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The ArtemIS project: Assessment for medium-depth geothermal energy utilization in Germany

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This document is a supplement to the article 'The ArtemIS Project: Assessment of Medium-Depth Geothermal Energy Utilization in Germany' published in Advances in Geosciences and provides additional details on the GeotIS platform as well as numerical simulations of Mesozoic sandstone reservoirs in the North German Basin conducted using COMSOL Multiphysics.

S1 Geothermal Information System GeotIS

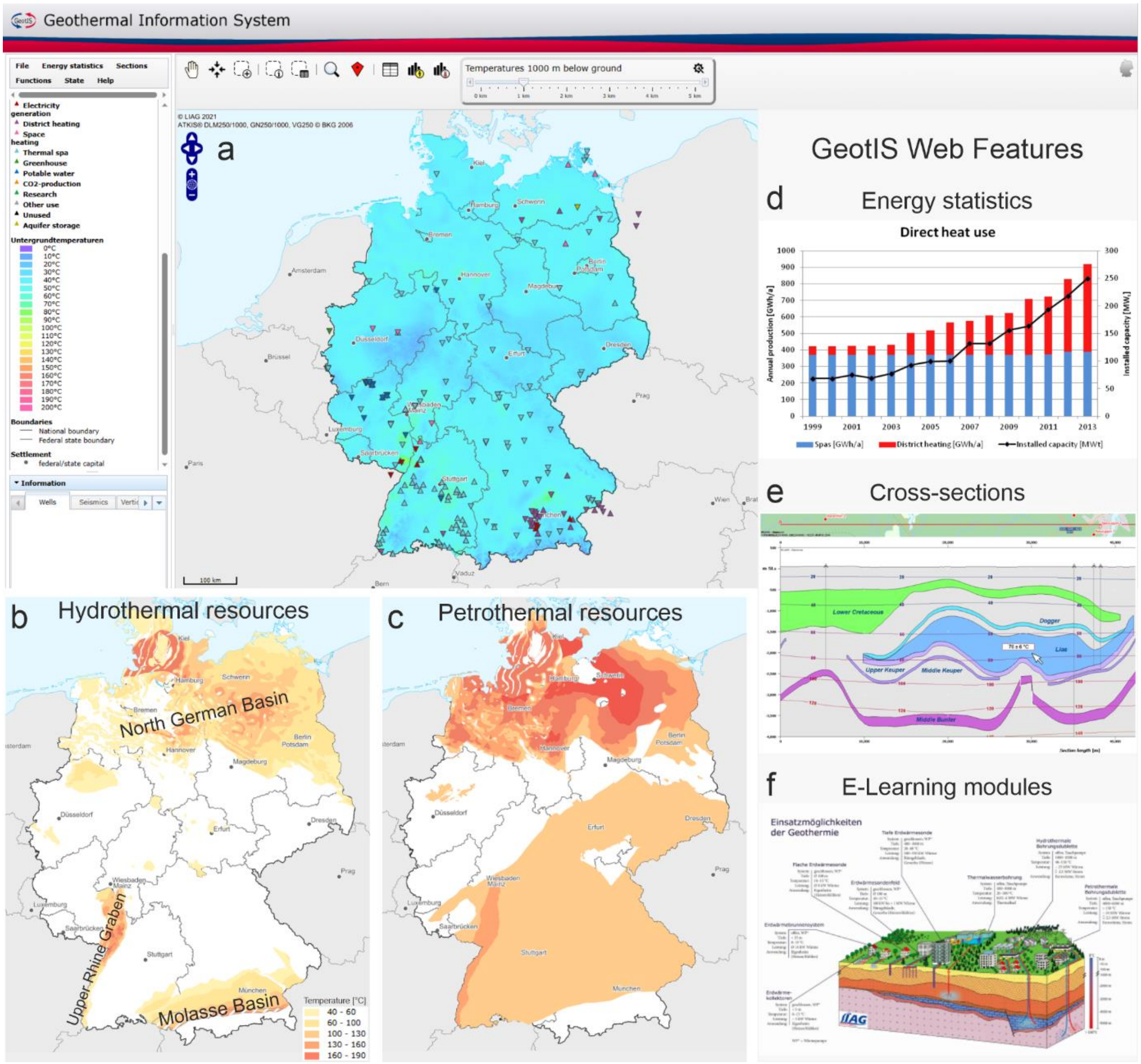

Figure S1: Overview of the GeotIS platform and examples of available web features: (a) subsurface temperature at 1000 m depth below ground and current geothermal installations, thematic maps showing (b) hydrothermal and (c) petrothermal resources in Germany, (d) energy statistics, (e) cross-sections and geological models, and (f) e-learning modules.

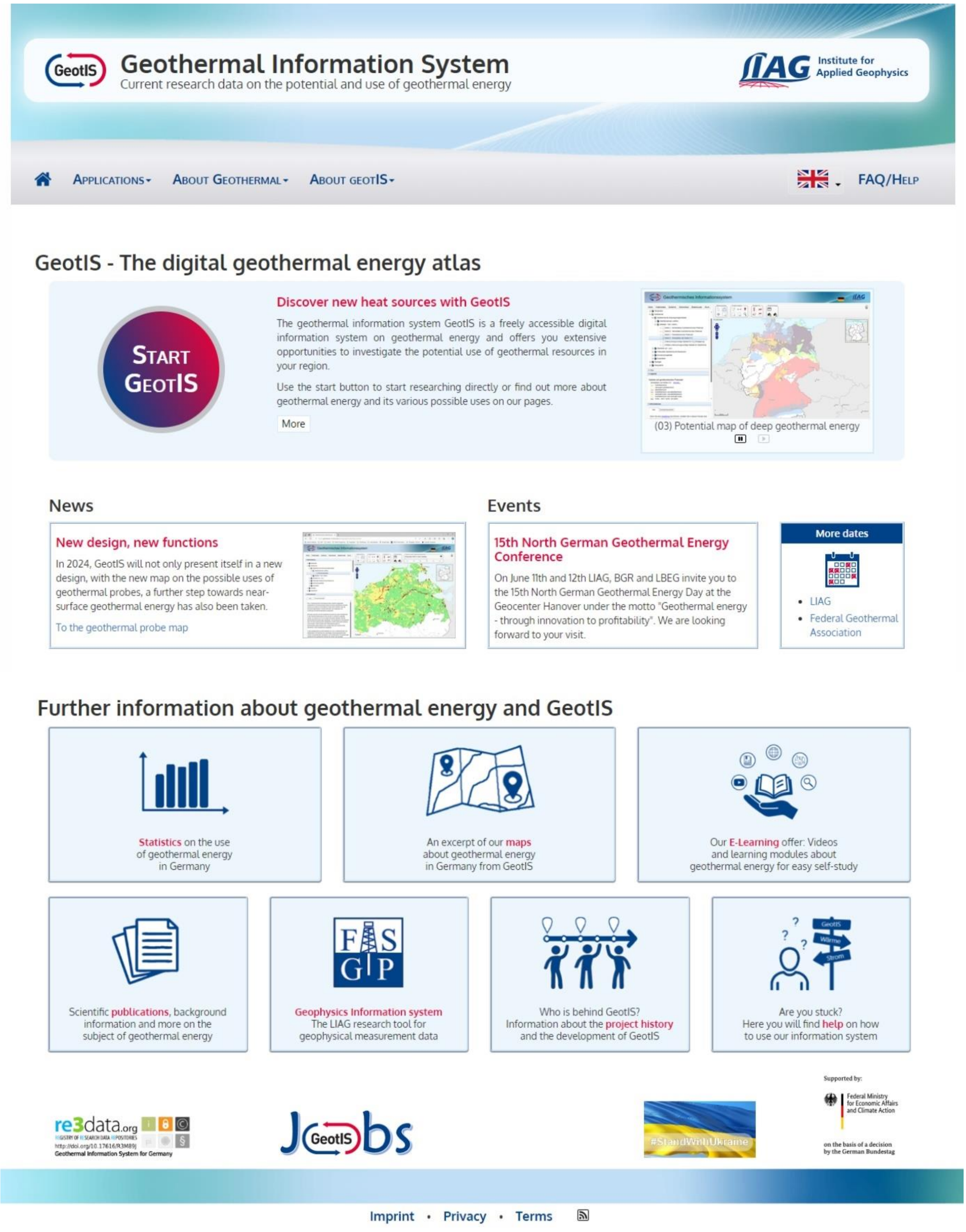

Figure S2: Updated design of the GeotIS platform with new interactive web features (www.geotis.de).

S2 Reservoir Simulations of Mesozoic Sandstones in the North German Basin

Motivated by the growing interest in middle-deep geothermal resources development, this work aims to develop a methodology for assessing the potential of middle-deep geothermal Mesozoic sandstone reservoirs in the North German Basin by estimating extractable geothermal energy through optimized multi-well configurations.

The following paragraphs provide additional information to section 3.3 in the original article in Advances in Geosciences. Detailed information can be found in Mantei et al. (2024, https://doi.org/10.21203/rs.3.rs-4808466/v1).

Geology

According to Franz et al. (2018), six main Mesozoic sandstone reservoirs can be found in the North German Basin (Fig. S3). These reservoirs often represent vertically compartmentalized hydraulic systems separated by fine-grained and impermeable shales, claystones, siltstones, or marls that act as aquitards. The lateral extent of these reservoirs is variable, but the reservoirs themselves can be described as homogeneous (Franz et al., 2018).

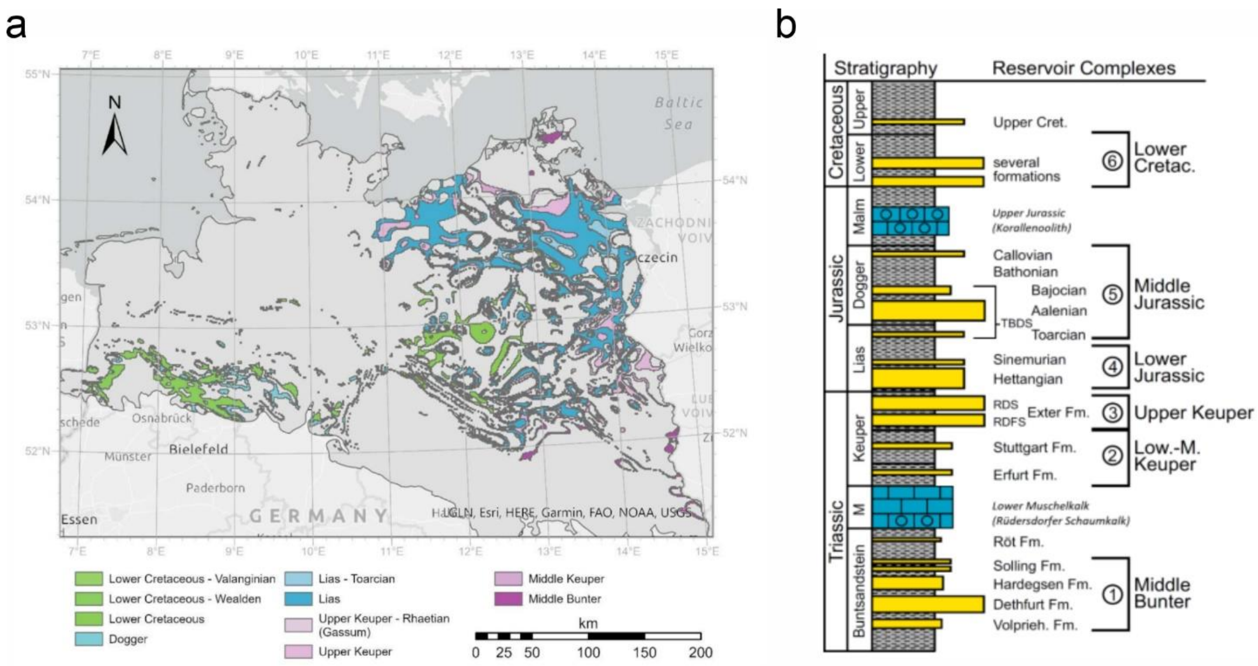

Figure S3: Overview map of the North German Basin (a) and the respective geothermal play types at 1000 m (bgl) based on the GeotIS database (www.geotis.de and references therein). (b) Schematic profile of the six main Mesozoic sandstone reservoirs (yellow) found in the North German Basin modified after Franz et al. (2018). Carbonate reservoirs are presented in blue. Single sandstone reservoirs are interlayered between non-permeable, exceedingly fine-grained shales, claystones, siltstones and/or marls (grey). RDS = Rhaetian Deltaic System; RDFS = Rhaetian distributive fluvial system; TBDS = Toarcian–Bajocian Deltaic System (TBDS).

Prominent examples are the massive, highly porous and permeable Bentheim sandstone with lateral continuity and homogeneous block-scale nature and the homogeneous Wealden sandstone (both Lower Cretaceous), which served as the basis for the reservoir simulations presented in this study. The Bentheim sandstone reaches a maximum thickness of 70 m and is sandwiched between impermeable layers consisting of clay and marly claystones with a thickness of 100s of meters. Thus, a fully saturated, confined aquifer sandwiched between impermeable aquitards can be assumed for the reservoir model.

Background

Various analytical and numerical techniques have been used in the past to assess the geothermal potential of a reservoir in terms of recoverable resources, including dynamic methods (Fan et al., 2022; Comerford et al., 2018; O'Sullivan and O'Sullivan, 2016; Williams, 2007; Jobmann and Schulz, 1989; Bödvarsson and Tsang, 1982). One of the main approaches is estimating the potentially extractable geothermal energy through multi-well configurations across large areas. While shallow, closed-loop geothermal systems are widely studied (Korhonen et al., 2023; Walch et al., 2021), few studies have focused on multi-well layouts in the middle- and deep-geothermal sectors on a large spatial scale. A pioneering study by Jobmann and Schulz (1989) applied this method on a capital city scale, using a large doublet array to estimate extractable energy from the Upper Jurassic aquifer in the German Molasse Basin. The authors examined doublet arrays and compared their performance to that of single doublets, focusing on the thermal breakthrough time and thermal utilization duration. Despite the simplifications of their 2D analytical model, they demonstrated the advantages of doublet arrays over single doublets. Analytical models, while efficient for quick results, often struggle with the complexities of thermal-hydraulic interactions between wells, limiting their accuracy (Schulz, 1987). Later studies focused on small doublet arrays to study neighboring well interactions, particularly in concession fields (Willems et al., 2017a; Willems et al., 2017b). These works explored the thermal breakthrough occurrence time in homogeneous sandstone reservoirs, but did not consider the behavior of production temperatures post-breakthrough or the long-term performance of geothermal systems. Similarly, Vörös et al. (2007) analyzed multi-well layouts for deep geothermal reservoirs in basement play types, highlighting the importance of inter-well distances but offering no detailed exploration of production temperature behavior or reservoir quality. Blank et al. (2021) proposed a computational framework for modeling and optimizing geothermal energy production, focusing on smart geothermal multi-well systems in heterogeneous fields. They explored optimal system configurations but did not consider the influence of operational profiles or reservoir quality parameters on the long-term economic viability of geothermal projects. Similarly, coupled thermo-hydraulic models (Fan et al., 2022; Comerford et al., 2018) have considered multiple well scenarios and operational parameters but mainly focused on energy production until thermal breakthrough, without further investigation of the cooling phase or long-term system performance. To date, no comprehensive study has systematically addressed the impact of reservoir quality, well configurations, and operational data on the full lifecycle of geothermal systems, particularly for middle-deep geothermal resources in Mesozoic sandstone formations in the North German Basin (NGB). Thus, the ArtemIS project aims to fill this gap by numerically investigating the reservoir performance of geothermal doublet arrays with varying well distances, reservoir properties, development strategies, and neighboring wells. The primary objectives are to analyze key performance metrics such as thermal breakthrough time, cooling rate after breakthrough, and the end production temperature over the geothermal facility's lifespan. This work seeks to provide a ranking of the factors influencing these parameters and compare doublet arrays with single doublets. By building on the results of previous analytical models (Jobmann and Schulz, 1989; Schulz, 1987), this study offers a more reliable methodology to assess the sustainable geothermal energy potential for urban areas in the NGB.

Model Set-Up

This paragraph represents a brief summary of the model set-up. For more information and mathematical equations please refer to Mantei et al. (2024).

Using the Bentheim sandstone as an example, a simple 8 x 8 km layer-cake model was set up in COMSOL Multiphysics (see Fig. 6 in the original article). COMSOL was selected for its robust, state-of-the-art capabilities in numerically simulating hydrothermal doublets within complex 3D settings. Additionally, it provides transparency (source codes) while offering users the flexibility to customize standard settings to suit specific needs. The model consists of two 100 m thick, non-permeable aquitards below and above one permeable aquifer at 1000 m depth (bgl). For the geothermal doublet array, a set of eight injection and eight production wells were placed in a chessboard pattern. Based on a geothermal gradient of 30 °C km^{-1} and considering a surface temperature of 10 °C, a reservoir temperature of 40 °C at 1000 m depth was assumed. For the fluid flow, Darcy velocities of ~10^{-8} m s^{-1} were used based on regional hydraulic gradient data.

For the models, the fluid flow was assumed to be laminar and one-phase in a saturated, confined environment, a condition frequently encountered in geothermal reservoirs (Armstead and Tester, 1987). Heat transport in these systems is driven primarily by thermal diffusion and advection, processes that govern energy transfer in geothermal reservoirs (Blank et al., 2021; Singh, 2013; Ostermann, 2011). The governing equations for fluid flow and heat transfer were derived from the principles of mass, momentum, and energy conservation, as outlined in Saeid et al. (2014, 2015). These equations form the basis for modeling the dynamics of geothermal fluid flow and the subsequent heat transport in a fully saturated medium, where the fluid and solid phases are assumed to be in thermal equilibrium. Boundary conditions applied in the numerical model play a crucial role in determining the behavior of geothermal reservoirs. First-order (Dirichlet) and second-order (Neumann) boundary conditions to simulate the fluid flow and heat transfer were applied. For the lateral boundaries, a first-order condition was used, where the hydraulic head is prescribed to maintain the natural pressure distribution in the reservoir, consistent with typical geothermal settings (Saeid et al., 2014; Blank et al., 2021). The top and bottom boundaries were treated as no-flow conditions, which is a special case of second-order boundary conditions (e.g., Watanabe et al., 2017). These no-flow boundaries are commonly applied in geothermal reservoir modeling to simulate confined aquifers, where no fluid exchange occurs between the reservoir and overlying or underlying layers (Armstead and Tester, 1987). In the case of geothermal wells, the wells were modeled as internal sources or sinks. The mass flow rate through the wells is represented as line elements that correspond to the injection or production of fluid within the reservoir. The mass flux was calculated across the lateral surface of the cylindrical well, which is mathematically expressed as a source term in the governing equations (Saeid et al., 2015; Bundschuh and Suárez Arriaga, 2010). Thermal boundary conditions were applied at the lateral boundaries with a geothermal gradient typical for the study area (30 °C km^{-1}), based on empirical data from the North German Basin (Ostermann, 2011). For the top and bottom boundaries, constant temperatures were applied, in line with the geothermal gradient. Injection wells were treated as heat sources, and their effect on the temperature field within the reservoir was modeled through a heat source term, accounting for the temperature of the injected fluid (Blank et al., 2021; Watanabe et al., 2017).

Thermal breakthrough of the hydrothermal doublets was calculated according to Schulz (1987):

$$t_{TB} = \frac{\rho_A c_A}{\rho_F c_F} \cdot \frac{M}{Q} \cdot A(\phi_0)$$

where ρA and cA represent the density and specific heat capacity at constant pressure of the aquifer, ρF and cF denote the corresponding properties of the fluid, M indicates the aquifer thickness, Q signifies the flow rate and $A(\phi 0)$ is given by the following expression:

$$A(\phi_0) = \frac{k_f Q}{M} \int_{\phi_0}^{\infty} \frac{1}{v^2} \, d\phi$$

where the integration contour is the streamline $\psi 0 = \psi(x0, y0)$, kf stands for the hydraulic conductivity, and v denotes the total velocity defined as the superposition of the natural groundwater flow and the fluid flow imposed by the geothermal doublet (Schulz, 1987; https://assets-eu.researchsquare.com/files/rs-4808466/v1/29e86c34894061f411a0ae7a.docx).

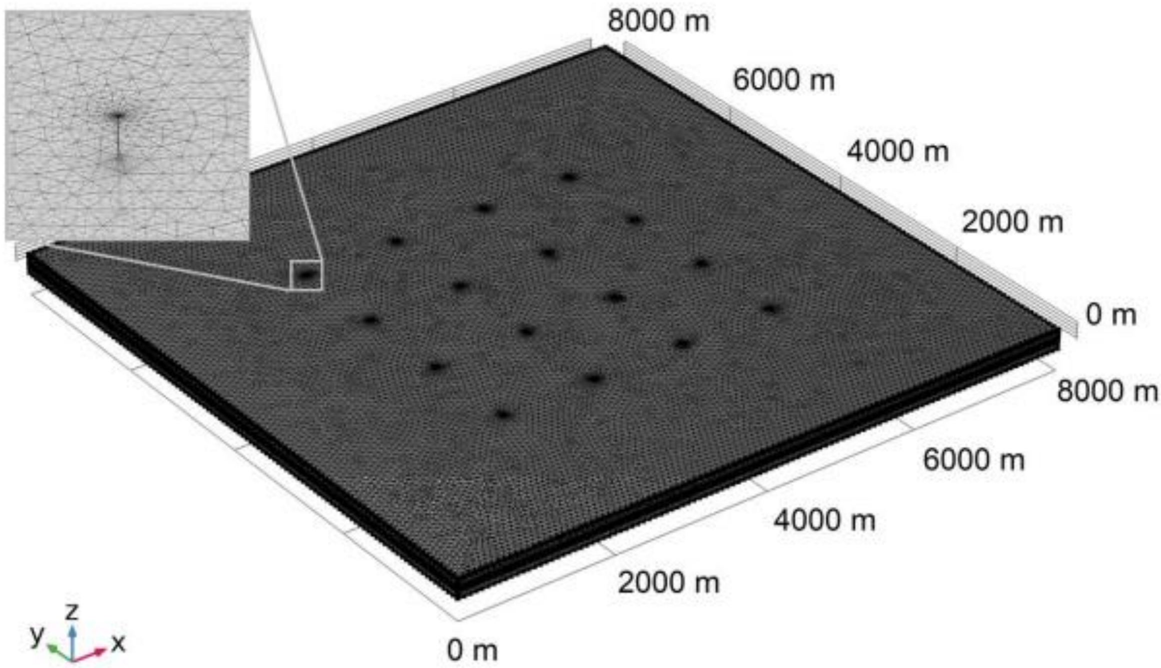

Figure S4: Example of the 3D volumetric mesh applied to simulate the hydrothermal doublet arrays (Mantei et al., 2024). The mesh comprises a higher resolution near the wells to improve the simulation of the fluid flow and heat transport in regions of high gradients.

The spatial discretization of the governing equations requires balancing resolution to capture high thermal and hydraulic gradients with computational efficiency. A fine mesh is used in areas of high gradient near wells (Fig. S4), while a coarser mesh is applied elsewhere. The number of generated volumetric tetrahedral elements is 3221328 and the mesh vertices is 556260. For time discretization, the implicit Euler method, also known as the backward Euler method, is applied. This method is commonly used in computational fluid dynamics and geothermal simulations due to its stability when dealing with stiff problems and its ability to handle large time steps (Blank et al., 2021; Ostermann, 2011).

The following modeling parameters were used (Table S1) to account for the varying geological conditions encountered in the Mesozoic sandstone aquifers in the NGB and to provide best-case and worst-case scenarios of the hydrothermal doublet performances. For references of the model parameters please refer to Mantei et al. (2024).

Table S 1: Overview of the model parameter combination used for different simulation scenarios

Parameter	Value
Inter-well distance [m]	500, 700, 900, 1200
Reservoir thickness [m]	20, 25, 30, 35
Injection temperature [°C]	17, 20, 23, 26
Pumping rate [$l\ s^{-1}$]	30, 40, 50, 60
Permeability (aquifer) [mD]	1, 10, 400, 800
Porosity (aquifer) [%]	15, 20, 25, 30

Additional Results

In total 55 thermo-hydraulic simulations with a simulation time of 50 years were carried out. The focus of the analyses was on specific controlling factors of the performance of a hydrothermal doublet such as thermal breakthrough occurrence time, maximum cooling rate and end temperature at the production wells. Furthermore, the influence of neighboring wells on the performance parameters were investigated.

Selected results are presented below in Figs. S5 and S6.

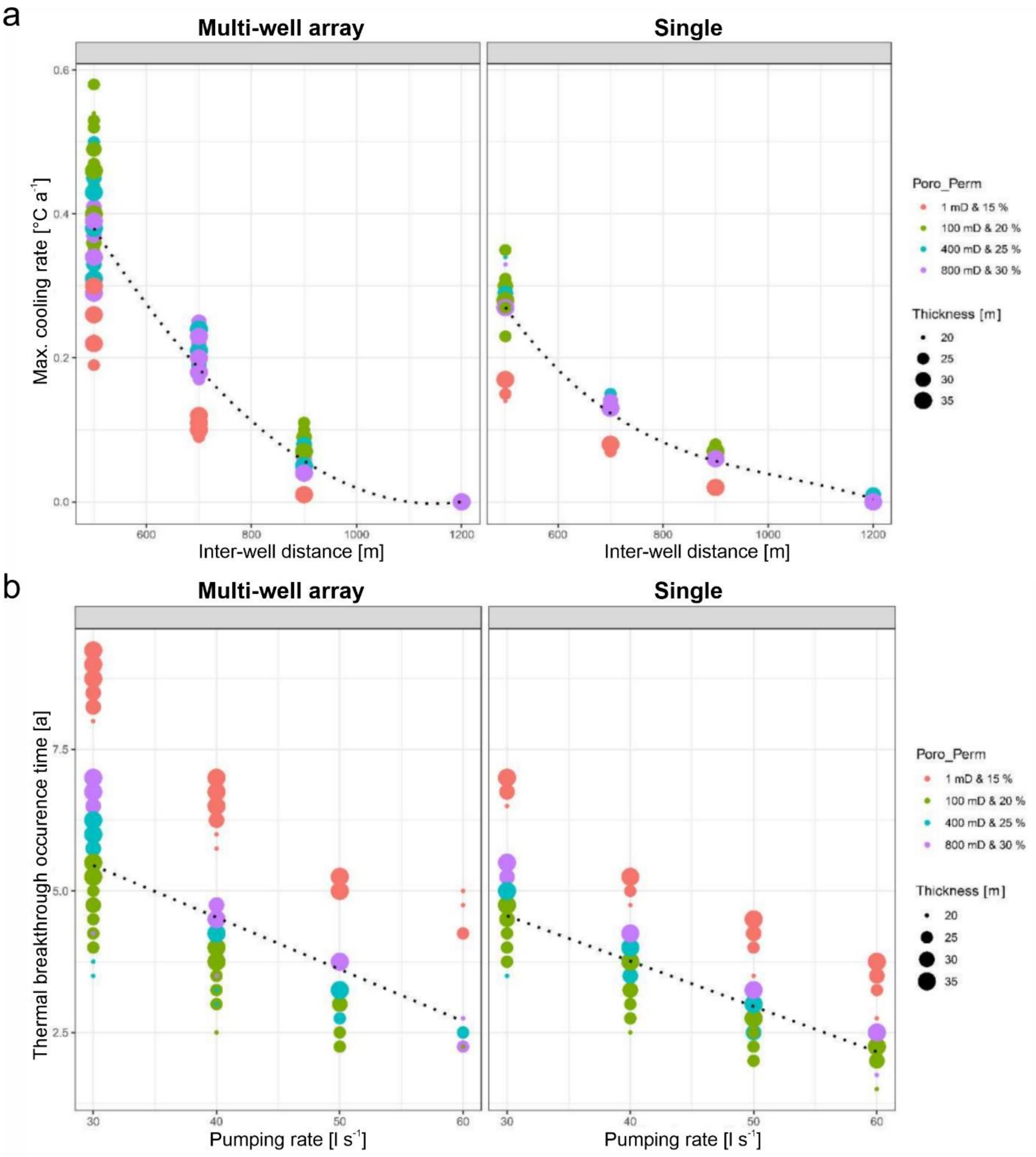

Figure S5: Influence of inter-well distance on the maximum cooling rate (a) and the effect of pumping rate on thermal breakthrough occurrence time (b) are analyzed with respect to single or multi-well arrays, as well as reservoir parameters such as porosity, permeability, and thickness. Graphics modified from Mantei et al. (2024).

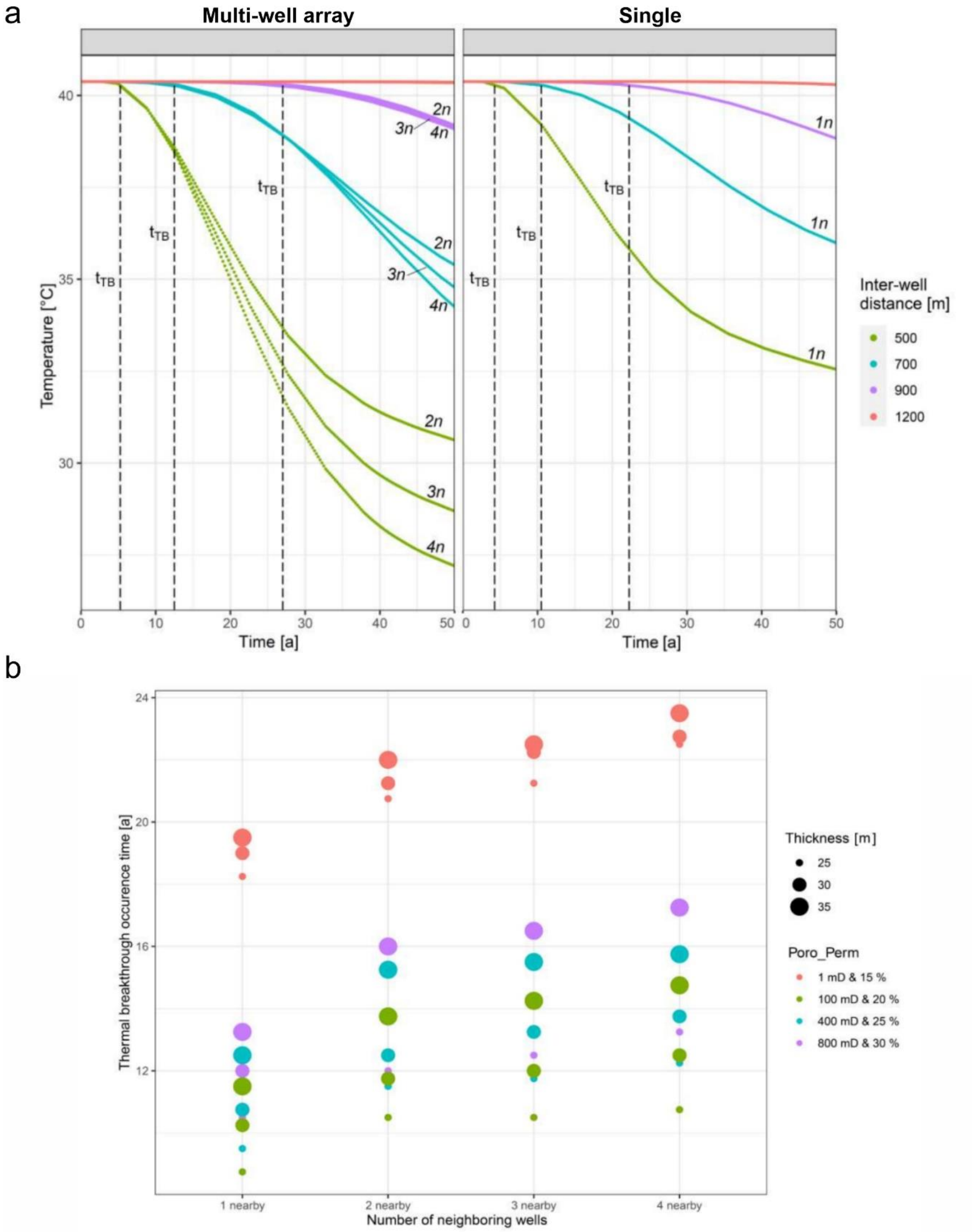

Figure S6: Temperature evolution over time in single or multi-well arrays (a) with respect to inter-well distance and the number of neighbouring wells. (b) Thermal breakthrough occurrence time is influenced by the number of neighbouring wells, reservoir thickness, porosity and permeability. Graphics modified from Mantei et al. (2024).

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