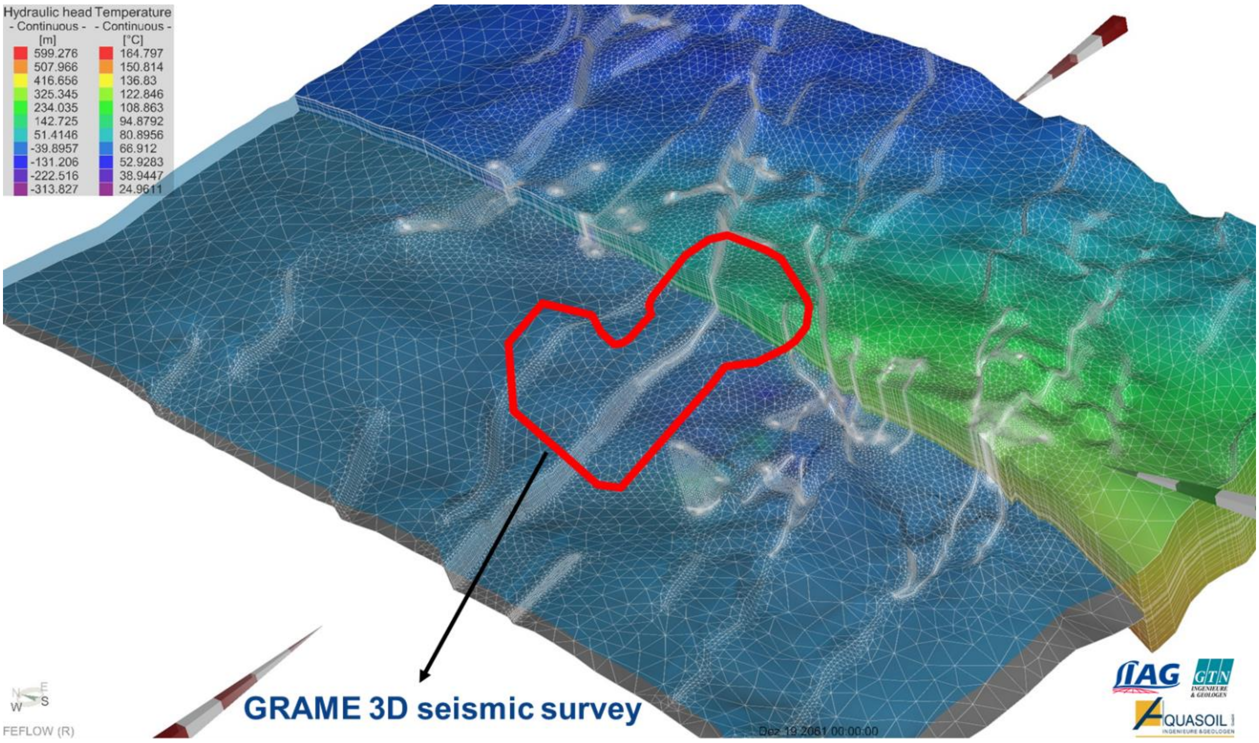

Figure 6: 3D numerical thermo-hydraulic model of the Upper Jurassic aquifer in the Greater Munich Region. Note the implemented geothermal doublets and triplets in zones with a high discretization resolution. Linear structures with finer mesh resolution represent existing faults. The area comprised in the red thick line corresponds to urban southern Munich, where a recent 3D seismic campaign was conducted.

4. RESERVOIR MODELING RESULTS (STATIC MODEL) FOR DYNAMIC FINITE-ELEMENT ANALYSES

To address dynamic finite-element reservoir simulation, volumetric estimations, well planning and production optimization the static reservoir modeling part has to be performed with these purposes in mind. Although some simplification and coarsening is needed, key heterogeneities affecting fluid flow and performance of the reservoir have to be captured. To start with, fault networks include only those faults that compartmentalize the reservoir. Other faults can be incorporated in a later phase of reservoir development and modeling. The grid quality and integrity is influenced by every single fault and in particular by the fault-fault and fault-horizon intersections (Fig. 7). Strict requirements are imposed to triangulated meshes, in particular at the fault-fault and fault-horizon intersections, for the construction of 3D tetrahedral volume meshes suitable for finite-element dynamic simulations. Finite-element modeling and simulation can be computationally intensive and time consuming. Constructing a consistent reservoir framework that can be gridded for 3D reservoir dynamic simulation is one of the most crucial steps in the reservoir modeling workflow.

The main objective of the facies model is to capture the main heterogeneities of the reservoir that result from the carbonate depositional model constrained by seismic attribute data. Facies boundaries act as hydraulic barriers to flow when the permeability contrast is considerable (Fig. 8). The main outcome is a grid that captures the internal reservoir geometry and constitutes the basis for modeling thermal and hydraulic properties.

A facies-constrained property model that represents the heterogeneity in the reservoir has been built in such a manner that the dynamics of fluid flow and heat transport can be simulated with reduced computational footprint (Fig. 9). Selecting the adequate method to distribute faces is a crucial step in the workflow of facies modeling. Essentially, the reservoir has been zoned in three main flow domains at this stage of reservoir development (Fig. 9). To make flow and heat transport simulations less computational expensive, the 3D grid resolution has been coarsened (grid upscaling). Volumetric calculations to estimate original, economically producible heat in place for the volume of interest has been done. Property modeling has been performed, populating the 3D grid with hydraulic and thermal properties (Fig. 10).

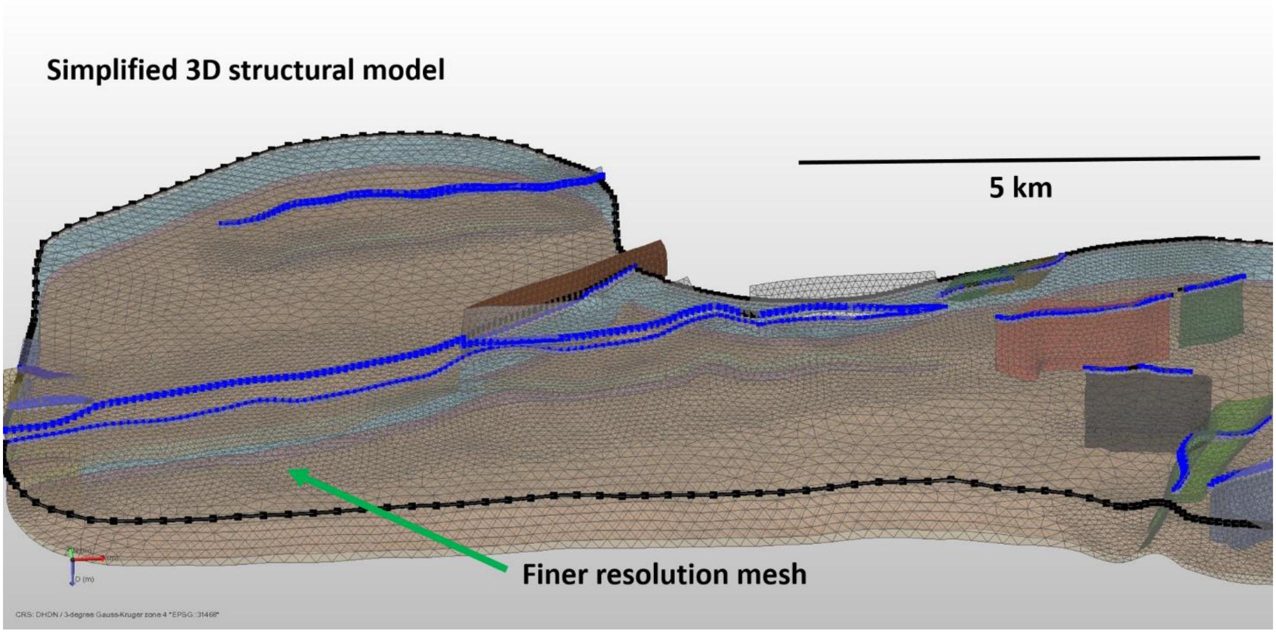

Figure 7: Triangulated mesh of the simplified structural model that contains main faults and horizons in the GRAME study area. Fault-fault and fault-horizon intersections have been properly handled, obtaining a "water-tight" mesh model with associated nodes, avoiding self-intersections. Triangulated meshes with high resolution in regions of particular interest and low resolution elsewhere are displayed. Homogenized and quality-controlled triangulated meshes are the basis for the 3D tetrahedral mesh.

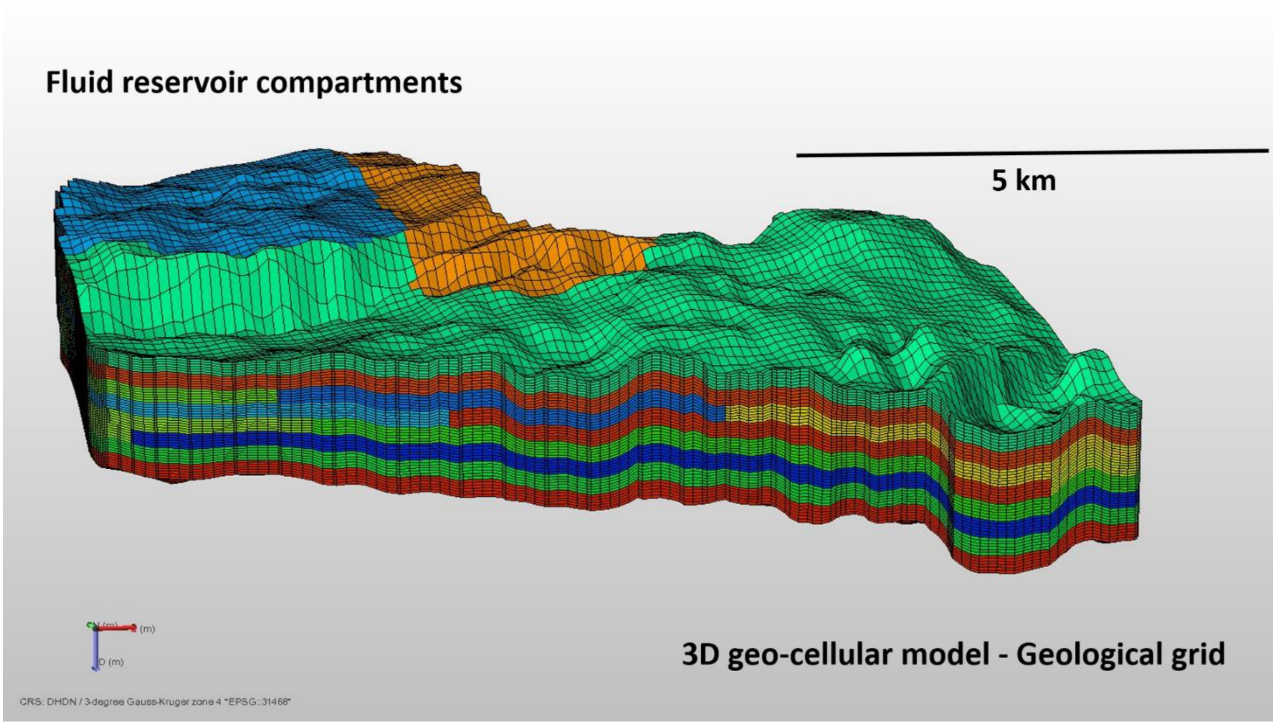

Figure 8: 3D reservoir compartments from the simplified facies model, following a facies modeling workflow. The Upper Jurassic aquifer has been divided vertically into 8 layers based on 3D seismic facies interpretation using the combination of different seismic attributes. Different carbonate sedimentary environments - laterally and vertically - have been recognized and modelled. Different colours represent different zones (reservoir compartments). At this stage of reservoir development, a simplified zonation in three different facies was done based on knowledge of the rough depositional environment.

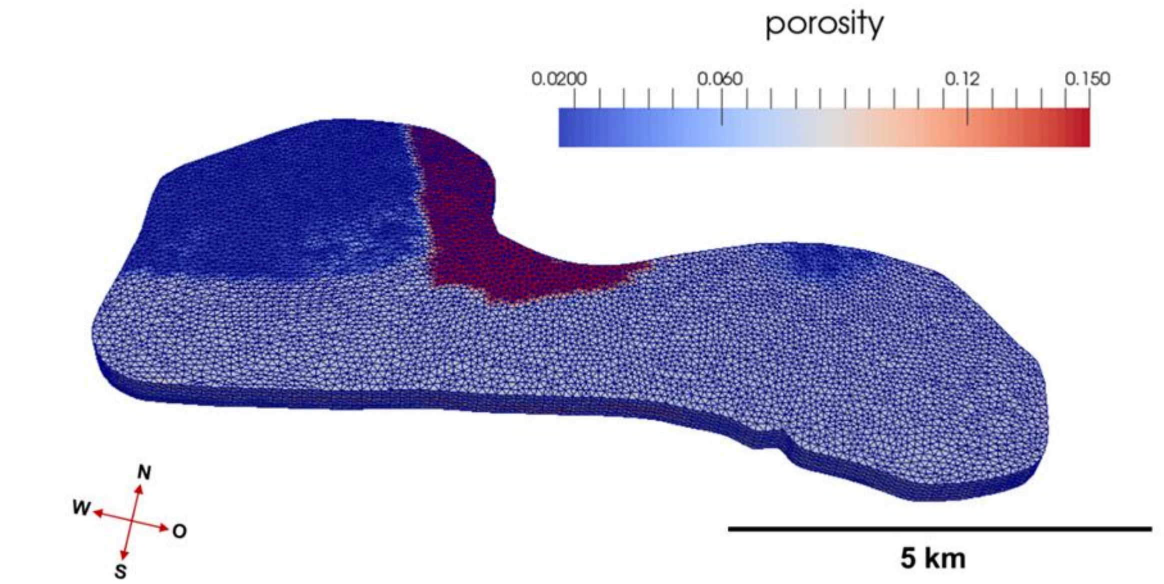

Figure 9: 3D tetrahedral volume mesh of the simplified facies model (reservoir compartments) of the Upper Jurassic aquifer for the GRAME investigation domain in Munich. TetGen has been used as mesh generator. The porosity distribution assumed for the simplified facies model is shown as an example for the petrophysical model (property model). The petrophysical model is based on carbonate sedimentological considerations in combination with 3D seismic interpretation and hydraulic and thermal values obtained from logging and laboratory data of the Upper Jurassic aquifer in the Greater Munich region (e.g., Dussel et al. 2016 and references therein). Each mesh element has been populated with porosity, hydraulic conductivity, specific storage coefficient, density, heat conductivity and volumetric heat capacity values.

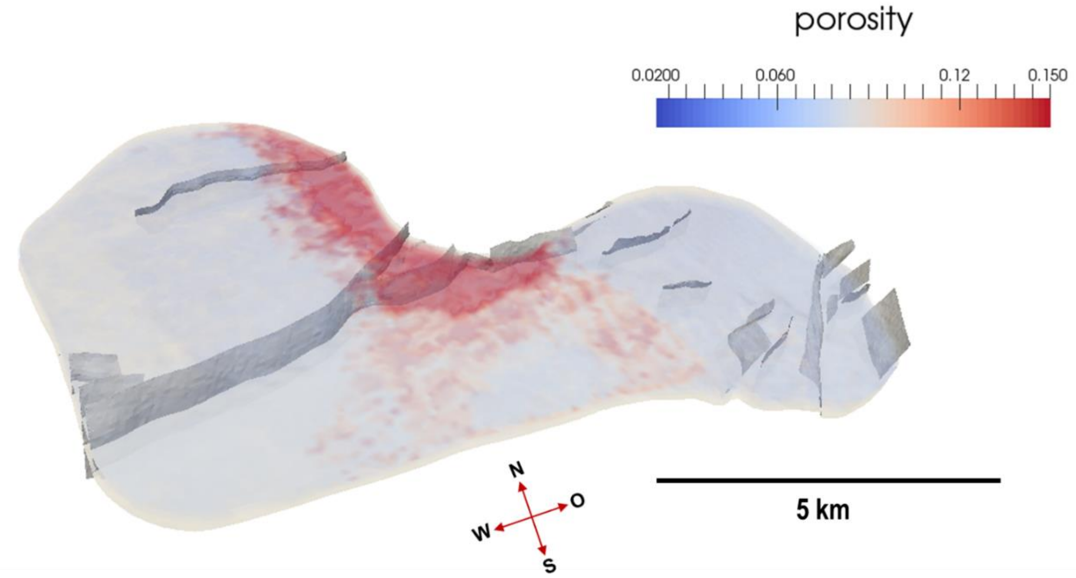

Figure 10: 3D simplified model of the Upper Jurassic reservoir in the GRAME study area in the city of Munich that integrates the structural and stratigraphic models, the facies and the property (petrophysical) models shown for the case of the porosity distribution (see Fig. 7, 8, and 9). Targeting high porosity compartments of the reservoir as well as high permeable compartments and hydrostratigraphic units is essential for optimal geothermal reservoir exploitation concepts. At this stage of data availability, a relatively simple model has been built. This model will be further refined as field development proceeds.

5. GEOTHERMAL RESERVOIR SIMULATION RESULTS

A considerable number of transient numerical thermo-hydraulic simulations with different grid-shaped arrangements of geothermal doublets and multi-well configurations (principle models) has been performed. Different exploitation strategies have been considered, varying the distance between injection and production wells, the injection and production rates and the reinjection temperature in the respective grid-shaped arrangements of geothermal doublets.

Geothermal reservoir management and the assessment of long-term sustainable reservoir exploitation strategies is analyzed by the implementation of diverse multi-well configurations and grid-shaped arrangements of geothermal doublets with different recovery concepts. Geothermal reservoir management is addressed in this work by studying the optimal placement of future wells in terms of positive thermo-hydraulic interference with neighbouring pre-existing geothermal wells already in operation for some years. A main focus is laid on the positive and negative thermo-hydraulic interferences that optimized multi-well configurations and geothermal doublet array may have among each other. Besides, the thermo-hydraulic interaction that such principle models of smart multi-well configurations and grid-shaped arrangements of wells may have with pre-existing geothermal wells already operating for several years in the immediate surroundings of the GRAME region is examined. Deploying such geothermal doublet arrays, covering southern urban Munich, also enables to make an estimate of the recoverable geothermal energy.

As can been seen in Fig. 11, geothermal reservoir performance depends on the key geological factors controlling heat transport caused by the extraction and reinjection of geothermal fluid by diverse deployment strategies of geothermal multi-well configurations and doublet arrays. Hydraulically active faults promote preferential flow and earlier thermal breakthrough but may delay the thermal breakthrough in other directions. Facies distribution also affects the spatiotemporal evolution of the cooling front at reinjection wells. Hydrostratigraphic units of the Upper Jurassic aquifer resulting from a vertical heterogeneous distribution of permeability influence considerably the shape and progress of the cooling front. Thermo-hydraulic modeling results suggest that major hydraulically active faults have a significant impact on the overall pressure drawdown and build-up that result from the hydraulic interaction of pre-existing geothermal wells with multiple arrays of geothermal doublets (Fig. 12).

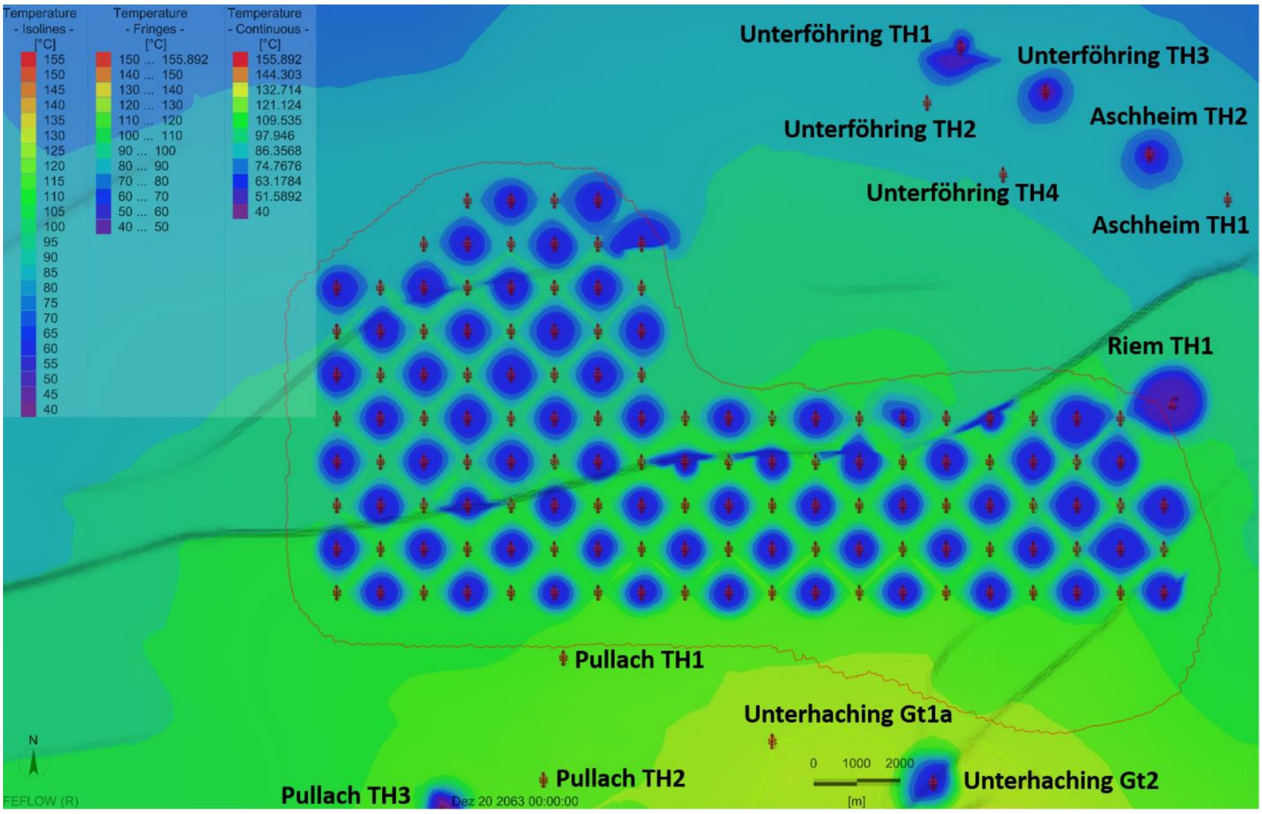

Figure 11: **Temperature distribution in the second main influx zone after 50 years modeling time for a grid-shaped arrangement of geothermal doublets of 1 km lattice spacing, 80 l/s permanent injection and production rates and 60 °C fluid injection temperature. Shaded linear structures represent major faults that compartmentalize the geothermal reservoir. Note that after 50 years of operation of such a principle model of geothermal doublets arrays the thermal breakthrough has not been established yet. Cross-symbols display location of extraction (production) and injection wells.**

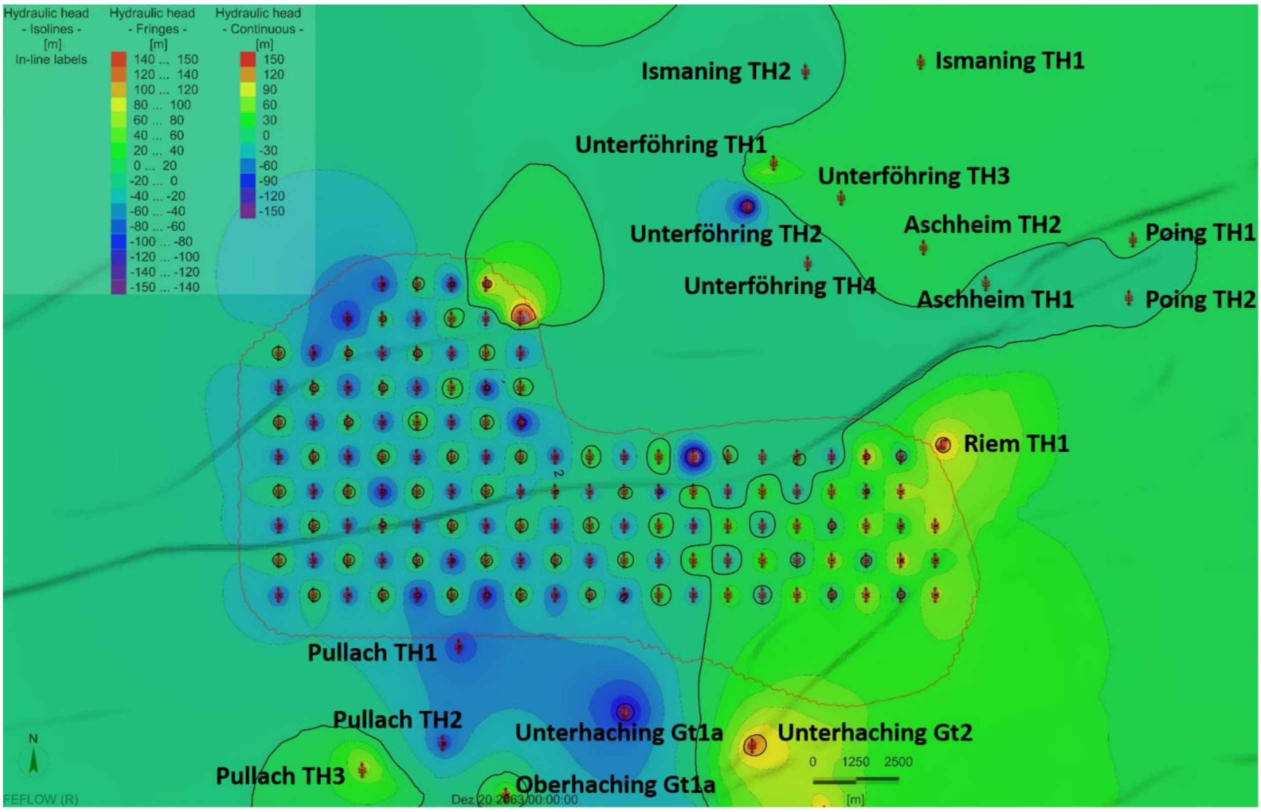

Figure 12: **Pressure field (hydraulic head) in the second main influx zone after 50 years modeling time for a grid-shaped arrangement of geothermal doublets of 1 km lattice spacing, 80 l/s permanent injection and production rates and 60 °C fluid injection temperature. Shaded linear structures represent major faults that compartmentalize the geothermal reservoir. Note the positive hydraulic interference of the geothermal wells within the grid-shaped arrangement (principle model) and the hydraulic interference with neighboring geothermal wells already in operation for some years. Cross-symbols display location of extraction (production) and injection wells.**

After 50 years of simulation time, around 60 m pressure build-up and drawdown result from the hydraulic interference of pre-existing neighbouring geothermal wells with grid-shaped arrangements of geothermal doublets for the scenario considered in Fig. 12.

Numerical modeling results demonstrate that grid-shaped arrangements of geothermal doublets with a geothermal well spacing between 1 to 2 km, injection and production rates between 80 to 100 l/s and reinjection temperatures of 50 to 60 °C are in principle possible well-placement designs that would deliver a thermal output of much more than 400 MW_{th}, as ambitioned by the municipal energy supplier of the city of Munich (SWM). Modeling results show that after 50 years of operation of multiple arrays of geothermal doublets the thermal breakthrough has not been established yet for 1 km well spacing, 80 l/s injection and production rates and 60 l/s reinjection temperature. After a couple years, the transient hydraulic state goes into a hydraulic steady state. Within such grid-shaped arrangements of geothermal doublets the pressure build-up and drawdown is more constrained than in the case of separate single doublets. This explains the numerical results indicating a delay in the establishment of the thermal breakthrough in the case of such grid-shaped arrangements of geothermal doublets than in the case of a separate single doublet (Meneses Rioseco et al. 2018).

6. CONCLUSIONS

The combined implementation of complex structural, stratigraphic and facies modeling for dynamic finite-element modeling and simulation has been achieved for the domain under investigation. However, the property model still has to be improved. Geological and geophysical data being currently gathered in the study area through multiple geothermal wells should contribute to a more detailed petrographic modeling. Properly updating geothermal reservoir models as new static and dynamic data are provided through the development of geothermal fields remain an ongoing effort. The numerical thermo-hydraulic modeling of various geothermal doublet arrays as well as multi-well systems within the 3D Greater Munich model enables optimal placement of future geothermal wells depending on well spacing, operating schemes, temperature distribution, permeability structure and adjacent geothermal plants. Modeling results show that geothermal energy can be used and operated sustainably for 50 years by the implementation of optimized geothermal doublet arrays and smart multi-well configurations. The heat transition in urban areas is possible since recoverable geothermal resources meet heating needs of big metropolises. Detailed numerical analysis, however, is required for optimized utilization concepts. 3D geothermal reservoir modeling and simulation of the Upper Jurassic aquifer in the Greater Munich region proved to be a strong tool for the reproduction of the historical development of the reservoir under the current exploitation strategies as well as for the quantitative assessment of reservoir future performance under different exploitation strategies. That way the sustainable reservoir management of the Upper Jurassic carbonates influenced by multiple geothermal wells can be quantitatively optimized for the Greater Munich region and in particular for southern urban Munich. This methodology for assessing the recoverable geothermal energy using optimized grid-shaped arrangements of geothermal doublets under diverse exploitation schemes can be applied to other hot sedimentary aquifers in urban cities.

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