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Sustainable Geothermal Energy Development for District Heating in Big Metropolises by Means of Optimized Geothermal Reservoir Management: A Case Study from Munich (Germany)

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Keywords: Deep geothermal energy; district heating; urban regions; geothermal reservoir modelling and simulation; 3D thermal-hydraulic numerical modelling; porous, fractured and karstified aquifer; Upper Jurassic carbonates; geologic controlling factors on permeability structure and on fluid and heat transport; thermal breakthrough; history matching; Greater Munich region; Germany.

ABSTRACT

Meeting the heat demand with renewable energy constitutes a joint endeavor made by many countries to reduce the carbon footprint in the energy sector. Since heat consumption represents more than 50% of the total energy consumption, providing a sustainable solution to the heat demand with renewable energy is of upmost importance. Specifically, deep geothermal energy utilization can significantly contribute to the decarbonization of district heating networks in urban cities where a considerable geothermal potential coincides with a large heat demand. The Bavarian Molasse Basin and in particular the so-called Greater Munich region, Germany has experienced in recent years one of the most dynamic developments in deep geothermal energy utilization. Remarkable efforts have been taken to provide heat to several villages in the outskirts of the city of Munich, where considerable heat is demanded. The successful case of geothermal energy development in the Greater Munich region evidences that substantial heat demand together with significant accessible geothermal resources and an economic, technological and political commitment to renewal energy are key elements for a sustainable and decarbonized district heating development. To accomplish this, major public or private companies such as the municipal energy supplier of Munich (Stadtwerke München - SWM) as well as central financial institutions extensively contributed. Based on the SWM's district heating vision, the heat demand of the city of Munich should be met by 2040 completely by renewable energy. To attain this goal, geothermal energy extracted from the Upper Jurassic carbonates should contribute most to the heat transition in the city of Munich. Multiple geothermal extraction and production wells are planned by 2040 in the city of Munich. The Greater Munich region is located in the Bavarian Molasse Basin, which classifies as a foreland basin and is one of the most studied foreland basins in the World. Because of recent geothermal exploration and production as well as previous intensive hydrocarbon exploration, extensive and detailed data on the subsurface has been collected to build a 3D thermal-hydraulic reservoir model. During the lifecycle of field development, as new static and dynamic data becomes available the reservoir model requires updating and refining. Subdomains of the reservoir, which have been modelled with less resolution at a regional scale due to lack of data, can be updated with more resolved and reliable data. Based on the 3D seismic survey conducted in southern Munich (GRAME-project) and subsequent interpretation of data, simplified structural, facies and property models fit for dynamic finite-element simulation have been constructed for that region. Besides, an optimized geothermal reservoir management involves the study of possible interferences of neighboring geothermal facilities. Ultimately, history matching of production and injection data with modelling and simulation results is a key ingredient in understanding the inter-well permeability structure and dynamics of the reservoir and thus hints at optimization aspects of field development. The occurrence of earlier than predicted temperature and/or pressure decline at production wells helps to study the possible causes of a premature thermal breakthrough and reservoir compartmentalization. This work concentrates on the study of the Poing, Taufkirchen and Kirchstockach geothermal doublets in order to examine the transferability and comparability of thermal-hydraulic modelling and simulation results in similar reservoir settings. A series of worst-case scenarios focused on the 3D thermal-hydraulic behavior of the reservoir by varying the permeability structure and under different exploitation schemes have been modelled and simulated. 3D thermal-hydraulic modelling and simulation results can be explained by the assumption of breached relay ramp structures that may have been further reworked by karstification processes, providing the permeability structure required. 3D modelling and simulation findings hint at channeled fluid flow between injection and production wells by high-permeability zones.

1. INTRODUCTION

Big cities and villages are distinguished by a high heat demand. Heat consumption represents a significant amount of the total energy consumption of countries. In highly urbanized regions where a huge heat demand coincides with a considerable geothermal potential, deep geothermal energy utilization can hugely contribute to the energy transition from fossil to renewable energy. The remarkable geothermal development in the Bavarian Molasse Basin and particularly in the so-called Greater Munich region in the last decades evidences the concerted and determined efforts in Germany to decarbonize the district heating networks in urban regions (see Fig. 1). The Bavarian Molasse Basin constitutes by far the most geothermally developed region in Germany (e.g. Agemar et al. 2014, Weber et al. 2019). Major public or private companies such as the municipal energy supplier of Munich (Stadtwerke München - SWM) as well as central financial institutions extensively contributed to the successful geothermal development in the Greater Munich region. As promoted by the SWM's district heating vision, the heat demand of the city of Munich should be satisfied by 2040 totally by renewable energy. To attain this goal, geothermal energy extracted from the Upper Jurassic carbonates should contribute most to the heat transition in the city of Munich. Outstanding examples of joint endeavors made by the SWM constitute the project GRAME (e.g. Buness et al. 2016) and the ongoing project GEOmaRE. Multiple geothermal extraction and production wells are planned by 2040 in the city of Munich. This implies the placement of multi-well arrangements (e.g. Meneses Rioseco et al. 2018, 2019) and a more detailed understanding of the reservoir behavior influenced by operating geothermal doublets and triplets. During the lifecycle of field development, as new static and dynamic data is gathered the reservoir model requires updating. Based on the recent 3D seismic campaign in Munich (GRAME seismic survey) and subsequent structural and facies interpretation, integrated structural, facies and property modelling has been conducted. Besides, history matching of production and injection data with 3D thermal-hydraulic modelling and simulation results has been carried out. By doing so, detailed knowledge and valuable insight into the reservoir structure and behavior at individual geothermal utilization sites can be gained. Moreover, the transferability of the thermal-hydraulic modelling and simulation results to other, neighboring geothermal facilities in similar reservoir conditions can be examined.

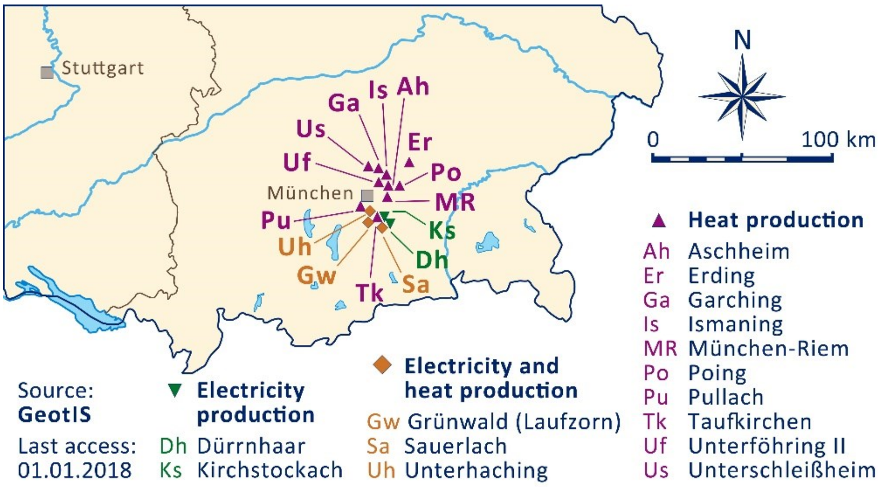

Figure 1: Map shows deep geothermal facilities already under operation for several years in the so-called Greater Munich region. Note that both electricity and heat are being produced. Each geothermal plant consists of a doublet or a triplet. Meanwhile two additional geothermal plants (Freiham and Holzkirchen) have gone into operation.

The Greater Munich region is situated in the Bavarian Molasse Basin, which classifies as a foreland basin and is one of the most studied foreland basins in the World (e.g. Moeck 2014, see Fig. 2). As a result, ample geological and geophysical data has been gathered on the structure and governing thermal and hydrogeological conditions in the basin. Particularly the Upper Jurassic aquifer as one of the most favorable geothermal reservoirs for the development of deep geothermal energy in middle Europe has been extensively studied (e.g. Dussel et al. 2016 and references therein).

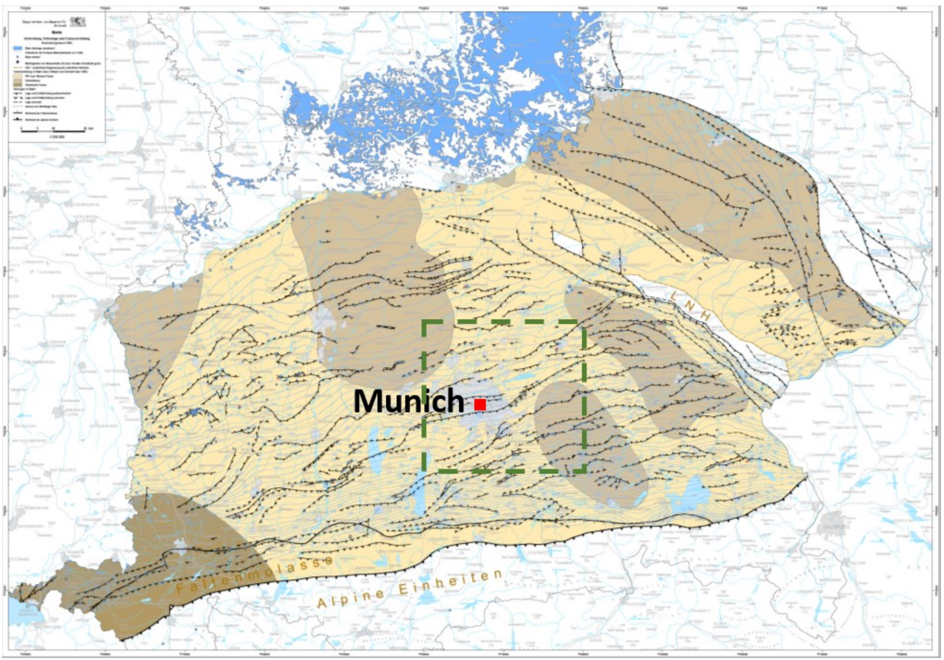

Figure 2: Map displays synthetic and antithetic faults in the Bavarian Molasse Basin. Note parallel faults to the Alpine front. Between parallel faults with normal and strike-slip displacement possible relay ramp structures may form. https://www.stmwi.bayern.de/fileadmin/user_upload/stmwivt/Themen/Energie_und_Rohstoffe/Dokumente_und_Cover/Geothermie/Geothermieatlas_Malm.pdf. Green dashed rectangle shows the region of Greater Munich. Map originates from the Bavarian Environment Agency (LfU), 07.11.2016 and has been subsequently modified.

This work focuses on the geothermal reservoir modelling and simulation of the Upper Jurassic geothermal aquifer in the Greater Munich region. Multiple scenarios of reservoir conditions and exploitation programs are realized to study their impact on possible thermal breakthroughs and/or pressure decline at the production wells of single operating geothermal facilities and future multi-well arrangements. These analyses aim at understanding the required reservoir conditions (e.g. permeability structure) and related geologic controls that would explain a possible earlier that predicted temperature and/or pressure decline at production wells.

2. GEOTHERMAL RESERVOIR MODEL OF THE UPPER JURASSIC CARBONATES IN THE GREATER MUNICH REGION

Concerted and interdisciplinary efforts over several years led to a full-field characterization and geothermal reservoir model of the Upper Jurassic carbonates in the study region (e.g. Dussel et al 2016, Schulz et al., 2015, 2012, see Fig. 3). Ample dataset, extensive 2D and 3D seismic data, facies analysis and well tests contributed to a detailed reservoir characterization. In addition, a three-dimensional hydrogeological model and a temperature model have been constructed to constraint the 3D thermal-hydraulic reservoir model (see Fig. 4 and 5). The numerical model was built with the simulation software FEFLOW (version 6.2) of the DHI-WASY GmbH Berlin and for the computations performed in this work it has been updated in the software version 7.2 (e.g. Diersch 2014).

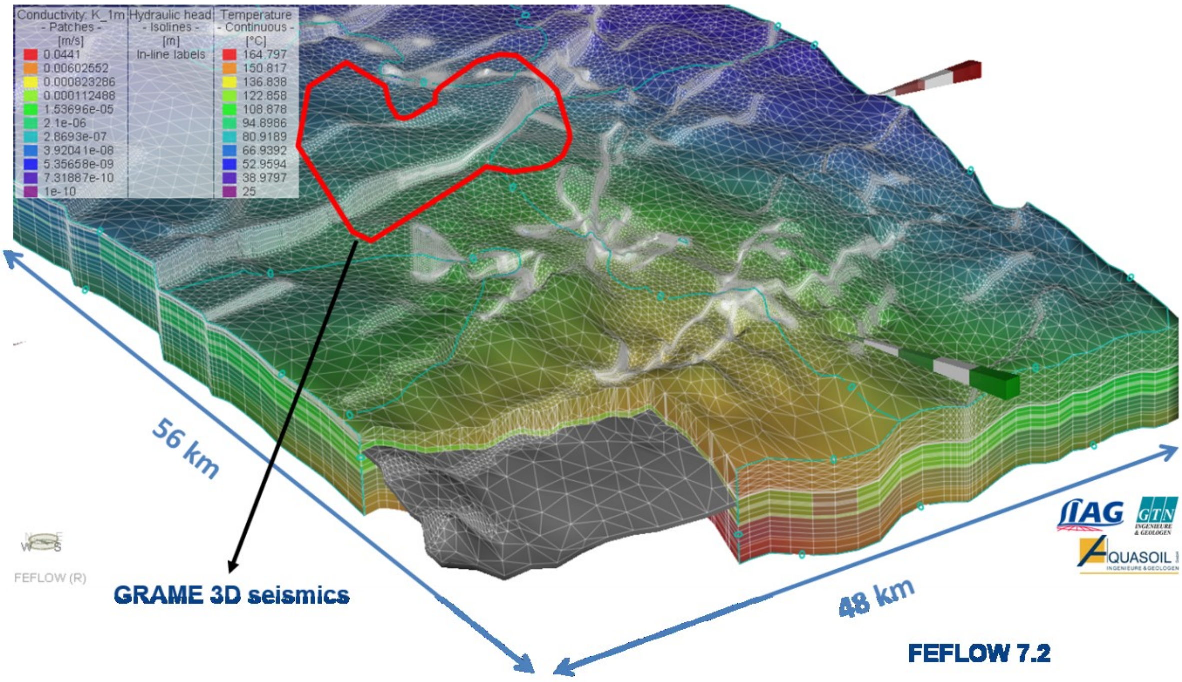

Figure 3: 3D finite-element, thermal-hydraulic reservoir model in the Greater Munich area. The model has been originally built with FEFLOW 6.2 (e.g. Dussel et al 2016, Schulz et al., 2015, 2012), subsequently modified with the incorporation of an unstructured mesh in the reservoir overriding layers and updated in FEFLOW 7.2. The main focus of this model, which was developed under the leadership of the Leibniz Institute for Applied Geophysics, is the approx. 600 m thick Upper Jurassic karstified and fractured aquifer in the central area of the Bavarian Molasse Basin under the influence of all the operating deep geothermal plants in the area (see Fig. 1). Red polygon shows the GRAME 3D seismics.

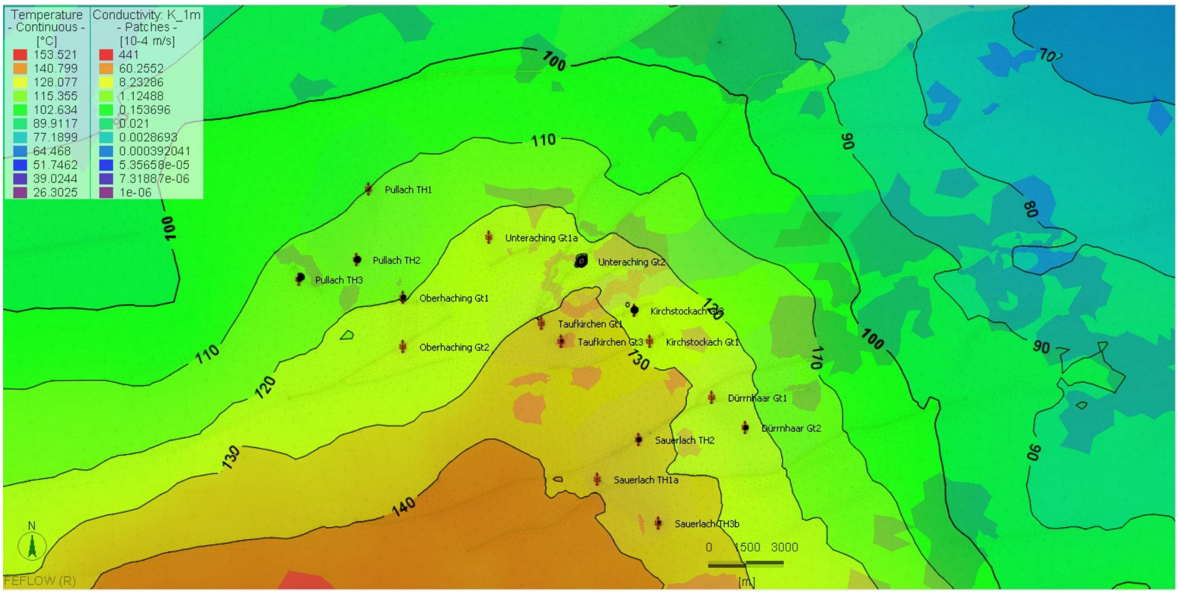

Figure 4: Temperature distribution in the upper (first) main influx zone as implemented in the regional, full-field reservoir model of the Upper Jurassic formation in the Greater Munich region. Shaded areas display bedded (or basin) facies. Note that temperature varies laterally, following the down-bending of the Upper Jurassic formation towards the SSE.

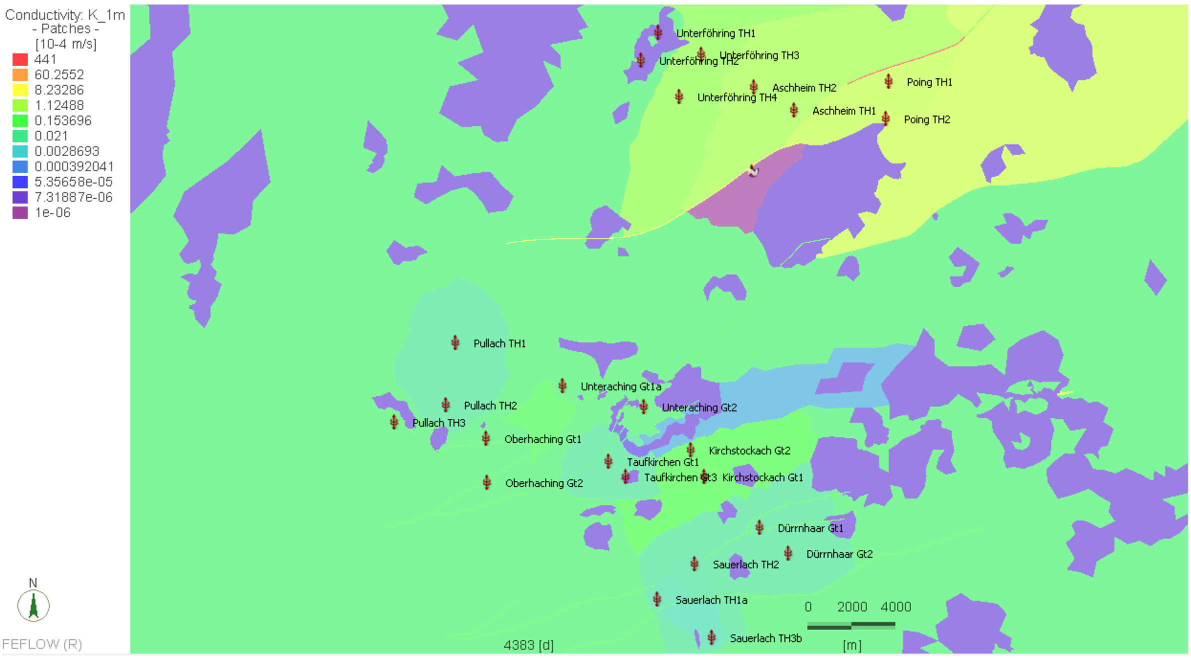

Figure 5: Permeability structure (hydraulic conductivity) in the upper (first) main influx zone as implemented in the regional, full-filed reservoir model in the Greater Munich area. Some geothermal production and injection wells are shown. Laterally and vertically varying permeability is the result of (I) a hydro-stratification – hydraulic standard model, (II) carbonate facies distribution and (III) hydraulic calibrations conducted at the respective geothermal sites.

Laterally and vertically varying temperature and hydraulic conductivity characterize the complex hydrogeological and geothermal setup of this geothermal reservoir model (see Fig. 4 and 5). Structural elements, carbonate facies distribution, and diagenetic processes are the main geologic controls on the permeability structure of the hydraulically heterogeneous and anisotropic Upper Jurassic aquifer. 2D seismic lines and other 3D seismic volumes from hydrocarbon and geothermal exploration were analyzed to create a regional structural and facies model. Besides, ample geological and geophysical borehole data from geothermal wells have been examined to implement a more detailed permeability structure at the respective geothermal well, that has been subsequently hydraulically calibrated. Fig. 6 shows an example of the vertical profile of hydraulic conductivity distribution at the Taufkirchen geothermal wells.

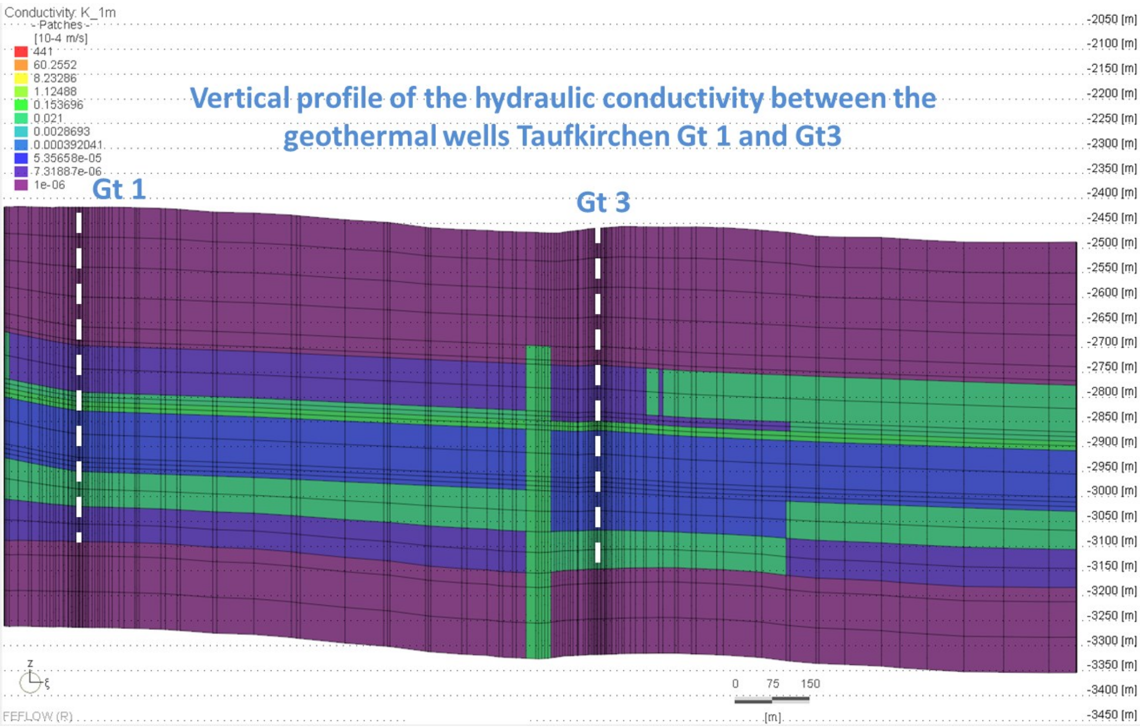

Figure 6: Vertical profile of the hydraulic conductivity distribution in the direct line connecting the Taufkirchen Gt1 and Gt3 geothermal wells. Note the complex hydro-stratigraphy of the Upper Jurassic aquifer at this geothermal site, which has been the result of seismic data interpretation, lithofacies analyses conducted at the respective geothermal wells and subsequent hydraulic calibration based on hydraulic tests. White dashed lines display geothermal wells.

Another important example of a complex permeability structure implemented in the Upper Jurassic reservoir model of Greater Munich constitutes the region comprising the Poing geothermal doublet (see Fig. 7). A heterogeneous and anisotropic permeability structure that results from an assumed relay ramp structure between two normal faults has been successfully incorporated in the reservoir model, leading to a resulting fluid flow oriented 55°. Since this structural element can be found in other modelling domains, it raises the question to what extend modelling and simulation results concerning reservoir behavior under several exploitation schemes can be transferred or applied to other modelling domains that exhibit similar reservoir conditions.

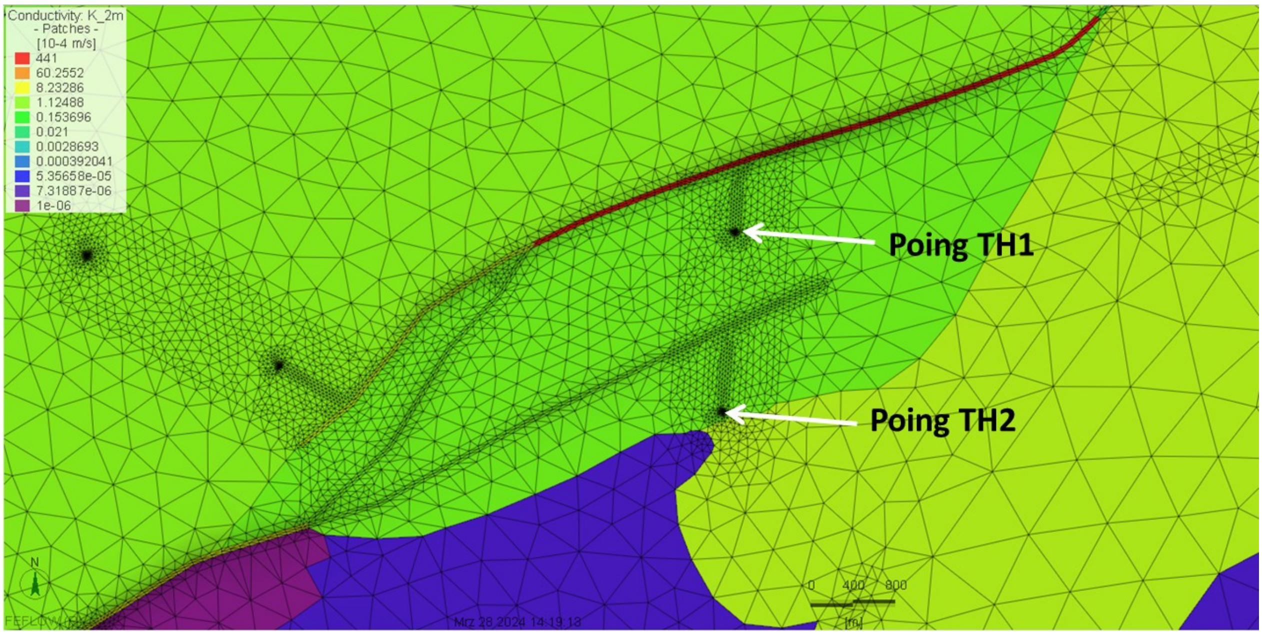

Figure 7: Hydraulic conductivity distribution in the first main inflow zone in the area of the Poing geothermal doublet in the north-south direction (K_2). It is worthwhile noting that the diagonal components of the second-order hydraulic conductivity tensor have been chosen in a way that the resulting flow direction is oriented at 55 ° (most hydraulically active structures).

Although the accommodation zone between two parallel normal faults in a relay ramp structure may exhibit a complex permeability structure, either preferentially oriented sub-seismic fractures or a completely damaged zone crossed by many sub-seismic fractures in a preferential and juxtaposed direction can normally be assumed (see section 3 as well as Fig. 10 and 11). Fig. 8 shows thermal-hydraulic simulation results after 30 years operation time of the Poing geothermal doublet for an assumed preferentially oriented permeability structure at 55°.

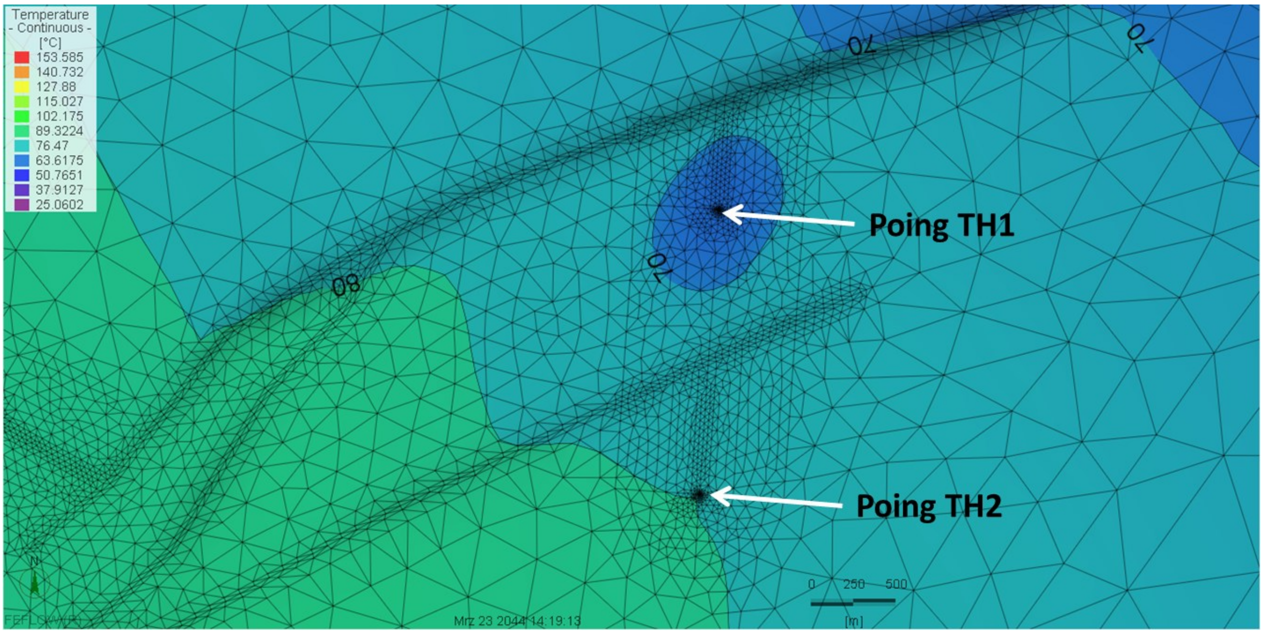

Figure 8: Temperature field in the first main inflow zone in the area of the Poing geothermal doublet Gt1 and Gt2 after approx. 30 years of operation (simulation time) under maximum allowed injection and production rates. Note the egg-shaped contour of the cold front that results from an assumed relay ramp structure between two normal faults with an anisotropic permeability due to hydraulically active fractures oriented at 55°. The active hydraulic fractures have not been explicitly modelled but rather an equivalent porous medium approach has been used.

Another important issue in closely spaced geothermal doublets and triplets constitutes the thermal-hydraulic interaction that neighboring geothermal facilities may have among each other. Such a regional reservoir model of the Greater Munich area enables the study and prediction of the scale and domain of influence of possible thermal-hydraulic interferences. Fig. 9 illustrates an example of hydraulic interferences between several deep geothermal facilities after some years of operation with real operational schemes.

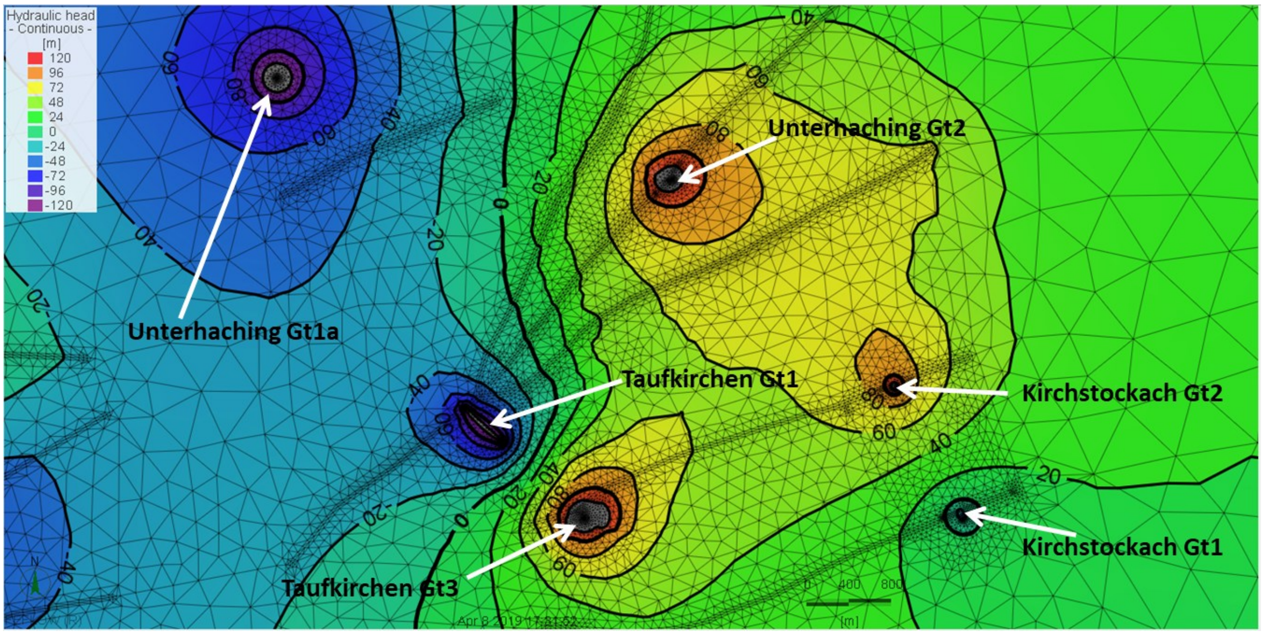

Figure 9: Pressure field (hydraulic head) in the first main inflow zone in the Taufkirchen-Kirchstockach-Unterhaching area after 5 years of operation (simulation time). It is worth noting the hydraulic interaction between the injection wells Taufkirchen Gt3, Kirchstockach Gt2 and Unterhaching Gt2. As a result of this hydraulic interference a pressure buildup of about 40 meters is formed after a short time. In contrast, there is a pressure drawdown area due to the hydraulic interaction between the production wells Taufkirchen Gt1, Unterhaching Gt1, and Oberhaching Gt2. This picture indicates that individual geothermal doublets closely spaced cannot be separately considered, but only in the interaction with neighboring geothermal plants. This illustrates one important advantage of the Greater Munich thermal-hydraulic reservoir model.

3. COMMON GEOLOGIC CONTROLS ON THE UPPER JURASSIC RESERVOIR PERMEABILITY STRUCTURE IN THE STUDY REGION

Fundamentally, the main geologic factors influencing the permeability structure and hence fluid and heat transport in carbonate reservoirs can be summarized in three major sections: (I) structural controls and (II) depositional environment controls, which are overprinted by (III) diagenetic processes throughout the entire burial history.

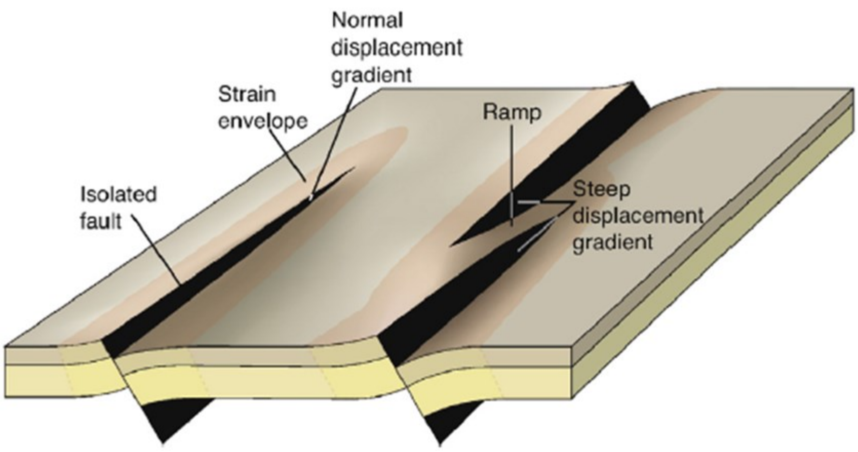

Figure 10: Schematic representation of a normal fault relay structure with a ramp linking the hanging wall and footwall, illustrating how relay ramps are created when neighboring parallel faults are near to each other and their two strain envelopes overlap (right). An individual, separate fault is displayed on the left-hand side of the picture, after Fossen & Rotevatn 2016.

Due to the apparently great relevance that normal fault relay structures have to the study area (see Fig. 2), it is postulated in this work that structural controls, reworked by succeeding karstification preferentially oriented along pre-existing structural elements, may provide the permeability structure required for a possible premature thermal breakthrough in geothermal wells that target parallel normal faults close to each other. Normal fault relay structures are created at all scales in a process that involves faults interaction or when faults step out of their own plane during development (see Fig. 10). Their subsequent arrangement and destruction serve as the most efficient way for faults to prolong (e.g. Fossen & Rotevatn 2016, Fossen 2016).

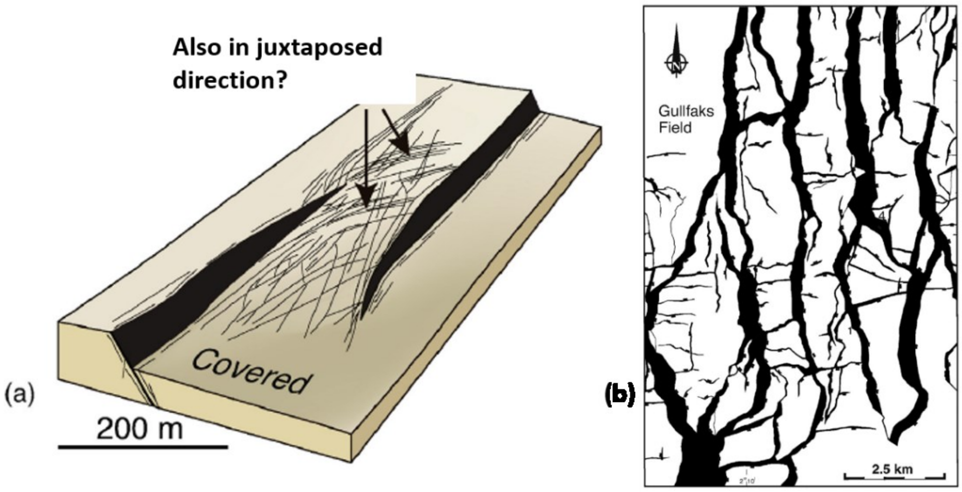

Figure 11: (a) Scheme of a relay ramp in the Arches National Park (modified after Fossen & Rotevatn 2016 and reference therein). (b) Mapped fault inventory from the North Sea region displaying a structurally matured relay ramp of Gullfaks Field, modified after Fossen & Rotevatn 2016 and reference therein.

The gradual growth of normal fault relay ramps starting from fault overlap to a fully breached fault comprises strain accumulation in the fault overlap domain, originally through bending of layers and auxiliarily by the creation of fractures and additional accompanying faults (e.g. Fossen & Rotevatn 2016, Fossen 2016, Kim et al. 2004, Peacock & Sanderson 1994). As displayed in Fig. 11, according to Fossen & Rotevatn 2016 these small-scale, partly sub-seismic structural elements have more complex orientation patterns than the commonly strike-parallel directions observed in conventional damage zones away from domains of intensive fault interaction. Although these small-scale fractures may serve as fluid channels, their hydraulic role as conduits or barriers in relay ramps is still debated (e.g. Rotevatn et al. 2007, Faulds and Hinz 2015).

4. STATIC RESERVOIR MODELLING RESULTS

Based on the recent 3D seismic campaign conducted in southern Munich (GRAME-project) and succeeding structural and facies interpretation, simplified fault and stratigraphic modelling as well as facies and property modelling fit for dynamic finite-element reservoir simulation purposes have been carried out in this work (see also Meneses Rioseco et al. 2018, 2019). The static reservoir modelling of the GRAME sub-domain of the Greater Munich model involves numerous fault-fault and fault-horizon intersections that must be properly handled when generating a 3D water-tight mesh that represents the large-scale geology (see Fig. 12 and 13).

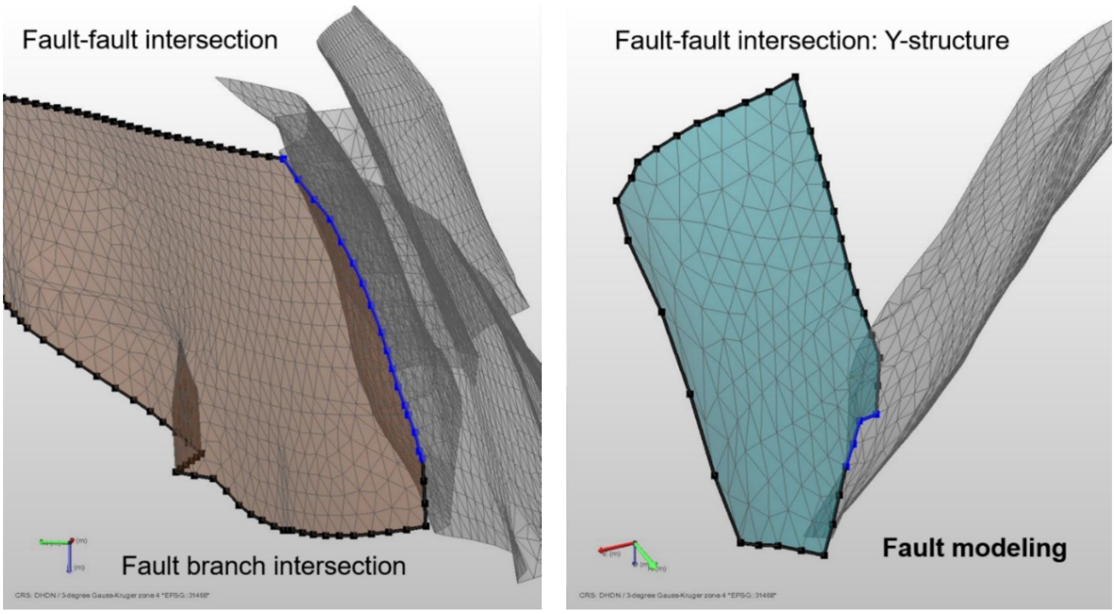

Figure 12: Fault-fault intersections have been successfully handled in the presence of multiple intricate fault systems with the subsurface modeling tool of the reservoir modelling software JewelSuite^{TM}. Left: Fault-Fault branching intersection. Right: Fault-fault intersection in form of a Y-structure in reservoir.

The reservoir modelling software JewelSuite™ has been used to create a consistent reservoir framework, going through the entire workflow of constructing the structural, facies and property models that are meshed for 3D dynamic finite-element simulation (see Fig. 12, 13, 14 and 15). Besides, different 3D mesh generators such as TetGen (e.g. Si 2015) and Gmsh (e.g. Genzaine & Remacle 2009) have been used for the generation of 3D finite-element grids in this work.

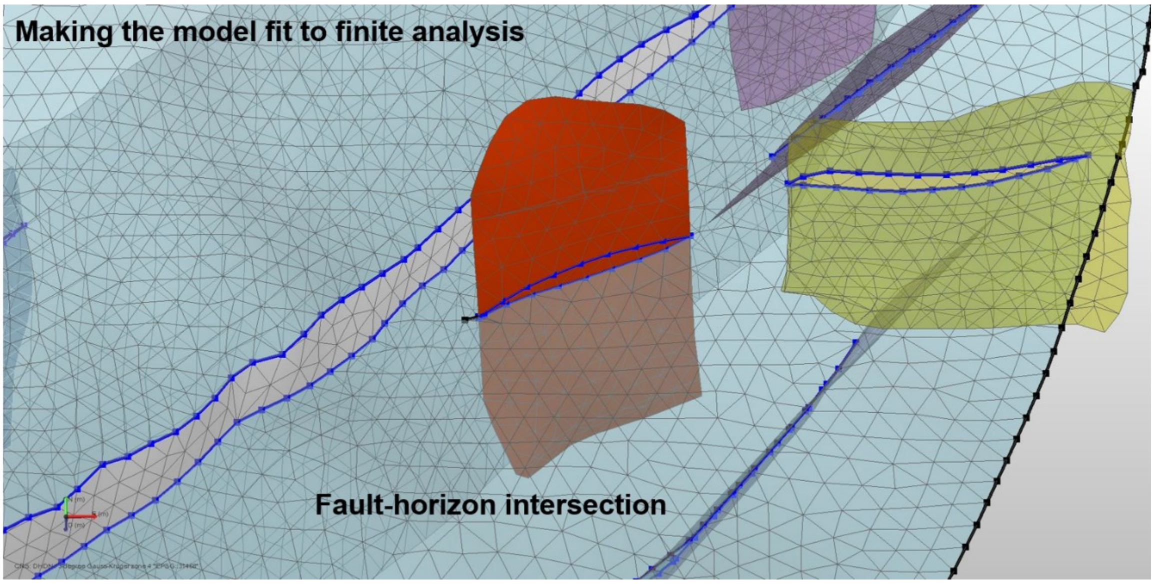

Figure 13: Fault-horizon intersections have been satisfactorily treated in the presence of numerous fault systems and complex horizon geometries (complex geology) with the subsurface modelling tool of the reservoir modeling software JewelSuite™.

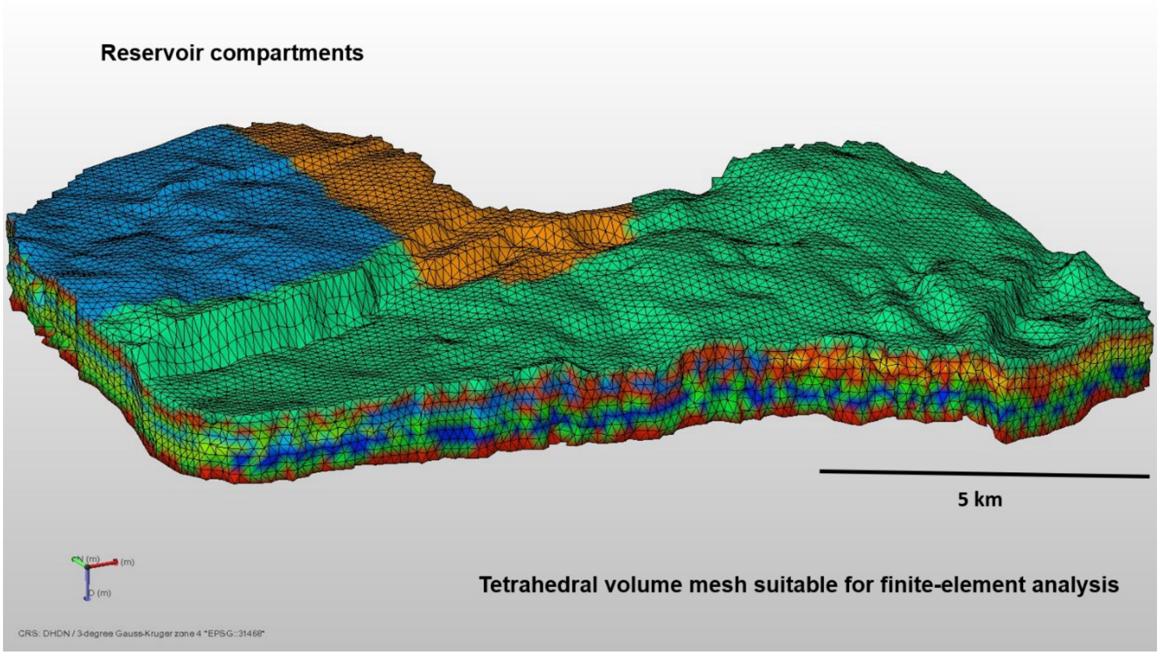

Figure 14: The geological grid and the 3D finite-element unstructured mesh (assigning data, upscaling, connecting facies volumes) for the facies model have been built with the facies modeling workflow of the reservoir modelling software JewelSuite™. Different colors represent different facies-controlled reservoir compartments.

Since at this stage of geothermal field development in southern Munich (GRAME region) only 3D seismic data that are not well-controlled is available, a simplified geothermal reservoir model that integrates a structural model, a facies model and a property model has been constructed. Specially in deep seated geothermal reservoirs in sedimentary basins, the purpose of the model and the data availability, which relates to the structural complexity and the reservoir depositional environment control the resulting model. In the case of carbonate reservoirs, the depositional model is overprinted by diagenetic processes. To understand fluid flow in the reservoir, a key element in reservoir modelling constitutes the construction of a model that captures the main heterogeneities and anisotropies at different scales. Different upscaling techniques related to finding the representative elementary volume have been addressed in this work. In addition, homogenization techniques and grid upscaling methods have been part of the static reservoir modelling workflow employed in this work. Considerable effort has been taken to understand connectivity in three-dimension in the reservoir. The property model is based on the facies model and is directly related to the inner architecture of the reservoir.

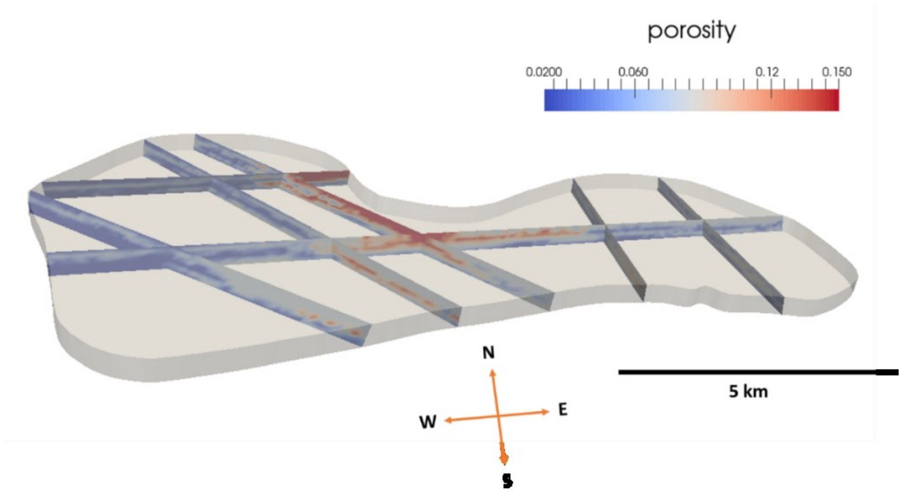

Figure 15: Property model (petrophysical model) related to the simplified facies model, which is based on seismic interpretation (see Fig. 14). Geological cells have been populated with hydraulic and thermal properties based on range of values implemented in the reservoir model of the Upper Jurassic carbonates in the Greater Munich area. Displayed is only porosity as a matter of example.

5. DYNAMIC RESERVOIR SIMULATION RESULTS

3D thermal-hydraulic simulation of the Upper Jurassic geothermal aquifer affected by multiple operating geothermal doublets and triplets in the Greater Munich region, Germany has been performed in this work. Several worst-case scenarios with different permeability structures representing unfavorable reservoir conditions for a sustainable reservoir management have been realized. This is aimed at gaining knowledge and understanding of the possible causes of an early than predicted temperature decline in the production wells of different deep geothermal facilities in the Upper Jurassic aquifer in the Greater Munich region. Essentially, the question related to what possible permeability structures would be required to explain presumed premature geothermal breakthroughs and the geologic factors that may account for such permeability structures is addressed in this work. As described earlier, the initial permeability structure of normal relay ramps, which may have been enhanced by karstification, are thought to account for anisotropic, high-permeability aquifers in the transfer-zone between two major parallel normal faults (e.g. Fossen 2016, Fossen & Rotevatn 2016, Faulds & Hinz 2015, Rotevatn et al. 2007, Kim & Peacock 2004, Peacock & Sanderson 1994). Annual injection and production data provided by the Bavarian Environment Agency (LFU) constitute the database for the history matching. Although several deep geothermal doublets and triplets have been investigated, the deep geothermal doublets Taufkirchen and Kirchstockach are most appropriate to demonstrate the comparison and transferability of modelling and simulation results of reservoir behavior to neighboring geothermal facilities in similar reservoir conditions. Different operational schemes have been implemented in order to gain insight into the impact of using different operational strategies on the occurrence of a premature thermal breakthrough.

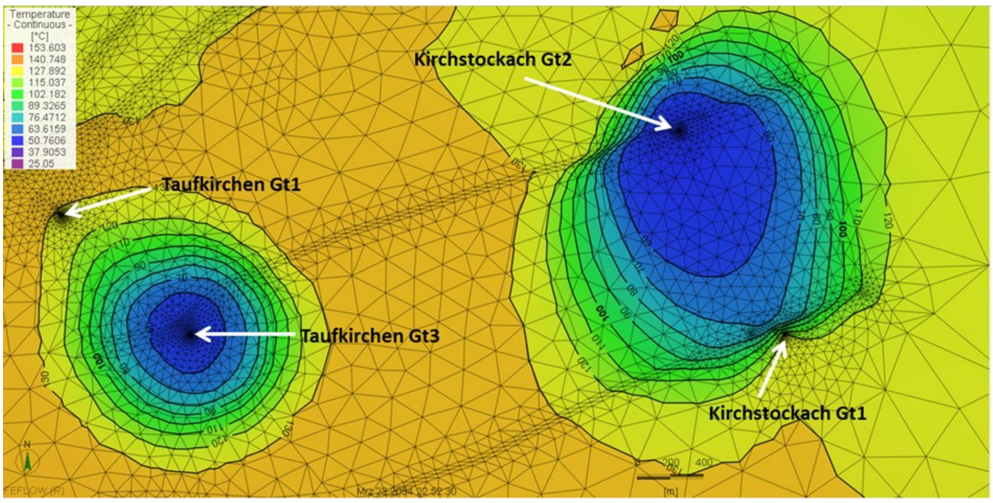

Figure 16: Temperature field in the first main inflow zone in the area of the geothermal doublet Kirchstockach Gt1 and Gt2 (and Taufkirchen Gt1 and Gt3 (left)) after 40 years of operation. Lower (second) main inflow zone and further inflow zone are considered as aquitards and an anisotropic, high hydraulic conductivity in the first main inflow zone has been implemented. This scenario corresponds to the case of a much thicker bedded (or basin) facies and oriented "channels" on the direct connecting line between the Kirchstockach Gt2 and Gt1 in the upper (first) main inflow zone with the approach of the equivalent pore space.

As a matter of example, Fig. 16 shows simulation results for the Taufkirchen and Kirchstockach deep geothermal facilities after 40 years of operation with their respective normal operational schemes. In the case of the Kirchstockach geothermal doublet, extreme assumptions have been made in the sense of worst-case scenarios. For the latter study case, the lower (second) main inflow zone and further inflow zone are considered as aquitards and an anisotropic, high hydraulic conductivity (two orders of magnitude higher) in the first main inflow zone has been implemented. This scenario corresponds to the case of a much thicker bedded (or basin) facies and an oriented "channel" in the direct connecting line between the Kirchstockach Gt2 and Gt1 in the upper (first) main inflow zone with the approach of the equivalent pore space. Simulation results suggest that even assuming such an extremely unfavorable permeability structure, the thermal breakthrough is not stablished in 10 years yet and a temperature decline of ca. 10°C is not attained before 25 years. In addition, different operational schemes have been tested for different geothermal facilities in order to estimate the impact that extremely exploitative operational schemes have on the progress of the cooling front. For instance, Fig. 17 displays simulation results for the case study of the Taufkirchen geothermal doublet. Simulation results suggest that in contrast to the permeability model parameter, the injection and production rates do not seem to significantly affect the spatiotemporal evolution of the cooling front. For the case study of the Taufkirchen geothermal doublet, simulation findings indicate that varying the circulation rate within a reasonable range has a negligible impact on the arrival of the cooling front at the production well for 50 years operation.

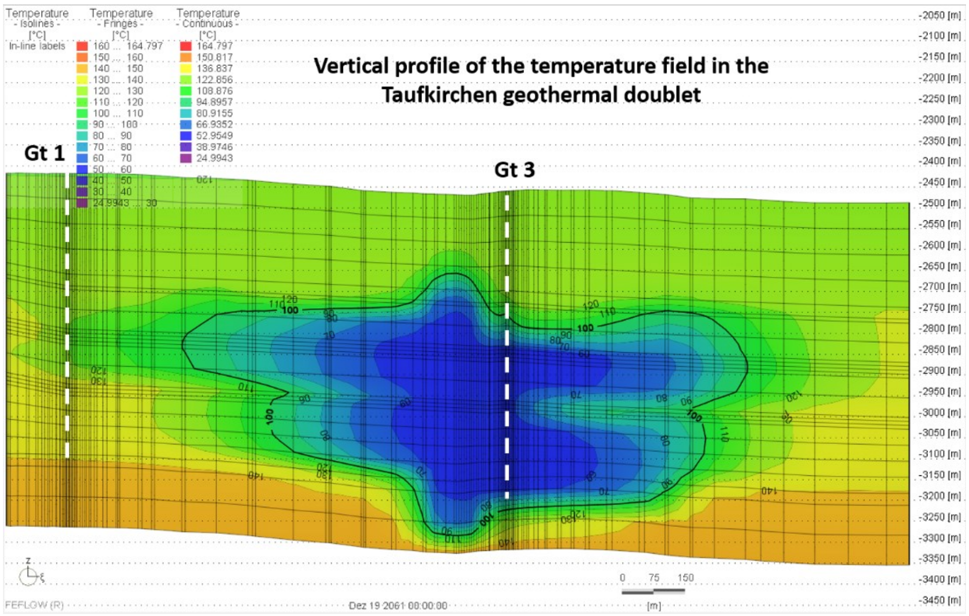

Figure 17: Vertical profile of the temperature field in the direct line connecting the geothermal wells Taufkirchen Gt1 and Gt3 after 50 years of operation (simulation time) with 145 l/s circulation rate. White dashed lines display wells.

Altogether, thermal-hydraulic modelling and simulation results suggest that for the deep geothermal facilities in the Greater Munich region a premature thermal breakthrough in less than 10 years with a temperature decline of ca. 10°C can only occur provided there exists an anisotropic high-permeability zone (channel). Considering the simplifying assumptions made in the reservoir model of the Upper Jurassic carbonates in Greater Munich, it is required that fluid flow is favorably channeled in the direction between the injection and production wells to explain such an early temperature decline of that magnitude at production wells. The interplay between different geologic controls on the permeability structure of carbonate reservoirs must be considered in detail to avoid such sustainability risks and contribute to an optimized reservoir management.

6. CONCLUSIONS

Geothermal reservoir modeling and simulation constitutes an indispensable management tool when it comes to sustainably developing a geothermal field. This work focusses on the geothermal reservoir modelling and simulation of the Upper Jurassic carbonates in the Bavarian Molasse Basin and in particular in the so-called Greater Munich region, Germany. This region has experienced one of the most dynamic geothermal developments in recent years in Europe. Several geothermal doublets and triplets have been operating for several years to provide with heat and electricity numerous villages in the outskirts of the city of Munich. Where considerable geothermal potential and high heat demand coincide, geothermal energy can substantially contribute to the energy transition of a country since heat consumption constitutes a significant part of the total energy consumption. The geothermal development in the city of Munich and its urban outskirts represents a prominent example of current efforts to decarbonize district heating networks, substantially contributing to the German heat transition. To develop sustainable geothermal exploitation strategies, a more detailed analysis using numerical modelling and simulation of the reservoir performance influenced by operating and planned well is needed. This work concentrates on the 3D thermal-hydraulic modelling and simulation of the Upper Jurassic aquifer influenced by several operating and future doublets and triples in the city of Munich. During the lifecycle of geothermal field development, as new static and dynamic data is being gathered, the reservoir model requires updating and refining. Static and dynamic geothermal reservoir modelling has been performed in this work. Based on the recent 3D seismic data and interpretation in southern Munich (GRAME-project) as well as borehole geophysical and geological data gathered at neighboring wells, simplified structural and facies models as well as a property model fit for finite-element dynamic simulation have been built.

Understanding the possible causes of a stablished premature geothermal breakthrough requires history matching of injection and production data with modelling and simulation results. In the case of the Upper Jurassic aquifer in the Bavarian Molasse Basin, a variety of structural, reservoir depositional environment and diagenetic factors can jointly result in an unfavorable permeability structure that enables such premature thermal breakthrough. 3D thermal-hydraulic modelling and simulation of diverse worst-case scenarios have been conducted for several geothermal doublets (e.g. Poing, Kirchstockach and Taufkirchen) to understand the impact that different permeability structures have on a presumed premature thermal breakthrough.

For the study case of the geothermal doublet Kirchstockach, it was studied what reservoir permeability structure may explain a premature thermal breakthrough in ca. 6 years of operation with actual operation schemes and a temperature decline of ca. 10 °C. Considering structural controls in conjunction with karstification processes, we postulate a matured, breached relay ramp structure between the two parallel normal faults that each Kirchstockach geothermal well targets. An anisotropic permeability structure that results from an assumed normal relay ramp structure in the Poing geothermal doublet has already been implemented in the reservoir model of Greater Munich. Recent 3D seismic interpretation in the city of Munich (GRAME 3D seismics) also shows relay ramp structures in this area. According to Ziesch et al. 2018, retro-deformation analyses not only show normal but also strike-slip displacement in prominent faults in southern Munich. It is broadly accepted that karstification preferentially follows pre-existing fractures and faults (e.g. Stevanović 2015, Lüschen et al. 2014, Dussel et al. 2016). Despite making extreme pessimistic assumptions of unfavorable permeability structures, no temperature decline of ca. 10 °C in ca. 6 years of operation could be matched. A highly fractured zone between the two major parallel faults targeted by the Kirchstockach wells may provide the high-permeability zone required to channel the fluid flow between the wells. Based on hydrotectonic analyses (e.g. Moeck 2005) and considering that the maximum horizontal stress is roughly oriented in the north-south direction in the study region (e.g. Reinecker et al. 2010), fractures and faults oriented in that direction within the relay ramp may be hydraulically active. Alternatively, pre-existing fractures within the relay ramp structure in the direct line connecting the Kirchstockach injection and production wells may have been karstified, providing the high-permeability channel for fluid flow between the wells. 3D thermal-hydraulic modelling results suggest that only the presence of such high-permeability oriented channels can explain the occurrence of such premature thermal breakthrough and temperature decline in ca. 1.5 km distance between injection and production wells in the reservoir. One of the major simplifications made in the regional reservoir model of Greater Munich relates to the vertical implementation of subvertical faults. Intersecting faults at depth may account for zones of high permeability.

Lessons learned from the conducted reservoir modelling and simulation may be transferred to neighboring geothermal facilities such as the Taufkirchen geothermal doublet to understand the scale and impact of the geological uncertainties on a possible earlier than predicted temperature decline in the production well. To what extend 3D numerical thermal-hydraulic modelling results of reservoir performance affected by the operation of one facility can be transferred to other neighboring facilities depends on many factors. Nevertheless, through the comparison of different reservoir performances with different permeability structures, significant insight can be gained on the possible causes of premature thermal breakthroughs. Specially carbonate reservoirs may be hugely heterogenous and care should be taken when it comes to the transferability of modelling results to neighboring facilities in similar reservoir conditions. In contrast to sandstone reservoirs, carbonate reservoirs may be highly fractured and prone to dissolution and precipitation processes. Carbonate rock mechanics as well as carbonate dissolution and precipitation processes at different scales may considerably alter permeability during the entire lifecycle of reservoir exploitation by extraction and injection of thermal fluids. This work focusses only on thermal-hydraulic reservoir processes driven by multiple operating geothermal doublets and triplets in complex permeability structures. However, a systematic and detailed investigation of the scale of impact that carbonate rock mechanics and geochemical processes have on the permeability structure, compared to the existing geological uncertainties, should be pursued.

Neighboring geothermal facilities may influence each other hydraulically and hence reveal the relative importance of such regional reservoir model. However, modelling and simulation results suggest that a more detailed reservoir modelling is required at the respective individual geothermal facilities to locally, more accurately capture the permeability structure of the reservoir. Such a regional reservoir model is rather fit for the study of regional effects and possible thermal-hydraulic interference between neighboring wells but may not be fit for the purpose of more accurately capturing the reservoir structure and dynamics at local individual geothermal facilities. Even though the Greater Munich model has been hydraulically calibrated at the respective individual geothermal facilities, which goes hand in hand with its predictive power, premature thermal breakthrough shows that the inter-well permeability structure is not well resolved yet. Inter-well structural elements, carbonate facies distribution and karstification (e.g. channels) at sub-seismic resolution constitute major geological uncertainties and may be decisive in the short- and long-term success or failure of geothermal facilities. In addition, to what extend reservoir models can be easily updated and refined depends on the capabilities of the selected reservoir modelling software and the level of detail of reservoir property implementation required. New, more detailed geothermal reservoir modelling and simulation based on extensive and profound data analysis is suggested to address the key question of to what extend can or should the permeability structure be implemented in the reservoir model.

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