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Application of Rapid Reservoir Modeling to Address Uncertainty in the Exploration of Faulted Geothermal Systems

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INTRODUCTION

Developing geothermal projects involves multifaceted risks, including technical, economic, and social factors. A major component of this overall risk arises from subsurface uncertainty, especially when reservoir architecture and petrophysical properties are poorly constrained. This challenge is further amplified by limited data availability, which is typical during early exploration stages (Witter et al., 2019; Kassem et al., 2025). Traditional reservoir modeling workflows are time-consuming and require extensive datasets, which restrict the number of geological scenarios that can be tested. Consequently, early-stage evaluations often rely on limited deterministic structural interpretations, hindering thorough uncertainty analysis, slowing down decision-making processes (i.e., drilling or not), and leading to poor risk assessment. To address these limitations, the EU-funded FindHeat initiative is developing a workflow that formalizes and accelerates conceptual model-based exploration approaches (Geiger et al., 2025). Our workflow follows the Play–Concept–Scenario-Realizations structure to evaluate plausible subsurface architectures systematically.

Within this broader context, fault-hosted geothermal reservoirs are particularly important and challenging to address, as there have been successful developments in some areas (Soultz-sous-Forêts) while also notable setbacks (induced seismicity at Basel) that underscore the role of addressing subsurface uncertainty (Deichmann et al., 2014; Baujard et al., 2017) For clarity when addressing the impact of different elements contributing to uncertainty, we explicitly define the architectural features considered. We distinguish first-order fault geometry, which comprises the seismically resolvable attributes such as fault trace, orientation, dip, length and height, and net displacement or throw. In contrast, the fault-zone architecture includes the embedded damage zone, which contains distributed fractures, deformation bands, breccia, gouge, and other sub-seismic features that control local porosity and permeability. The combination of the first-order fault geometry and small-scale features in the fault damage zone together defines the bulk flow behavior through the fault (Caine et al., 1996; Faulkner et al., 2010; Choi et al., 2016; Torabi et al., 2020). While first-order fault geometry can be imaged at seismic scale, damage-zone attributes and porosity and permeability variations lie below seismic resolution and therefore cannot be directly imaged, which creates uncertainty in predicting fluid flow and heat-extraction potential. Despite this, reservoir models often simplify faults as discrete planes, whereas these structural objects form three-dimensional deformation zones with multiple features that control fluid pathways (Wibberley et al., 2008). This combination of geometric complexity, limited direct imaging, and first-order control on flow behavior implications motivates a scenario-generation approach.

Building on this rationale, this study focuses on the Rittershoffen geothermal field in the Upper Rhine Graben (URG). The play type in this area is granitic basement. The concept is a fault-hosted geothermal reservoir where the fault and its associated damage zone act as the main fluid pathway. The scenarios are linked to the geometry and properties of this fault, and the realizations explore the equiprobable versions of those scenarios. Two geothermal boreholes, GRT-1 and GRT-2, were drilled between 2012 and 2014, targeting the regional Ritttershoffen normal fault, which strikes north-south, dips 45º westward, and has a vertical offset of approximately 200 to 250 m. The fault has been identified as a geothermal target due to its high temperature gradients. Despite extensive investigation, the geometry of the main controlling fault remains only partially understood (Baujard et al., 2017; Vidal et al., 2017). The high injectivity observed in wells GRT-1 and GRT-2 has been attributed to high fracture density, damage-zone development, mineral alteration patterns, and the alignment of permeable structures with the current stress field. Acoustic-image logs and well-log data revealed multiple open fracture zones in both wells, indicating that permeability is concentrated in these damage zone-

related fractures. These permeable fracture zones often coincide with temperature anomalies, mud losses, and low electrical resistivity signatures interpreted as hydrothermal circulation, confirming their role as primary fluid conduits (Baujard et al., 2017; Vidal et al., 2017; Glaas et al., 2021).

The structural complexity at Rittershoffen highlights the need for approaches that can efficiently explore alternative geological scenarios. Rapid Reservoir Modeling (RRM) enables geoscientists to quickly sketch multiple plausible subsurface architectures (Jacquemyn et al., 2021). This study integrates RRM with an experimental design framework to systematically sample alternative fault zone configurations. These scenarios are then evaluated through thermo-hydraulic simulations using the Open Delft Advanced Research Terra Simulator (open-DARTS; Voskov et al., 2024), allowing direct quantification of how structural and petrophysical uncertainties influence fluid flow and heat transport behavior in fault-controlled geothermal systems. This study supports the broader FindHeat objective of accelerating conceptual model exploration and establishing a structured methodology for linking geological uncertainty to performance predictions.

1 METHODS AND PRELIMINARY RESULTS

To investigate the influence of fault-related heterogeneities in Rittershoffen, the screening methodology of Dong et al. (2025) is adopted as a reference. Their approach, which integrates a fractional-factorial experimental design, sketch-based 3D reservoir modeling using RRM, and single-phase flow diagnostics, is modified to fit the URG case study by integrating a full-factorial experimental design, RRM, and thermo-hydraulic simulations using open-DARTS.

1.1 Design of Experiment

Caers (2011) highlighted that experimental design plays a crucial role in systematically exploring this uncertainty and prioritizing key factors with a limited number of model evaluations.

The aim of this experimental design is to assess the impact of geometrical features, petrophysical properties, and their interaction. The geometrical features explored include the width and symmetry of the fault damage zone and the shape of the fault trace, while the petrophysical properties focus on porosity and permeability enhancements possibly linked to open fractures (see Table 1).

Table 1 Design of Experiment Factors and Levels. The total number of experimental runs is calculated as N=2×3×2×3×2=72and covers every combination of levels for factors A, B, C, D, and E.

Type	Factor	Levels	Settings
Geometry	A. Total damage zone width (TDZ)	2	Low: 130 m High: 300 m
	B. Damage zone symmetry expressed in a relationship between hanging wall (HW) and footwall (FW) thickness	3	Low: HW = FW = 0.5 DZT Medium: HW = 0.75 TDZ, FW = 0.25 TDZ High: HW = 0.95 TDZ, FW = 0.05 TDZ
	C. Fault trace geometry	2	Low: Straight line High: Tortuous and based on seismic data
Petrophysics	D. Open fractures in the damage zone expressed in terms of porosity (ϕ [%]) and permeability (k [m^2])	3	Low: ϕ=0.1, k=2.8 x 10^{-15} Medium: ϕ=1.75, k=2.8 x 10^{-14} High: ϕ=15, k=2.8 x 10^{-13}
	E. Background fracture network of the granite expressed in terms of porosity (ϕ [%]) and permeability (k [m^2])	2	Low: ϕ=0.1, k=1 x 10^{-16} High: ϕ=0.8, k=1 x 10^{-14}

1.2 3D modeling of Scenarios using RRM

The factors related to geometry are explicitly captured in 3D models created using RRM. Initially, the models' dimensions are 6.6 x 6.6 x 3.3 km, to represent the full extent of the field. However, to reduce the simulation time, the models used for thermo-hydraulic simulations span 3 x 3 x 3 km. The combinations of geometric factors and levels yield twelve 3D RRM models. Figure 1 shows a sketched model example (a) and how it is produced in RRM (b and c). The map view reflects changes to the fault trace; when nothing is explicitly drawn, the fault trace is linear (b).

Additionally, an initial sensitivity analysis was performed to evaluate the impact of grid discretization in RRM. The results indicated that breakthrough times, Lorenz coefficient, and recovery values converge when the cell

size is approximately 30 meters in all directions. Consequently, this resolution was chosen for Δx, Δy, and Δz in the subsequent simulation stage.

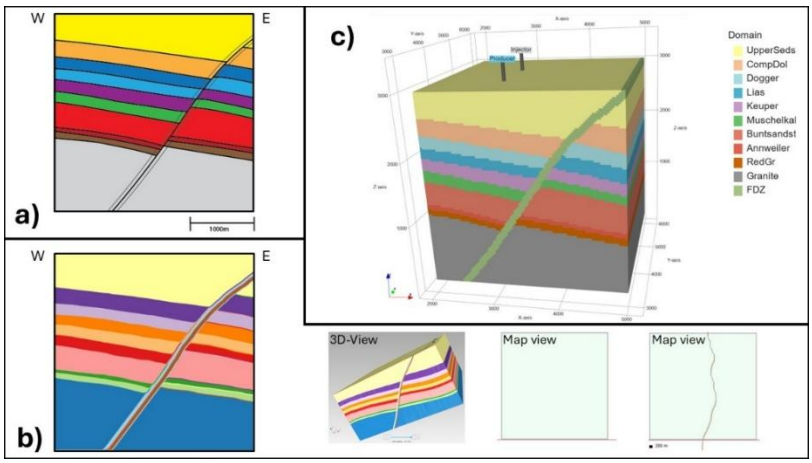


Figure 1. Creation of 3D models using RRM. a) Conceptual model sketch of the Rittershofen area. b) Different views of the RRM interface.c) Fluid diagnostics module that allows the display and modification of properties such as the porosity, permeability, or pressure. In this case, the domains (or lithological units) are shown.

1.3 Thermo-hydraulic simulations using open-DARTS

Simulations are performed in open-DARTS (Voskov et al., 2024), featuring an injector and a producer well located 1 km apart and placed along the fault strike. The perforation in both wells is limited to the fault interval.

The reservoir conditions are based on the parameters defined by Baujard et al. (2017) and Daniilidis et al. (2021). The initial reservoir temperature is 443.15 K (~170ºC) at approximately 3 km depth. The initial conditions assume a uniform temperature with this value, later simulations will employ the geothermal gradient of the area. Both the injection and production rates are set at 600 m^3/day, with an injection temperature of 323.15 K (50ºC). No extra overburden, underburden, or sideburden layers are added. Boundary volumes are only defined on the -YZ plane, which limits the west side of the model where the fault does not intersect the borders.

1.4 Preliminary results

To illustrate how variations in fault-zone geometry influence thermal performance, we present a subset of six dynamic simulations derived from the experimental design. These realizations isolate geometric effects by fixing petrophysical properties: open fractures within the damage zone follow the medium-permeability configuration, whereas the background fracture network in the granite follows the low-permeability configuration. Models are numbered from 1 to 6. Odd-numbered models incorporate a linear fault trace, and even-numbered models incorporate a tortuous trace. The degree of fault-damage-zone (FDZ) asymmetry is defined by the relative hanging-wall (HW) and footwall (FW) thicknesses explored in the design: models 1 and 2 assign both HW and FW to 0.5 times the damage-zone thickness (DZT); models 3 and 4 assign HW to 0.75 DZT and FW to 0.25 DZT; and models 5 and 6 assign HW to 0.95 DZT and FW to 0.05 DZT.

Additionally, this study utilizes the thermal lifetime, as defined by Daniilidis et al. (2021):

$$T_{prod_t} \leq 0.95\, T_{prod_{t-0}} \tag{1}$$

Where T_{prod_t} is the production temperature at a given time t, and $T_{prod_{t-0}}$ is the initial reservoir temperature. At Rittershoffen conditions, this criterion corresponds to a breakthrough temperature of 421 K (147.85 °C).

Figure 2 shows the output temperatures over time from the dynamic simulations and a horizontal line representing the thermal lifetime. The models exhibit a spread of lifetime of five years. For models sharing the same FDZ asymmetry, those with a linear fault trace reach breakthrough earlier than those with a tortuous trace. The most significant curve separation occurs between models 5 and 6, which correspond to the most asymmetric FDZ configuration, characterized by the thickest HW. Overall, the results show that greater asymmetry in the FDZ leads to later breakthrough times.

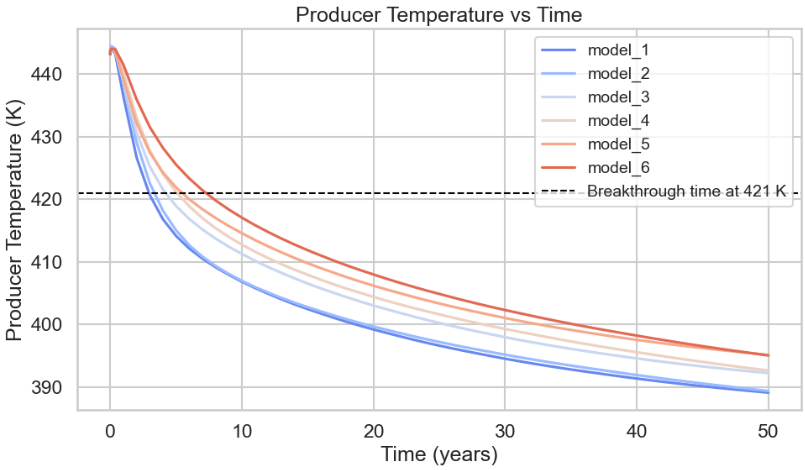


Figure 2. Simulated producer temperature vs. time for the subset of 6 models.

2 DISCUSSION AND CONCLUSION

The simulations indicate that variations in fault-zone geometry are a first-order control on thermal-breakthrough behavior: tortuous fault traces tend to delay breakthrough relative to linear traces, and increasing FDZ asymmetry correlates with later breakthrough times in the model suite. These findings align with the conceptual and field evidence that fault-zone architecture governs fluid pathways and transmissivity (Caine et al., 1996; Faulkner et al., 2010) and with observations that permeability in crystalline reservoirs concentrates in fault-related fracture zones (Evans et al., 1997; Glaas et al., 2021). Importantly, we represent the fault as a three-dimensional volumetric deformation zone that includes a damage zone and associated permeability related to distributed open fracture sets, consistent with fault-zone characterizations in the structural geology literature (Choi et al., 2016), rather than as an idealized planar discontinuity. This volumetric representation is central to this study because it resolves the spatial extent of the damage zone, enabling variations in HW/FW proportions and trace tortuosity to influence simulated flow paths and heat transport.

A few limitations should be noted. This subset of six models keeps petrophysical parameters fixed to isolate geometric effects, so trends reflect interactions under specific permeability contrasts. Thermal breakthrough times are shorter than expected at Rittershoffen, indicating that simulation parameters, particularly well spacing and injection rates, can be refined to improve realism. Moreover, while field data confirm that permeability concentrates in fault-related fracture zones (Baujard et al., 2017; Vidal et al., 2017; Glaas et al., 2021), extrapolating well-scale observations to reservoir scale remains uncertain.

Future work will extend the analysis to the full experimental design and apply distance-based generalized sensitivity analysis (DGSA) to quantify parameter sensitivities and interactions across the ensemble. This will test whether trends observed in this model subset persist under broader petrophysical and geometric variations and will rank key contributors to reservoir performance. Together, these results demonstrate that volumetric fault representations combined with scenario-based simulation provide a powerful framework for linking structural uncertainty to decision-relevant metrics in fault-hosted geothermal exploration, guiding more informed appraisal and development strategies.

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