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Geothermal assessment of medium-deep reservoirs in the Upper Rhine Graben (Germany) – the ArtemIS project

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INTRODUCTION

The Upper Rhine Graben (URG) is an approximately 300 km long, 30–40 km wide active Cenozoic rift system located in the south-west of Germany. It hosts siliciclastic and carbonate reservoirs with sedimentary layers up to 4.5 km thick overlying a crystalline basement. Large fault zones facilitate the movement of hot fluids, locally resulting in a geothermal gradient of up to 42 °C km^{-1} (Agemar et al., 2012). The URG is one of Germany's most significant geothermal play types, with several successful deep geothermal projects and ongoing exploration for lithium-bearing brines (Moeck et al., 2019; Frey et al., 2022). Despite this, the geothermal potential of medium-depth reservoirs (400–1500 m) remains insufficiently evaluated, even though these resources could make a substantial contribution to Germany's heat transition. To address this gap, the ArtemIS project (Weydt et al., 2023, 2025) was initiated to extend the German Geothermal Information System (GeotIS, www.geotis.de) to include medium-depth geothermal resources. Its objective is to provide comprehensive geological and technical information for municipalities, energy providers, and non-experts, thereby enabling preliminary geothermal resource assessments and thus, accelerating the heat transition. In addition to a large-scale regional heat assessment, the project includes the development of generic local-scale geothermal use scenario models implemented in COMSOL Multiphysics (e.g., hydrothermal doublets; Mantei et al., 2025), designed to offer GeotIS users insights into the geothermal potential of various locations and geological settings within the URG. All data and results are intended to be made accessible through a COMSOL server and an interactive App integrated into the GeotIS platform. For this purpose, a 3D structural geological model of the URG was developed using data from seismic surveys, well logs, and findings from previous research projects. Literature data, combined with new laboratory measurements on core samples, were used to parameterize the model and estimate the regional heat potential using the Heat-in-Place method. This structural model then served as the basis for creating several localized numerical models in COMSOL Multiphysics, representing different geological settings within the URG. These models were used to evaluate the heat potential and performance of e. g., hydrothermal doublets, borehole heat exchangers (BHE) or aquifer thermal energy storage (ATES) systems. To capture both best- and worst-case scenarios, depth (500–1500 m), geological parameters (e.g., porosity, permeability, thermal conductivity), and operational conditions (e.g., well spacing, pumping rate, injection temperature) were systematically varied.

1 GEOLOGICAL SETTING

The URG forms the central segment of the European Cenozoic Rift System and is bounded by the Vosges, Black Forest, and Swiss Jura (Fig. 1a). It developed during the Oligocene due to intraplate compressional stresses linked to the Alpine and Pyrenean orogenies (van der Vaart et al., 2021). The URG is characterized by a complex hemi-graben structure with a variable position of the depocenters, and a switch of asymmetry. The main striking direction in the central and southern part is NNE-SSW and roughly N-S in the northern part. Geothermal targets are generally related to large fault zones (at > 3.4 to > 5.5 km depth), where the fractured reservoirs show natural permeability (Frey et al., 2022). The sedimentary units overly a variety of plutonic and metamorphic rocks of the Variscan crystalline basement. In the northern part of the URG, Permo-Carboniferous sandstones attain thicknesses of up to 2000 m and comprise a lithologically diverse succession of fine- to coarse-grained siliciclastic and volcanic rocks, with minor carbonate intercalations. Major Triassic geothermal reservoir units include the Buntsandstein and the Upper Muschelkalk formations. The Buntsandstein, ranging from approximately 65 to 500 m in thickness, consists predominantly of porous sandstones that exhibit enhanced hydraulic conductivity in proximity to fault zones. The Upper Muschelkalk, which can reach about 100 m in thickness, is limited to the central and southern segments of the graben and is characterized by intense

fracturing and variable degrees of karstification. Further south, additional geothermal targets are provided by the Middle Jurassic Hauptrogenstein (up to 140 m) and by Upper Jurassic limestones and marls (up to 100 m), both offering high pore volumes, extensive fracturing, and karst features that collectively increase their geothermal potential. The Cenozoic infill of the graben, with a cumulative thickness of as much as 4.5 km, comprises a sequence of fluvial, lacustrine, and marine sediments. Oligocene deposits are the most widespread, whereas younger strata are largely restricted to the northern sector. Coarse-grained marginal facies along the graben shoulders typically display superior hydraulic connectivity compared to the fine-grained deposits in the central basin. In particular, the Pechelbronn Group, Froidefontaine Subgroup, and Niederrödern Group contain medium- to coarse-grained sediments that reach temperature ranges favorable for economically viable direct-use heat extraction.

2 METHODS

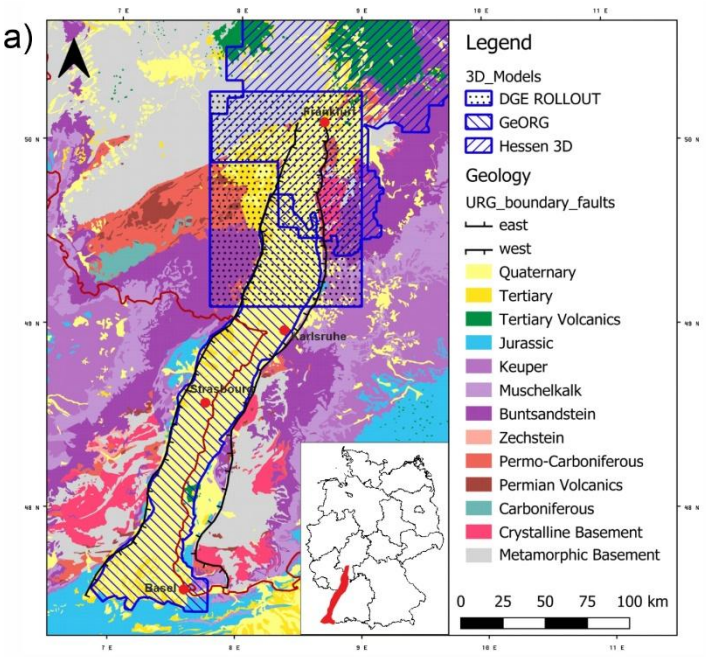
For the construction of the Upper Rhine Graben 3D model, existing datasets and 3D geological models from earlier research initiatives including DGE Rollout (van der Vaart et al., 2021), Hessen 3D (Bär et al., 2021), and GeORG (GeORG Projektteam, 2013) were integrated within the Petrel modeling software. Newly acquired 3D seismic data was processed to refine and validate the preliminary structural framework. Lithological and geophysical logs provided by geological surveys were digitized to improve the definition of key horizons. Laboratory measurements of rock properties from core and outcrop material obtained from published literature and additional data supplied by the Geological Survey of Hesse (HLNUG) were compiled to support the parameterization of the model (e.g., Bär et al., 2020, 2021). For the northern part of the Upper Rhine Graben, an initial 3D structural model was developed, and a regional Heat-in-Place estimation was performed following the approach of Muffler and Cataldi (1978). In order to perform numerical simulations with COMSOL Multiphysics, small-scale models of representative sites within the URG were created within Petrel and the horizons and major fault planes were exported as point clouds and converted into STL format via Python to ensure a seamless integration into COMSOL Multiphysics (Fig. 2a). The resulting files were imported into COMSOL Multiphysics, where a generic block was partitioned by these surfaces into subvolumes that represent geological layers (volumes) and faults (surfaces). Reservoir properties such as porosity, permeability and thermal conductivity were assigned using a scenario-based approach employing minimum, mean, and maximum parameter values to capture the full range of possible heat-extraction rates and recovery efficiencies. These geological scenarios were combined with variable operational conditions, including time-dependent mass flow, injection temperature, and well depth. The initial geothermal field was derived from the built-in temperature model provided by GeotIS and each simulation covers a period of 30 years. For each test site hydrothermal doublets, ATES and BHE were simulated. Following completion of the simulations, system-specific extraction rates and recovery efficiencies were evaluated by grouping the results according to operational parameters.

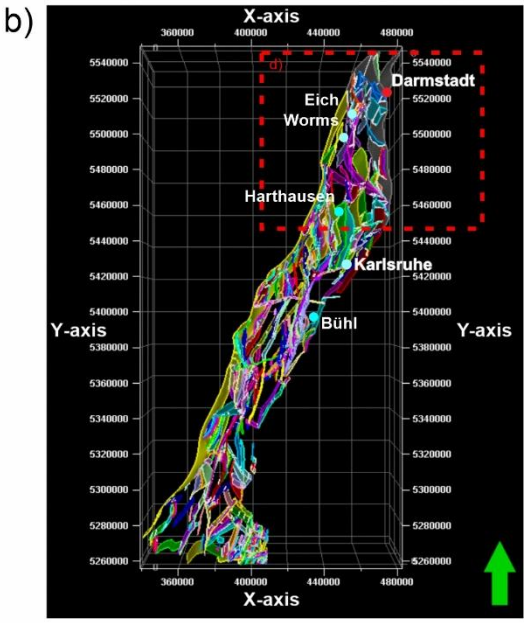
3 RESULTS

A comprehensive 3D static fault model for the whole URG was created (Fig. 1b), which shows complex fault systems that vary throughout the study area. Based on the available data, the model currently differentiates five major units, which are 1) the Niederrödern Fm., 2) the Froidefontaine Fm., 3) and the Pechelbronn Fm. (all three units belonging to the Tertiary), as well as 4) the Triassic unit, and 5) the Permo-Carboniferous (mainly including the Rotliegend). These units lie on top of the crystalline basement. Based on literature research, representative rock property ranges were defined and subsequently used to parametrize the model units and assess the regional heat potential (Fig. 1c). Figure 1d shows the complete 3D model of the northern section of the URG and the results of the heat-in-place calculation, which indicate a good geothermal potential at shallow to intermediate depth for heat generation.

Several small-scale 3D models—such as those for Harthausen, Worms, and Karlsruhe—were created in Petrel to serve as input for the COMSOL simulations. The sites were selected based on the availability of subsurface information (e.g., well logs, lithological profiles, and drilling reports) to ensure that model construction and parameterization were as realistic as possible. To simulate hydrothermal doublet systems, the injection and production wells were placed on opposite sides of a fault plane, whereas for ATES or BHE configurations the fault plane was excluded from the simulations. Figure 2b presents the temperature model of a hydrothermal doublet simulation at Harthausen after 30 years, and Figure 2c shows the corresponding Darcy velocity field along the fault plane. The resulting temperature distribution illustrates the localized thermal perturbation caused by well operation, as well as the upward migration of warm water from deeper strata along the fault structure. Additionally, the geological and operational parameters were varied, resulting in, for example, 243 test runs for the hydrothermal doublet simulation. These were generated by combining the three subsurface-property scenarios (minimum, mean, maximum) with three well depths, three pumping rates, and three injection temperatures. This full-factorial design (3 × 3 × 3 × 3 × 3) ensures a comprehensive assessment of parameter

interactions and their impact on doublet efficiency. In the final step, potential heat-extraction rates were estimated by calculating the thermal power delivered in each scenario. Substantial variations in target metrics are observed across the different scenarios, with mean values representing conservative estimates. For example, Figures 2d and 2e illustrate the average extractable power of a hydrothermal doublet at the Harthausen test site as a function of pump rate and well depth.





c)

Reservoir properties based on literature data

Model unit	Density [g cm^{-3}]	Porosity [%]	Spec. heat capacity [J kg^{-1} K^{-1}]
1. Niederrödern	2.72	16.9	696
2. Froidefontaine	2.72	12.9	750
3. Pechelbronn	2.69	13.9	770
4. Triassic	2.65	12.6	728
5. Permo-Carboniferous	2.68	13.0	741

Regional heat potential in the northern Upper Rhine Graben

Model unit	Thickness [m]	Heat potential [J]	Heat potential [TWh]
1. Niederrödern	437	2,75E+20	7,64E+04
2. Froidefontaine	226	1,64E+20	4,56E+04
3. Pechelbronn	472	3,21E+20	8,92E+04
4. Triassic	760	4,36E+20	1,21E+05
5. Permo-Carboniferous	497	4,37E+20	1,21E+05
Total	**2392**	**1,63E+21**	**4,53E+05**

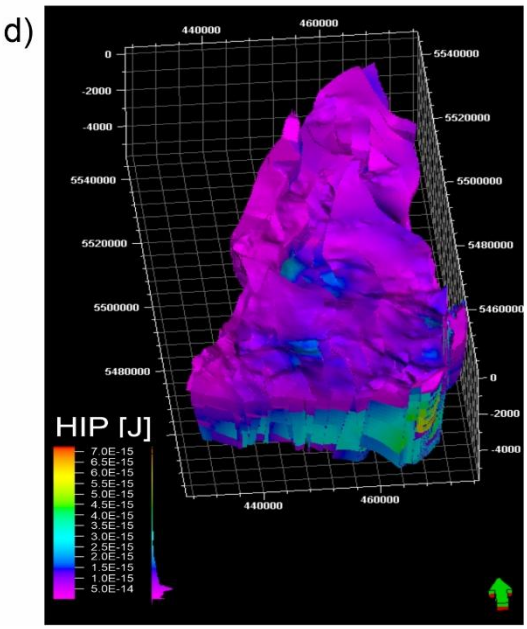


Figure 1: a) Simplified geological map of the study area (Weydt et al., 2025 and references therein). b) 3D structural model of the Upper Rhine Graben with the investigated test sites of the numeric simulations marked in blue. c) Overview of the investigated reservoir units, their rock properties and heat potential. d) 3D model of the northern Upper Rhine Graben and the results of the Heat-in-Place calculation.

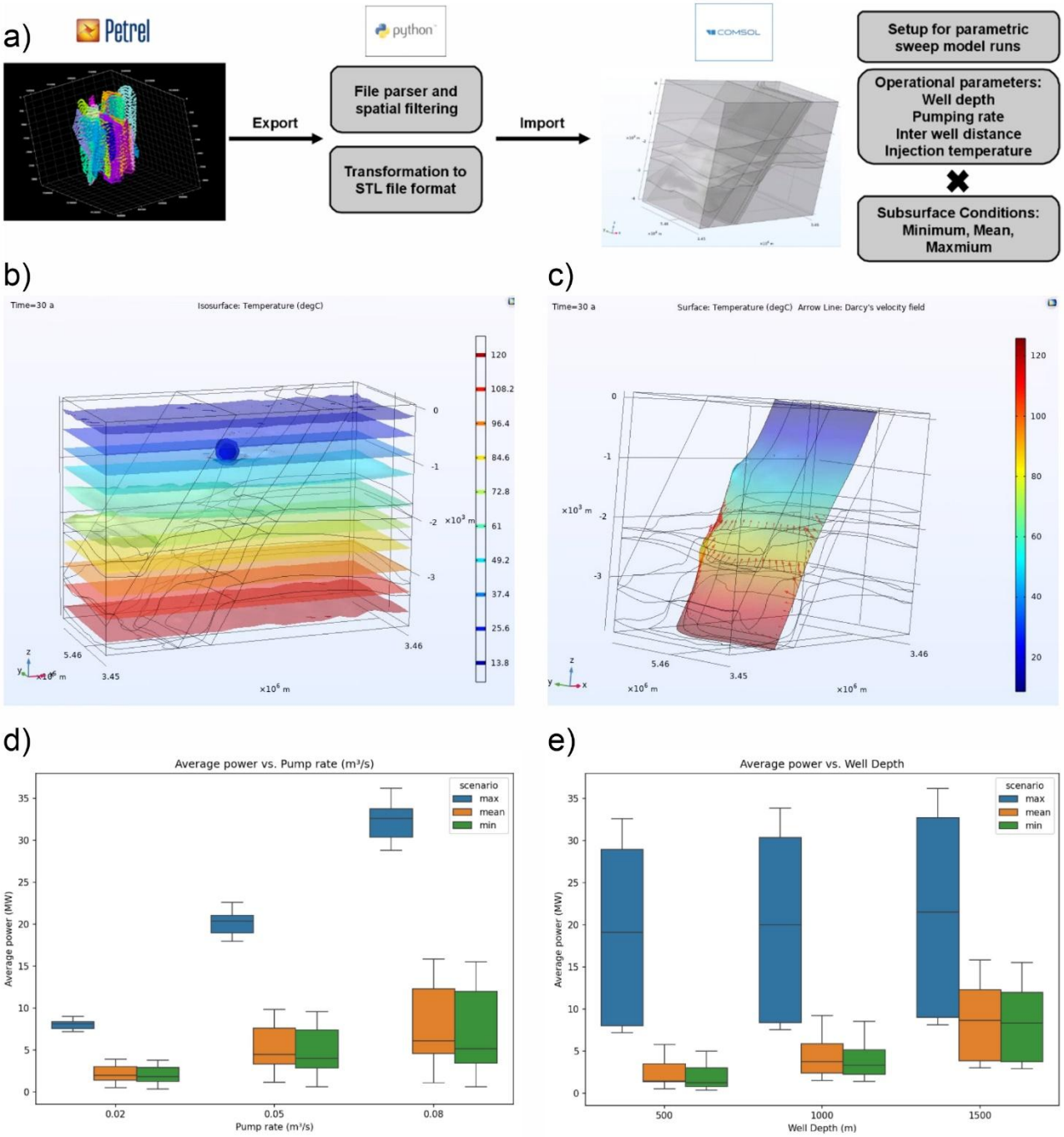


Figure 2: a) Schematic workflow showing the different steps required to incorporate the 3D Structural model from Petrel into COMSOL Multiphysics as well as operational and geological parameters used for the parametric sweep. b) Temperature model of the Harthausen test site after 30 years. c) Darcy velocity model of the same test site, illustrating upward migration of the reservoir fluids along the fault plane. Average power as a function of d) pump rate and e) well depth at the Harthausen test site.

4 CONCLUSION AND OUTLOOK

This paper presents new results from the ArtemIS project, which aims to assess the medium-depth geothermal potential for different play types in Germany—focusing here on the Upper Rhine Graben, a major graben system located in the southwest of the country. Based on literature data, well logs and seismic data, potential geothermal reservoir units within the URG were defined and a comprehensive 3D structural model of the URG was created in Petrel. Subsequently, the regional heat potential was calculated indicating promising results for heat generation even at shallow to intermediate depth. The structural model then served as the basis for simulating e.g., hydrothermal doublets and estimating local-scale heat extraction rates. Therefore, a new work

flow was developed which allowed the incorporation of the local-scale 3D structural models into COMSOL Multiphysics. Various locations within the URG were then selected to reflect the range of geological settings within the URG, while operational parameters—such as well depth, pumping rate, inter-well distance, and injection temperature—were systematically varied. In addition, reservoir properties were adjusted to simulate best-case and worst-case scenarios. These simulations provide valuable insights into the thermal performance and feasibility of geothermal exploitation at different locations. In future work, the here presented approach will be extended to additional sites across the URG to provide representative local-scale geothermal potential assessments and support optimized planning of geothermal development projects. The data will subsequently be made available through the GeotIS platform and the GeotIS Web App, ensuring broad accessibility for stakeholders, planners, and researchers. This integration will support informed decision-making by providing up-to-date geothermal resource data in an interactive and user-friendly format.

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