

Tradeoffs Between Planar and Geologic Discrete Fracture Networks for EGS: Insights from Utah FORGE

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ABSTRACT

Discrete Fracture Network (DFN) models are widely used to evaluate fluid flow and heat transfer in Enhanced Geothermal Systems (EGS). However, the choice of fracture representation introduces a fundamental tradeoff between complexity and computational efficiency. In this study, we compare two DFN approaches applied to the Utah FORGE site: a geologic DFN derived from microseismic data, geomechanical characterization, and borehole observations, and a simplified planar fracture DFN in which fractures are represented as idealized planes connecting injection and production wells. The geologic DFN captures the heterogeneity of natural fracture systems, including variable orientations, lengths, and connectivity. This complexity ideally leads to more realistic predictions of fluid circulation pathways and thermal drawdown, but it comes at the cost of high computational demand. By contrast, the planar fracture DFN sacrifices geologic realism for efficiency, allowing rapid parameter exploration and long-term forecasting. While this simplification enables broader scenario testing, it risks overestimating fracture connectivity and sweep efficiency. Simulation results indicate that fracture connectivity, rather than fracture count or geometry alone, exerts the strongest control on long-term heat recovery. The geologic DFN better represents site-specific variability, while the planar DFN is more practical for sensitivity studies and optimization tasks. This comparison highlights the importance of selecting the appropriate DFN representation based on research objectives, balancing the need for geological accuracy with computational tractability in EGS modeling.

1. INTRODUCTION

Utah FORGE is a U.S. Department of Energy–sponsored field laboratory established to accelerate the development and commercialization of Enhanced Geothermal Systems (EGS). Situated in the Mineral Mountains of Utah, the site targets a high-temperature granitic basement reservoir at depths of approximately 2–3 km, where temperatures exceed 175–225 °C (Allis et al., 2016). Although these conditions are favorable for geothermal energy production, the crystalline rock exhibits extremely low native permeability, necessitating hydraulic stimulation to create a viable heat-exchange system. Utah FORGE provides a uniquely controlled environment in which stimulation, circulation, and reservoir modeling can be integrated and evaluated at field scale.

The geological framework of the FORGE reservoir is characterized by relatively massive granitoid rock with multiple pre-existing fracture sets that exhibit limited natural connectivity. Borehole image logs, core analyses, and petrophysical measurements indicate that while fractures are present, they do not form a hydraulically connected network capable of sustaining circulation prior to stimulation. (Jones et al., 2024) As a result, reservoir performance depends critically on the ability of stimulation treatments to enhance fracture connectivity and create flow paths between injection and production wells. Understanding how these induced fracture networks evolve and function is essential for predicting pressure response, circulation efficiency, and long-term thermal sustainability.

Operational experience at Utah FORGE has demonstrated that fluid flow is strongly localized within a subset of “stimulated” fractures. Microseismic monitoring, production logging, and fiber-optic measurements indicate that only a fraction of fractures in stage 8- 10 contribute significantly to flow, leading to pronounced channeling (Xing et al., 2025.). Such channelized flow can reduce effective reservoir volume, accelerate thermal breakthrough, and limit heat recovery if not properly managed. Conversely, more distributed flow across multiple fractures enhances fracture–matrix heat exchange and improves long-term thermal performance. Accurately capturing these competing behaviors is therefore a central challenge in reservoir modeling at FORGE.

Coupled thermo-hydraulic (TH) modeling is required to evaluate these processes because pressure propagation, flow redistribution, and heat transport are inherently linked. TH simulations resolve both advective heat transport within fractures and conductive heat transfer between fractures and the surrounding rock matrix, enabling prediction of thermal breakthrough timing and production temperature decline. While fully coupled thermo-hydro-mechanical (THM) models can capture fracture aperture evolution under stress, their computational cost, numerical stability and complexity limit their applicability for systematic scenario testing (Podgorney et al., 2023). For operational analysis at Utah FORGE, TH modeling provides a practical balance between physical realism and computational efficiency.

This study compares two Discrete Fracture Network (DFN) representations of the Utah FORGE reservoir: an idealized DFN and a geologically constrained, data-informed DFN. The idealized DFN comprises simplified, symmetric fracture geometries intended to capture reservoir behavior under planned stimulation scenarios from stage 1-10 perforation locations specifically. In our previous work, we presented simplified modeling approaches to predict reservoir performance (Kumawat et al., 2025a; Chan, 2025; Kumawat et al., 2025b). In contrast, the geologic DFN incorporates fracture orientations, lengths, and spatial distributions derived from site-specific datasets, including borehole image logs, microseismic mapping, and flow diagnostics. Munday and Podgorney (2025), presented a history-matched model based on this geologic DFN. Together, these two DFN representations reflect alternative modeling strategies commonly employed in enhanced geothermal system (EGS) studies and provide a framework for evaluating how fracture representation influences predicted reservoir performance. In this paper, both models are compared under identical reservoir characteristics, including boundary conditions, physical parameters, and material properties.

Both DFNs representations are implemented within a finite-element modeling framework that explicitly resolves fractures as lower-dimensional features embedded in a three-dimensional rock matrix. The finite element method offers flexibility in handling complex fracture geometries and resolving sharp pressure and temperature gradients at fracture–matrix interfaces. Simulations are conducted under identical injection and production conditions to ensure that differences in model outcomes can be attributed solely to fracture network representation rather than operational parameters.

By restricting the analysis to thermo-hydraulic processes and excluding mechanical coupling, the study isolates the influence of fracture geometry and connectivity on reservoir behavior. Model outputs include pressure evolution, flow distribution, thermal breakthrough timing, cumulative heat recovery, and computational cost over a 10-year production period. The results provide operationally relevant insight into the trade-offs between DFN complexity and predictive capability at Utah FORGE, informing decisions related to model selection, stimulation strategy evaluation, and long-term reservoir management.

2. CONCEPTUAL DISCRETE FRACTURE NETWORK

2.1 Idealized DFN

In this study, an idealized DFN refers to a simplified, engineered fracture representation constructed solely from well perforation locations, with no inclusion of pre-existing natural fractures. Fractures are initiated deterministically at perforation points or clusters and are assigned idealized geometries, orientations, and sizes based on assumed stress conditions and stimulation design parameters. This approach isolates the hydraulic fracture system created during stimulation and removes geological complexity associated with natural fracture networks, allowing focused evaluation of perforation spacing, fracture connectivity, and flow behavior driven exclusively by engineered fractures.

At the Utah FORGE site, the stimulation program was conducted in two distinct phases. In April 2022, three stimulation stages were completed over the interval from 3084 m to 3349 m measured depth. Subsequently, in April 2024, an additional twelve fracturing stages were executed: eight stages were pumped in the injection well, and four stages were pumped in a vertically offset but parallel production well. The 2024 injection well stages continued uphole from the three stages previously stimulated in 2022, including the re-fracturing of Stage 3. In the production well, five stages were perforated based on fracture hit indications identified from measurements from fiber-optic cables that had been cemented on the exterior of the casing (McLennan et al., 2025).

In the idealized DFN developed for this study, 27 fractures associated with Stages 1 through 10 in the injection well are considered and presented in Figure 1. Fractures from the production well and any potential interactions with natural fractures are excluded, ensuring that the DFN represents a purely engineered hydraulic fracture system for controlled analysis.

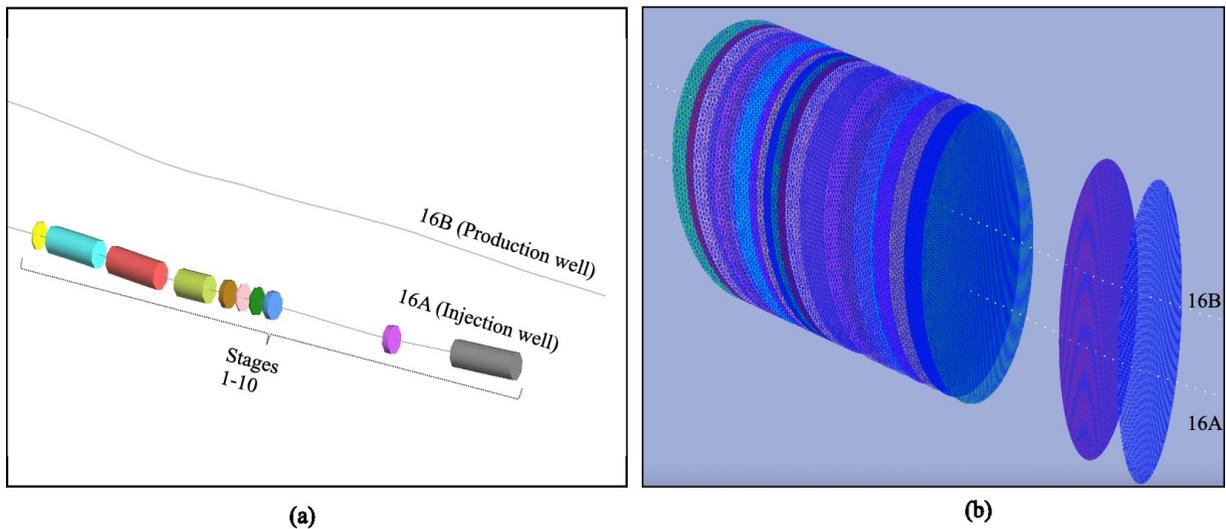


Figure 1: Idealized DFN showing (a) stages 1–10, where color length corresponds to the 465m of stimulated region, and (b) the meshed DFN with circular plates.

2.2 Geology Based DFN

The Reference Discrete Fracture Network (DFN) for the Utah FORGE site was created by integrating fracture, lithologic, and geophysical data from five deep wells drilled into crystalline basement rock. Fracture orientations and intensities were primarily interpreted from FMI and UBI image logs, while acoustic, gamma ray, and porosity logs were analyzed using k-means clustering to identify intervals with distinct rock types or mechanical properties. These clusters helped define meaningful depth intervals and identify significant fracture zones, with results validated against available core data. Across the wells, four dominant fracture sets were identified, and their orientations and relative proportions were updated as new well data became available, rather than forcing uniform behavior across the reservoir (Finnila and Jones, 2024).

The DFN itself was constructed by combining a stochastic background fracture network with discrete, deterministic features. Stochastic fractures were generated using a truncated power-law size distribution, hexagonal fracture shapes, and fracture intensities derived from volumetric calculations that correct for well-orientation bias. Stochastic fractures intersecting the wellbores were removed and replaced with fractures explicitly interpreted from image logs, while additional discrete features were added to represent major fracture zones, faults, and planar features inferred from microseismic data during hydraulic stimulation. The latest DFN consist of fracture planes fitted to the latest MEQ catalog datasets, and an alternative connected DFN for modeling purposes. It should be noted in this work all initial apertures and conductivity are not function of dips, and normal stress. The resulting DFN provides a geologically constrained, three-dimensional representation of fracture connectivity suitable for simulating stimulation, flow, and thermal behavior at the FORGE site. The DFN adapted for this study is developed by Finnila (2025), is presented in Figure 2 and can be accessed via GDR. The uncertainties in these DFN representations are aperture, length, conductivity, cohesion and friction angle.

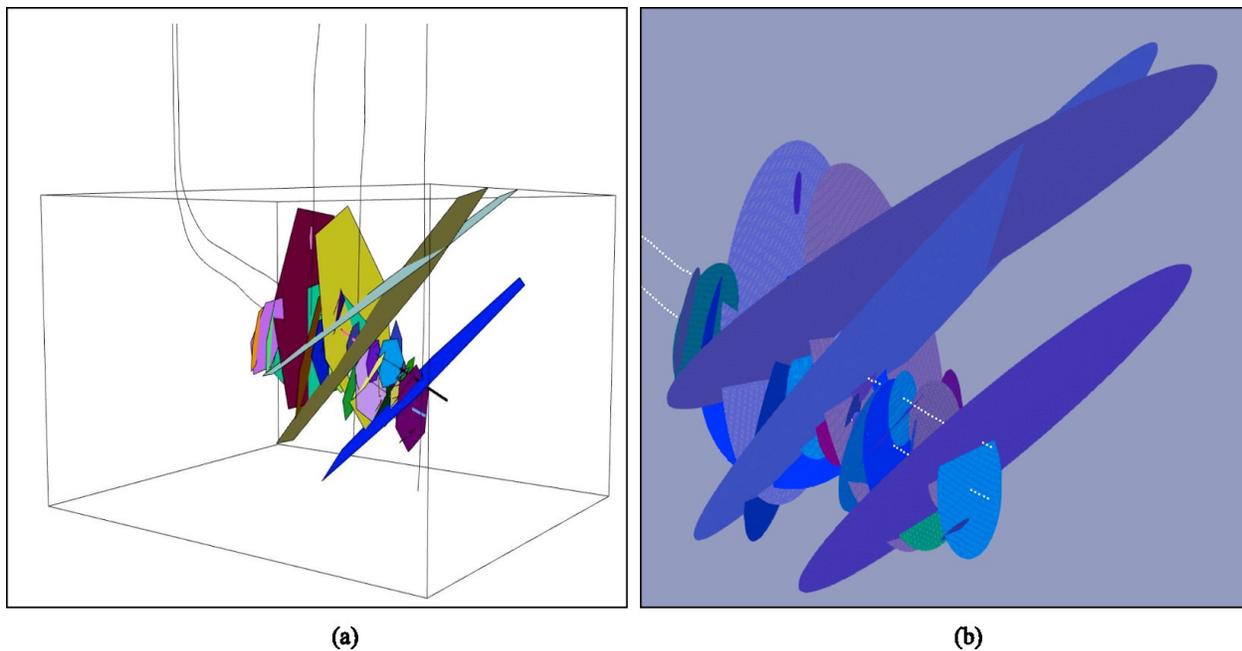


Figure 2: Geologic DFN (a) schematic of DFN adopted by Finnila (2025) (b) meshed DFN used for the study

3. METHODOLOGY

The numerical domain represents a 3D volume encompassing the interwell region between the injection well 16A(78)-32 and the production well 16B(78)-32. The model dimensions are chosen to fully capture the stimulated zone and allow sufficient buffer from boundary effects. The mesh is constructed using unstructured tetrahedral elements with localized refinement near fracture surfaces to resolve steep gradients in pressure and temperature. The mesh ranges in size from 10m on the fractures to 200m on the boundaries.

Fractures from each DFN realization are explicitly represented as two-dimensional planar features embedded within the three-dimensional rock matrix. In the idealized DFN, all fractures are assumed to be identical and to contribute equally to fluid flow, as summarized in Table 1. In contrast, the geologic DFN incorporates designed fracture geometries, with flow allocation informed by the 2024 circulation test conducted at Utah FORGE, presented in Table 1. It should be noted that all physical and material properties listed in Table 2 are identical for all fractures and for the matrix system. The only differences between the two DFN models arise from the fracture representations themselves, which are primarily governed by fracture shape, size, and orientation.

Fracture flow properties are governed by the fracture aperture, a , which is allowed to vary as a function of pore pressure. Aperture evolution is represented using a linear elastic relationship in which the aperture increases from a reference value, a_0 , at reference pressure p_0 in proportion to changes in pore pressure scaled by the bulk modulus of the surrounding rock matrix, K (Equation 1). This formulation provides a first-order approximation of pressure-induced aperture changes resulting from elastic deformation of the host rock, assuming a half-space geometry.

$$a = a_0 + \frac{1}{K}(p - p_0) \quad (1)$$

Table 1: Flow distribution in both DFNs

Stage (cluster)	Idealized DFN-1	Geologic DFN
Stage 1	3.7%	5.70%
Stage 2	3.7%	3.30%
Stage 3	3.7%	9.40%
Stage 4	3.7%	8.00%
Stage 5	3.7%	4.20%
Stage 6 (2)	3.7%	-
Stage 6 (1)	3.7%	-
Stage 7 (3)	3.7%	-
Stage 7 (2)	3.7%	-
Stage 7 (1)	3.7%	-
Stage 8 (8)	3.7%	-
Stage 8 (7)	3.7%	1.80%
Stage 8 (6)	3.7%	-
Stage 8 (5)	3.7%	-
Stage 8 (4)	3.7%	10.10%
Stage 8 (3)	3.7%	7.54%
Stage 8 (2)	3.7%	3.50%
Stage 8 (1)	3.7%	3.30%
Stage 9 (8)	3.7%	1.61%
Stage 9 (7)	3.7%	2.71%
Stage 9 (6)	3.7%	4.71%
Stage 9 (5)	3.7%	5.21%
Stage 9 (4)	3.7%	1.21%
Stage 9 (3)	3.7%	-
Stage 9 (2)	3.7%	-
Stage 9 (1)	3.7%	2.01%
Stage 10	3.7%	25.80%

Flow within fractures is modeled using lower-dimensional porous flow equations that are integrated over the fracture surface and scaled by the aperture to obtain an equivalent volumetric representation. This approach effectively scales both fracture porosity and permeability by the fracture aperture. Fractures are assumed to be fully saturated with fluid, such that the intrinsic fracture porosity is unity and the effective porosity equals the aperture. Fracture permeability is derived from the classical parallel-plate approximation, with additional modification to account for fracture surface roughness and reduced dimensionality. The resulting effective permeability scales with the cube of the aperture and includes a dimensionless roughness parameter, r (Equation 2). For the comparative analysis it was assumed that all fractures are identical in terms of initial conductivity and have been assigned with initial identical aperture and material properties, independent of injected flow allocation, reflecting measured or representative values for the granitic host rock at Utah FORGE. Owing to the low permeability of the surrounding matrix, fluid circulation and heat transfer are strongly concentrated within/adjacent to the discrete fracture network.

$$\tilde{k} = rk_p a = r \frac{a^3}{12} \quad (2)$$

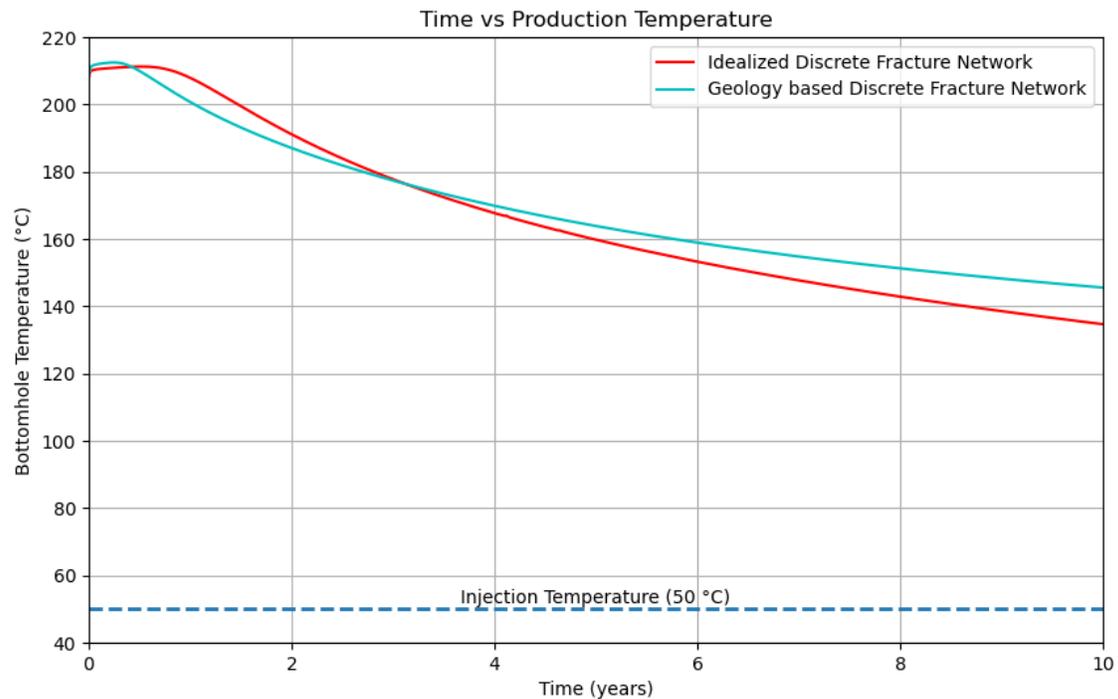
Table 2: Model parameters used for numerical simulation

Parameter	Units	Value
Matrix Size	m	2200 (x) × 2000 (y) × 1900 (z)
Matrix Permeability	m ²	1×10^{-16}
Matrix Porosity	-	2×10^{-4}
Fracture Aperture	m	2×10^{-4}
Fracture Roughness	-	12×10^{-3}
Biot Coefficient	-	0.47
Bottomhole Injection Temperature	K	323.15 (50°C)
Injection Rate (water)	kg/s	26.5

The numerical simulations were conducted using a consistent TH modeling framework. All simulations were performed using FALCON (Fracturing And Liquid CONvection), an open-source, finite-element-based simulator developed within the MOOSE (Multiphysics Object-Oriented Simulation Environment) framework by Idaho National Laboratory. FALCON is specifically designed to simulate coupled multiphysics processes in subsurface environments. In this study, we focus exclusively on coupled thermal-hydraulic (TH) processes, which are the dominant physical mechanisms governing heat extraction and fluid transport in an EGS. (Permann et al., 2020)

3. RESULTS AND DISCUSSION

The following section summarizes the thermo-hydraulic response of the Utah FORGE reservoir as predicted by the idealized and geologic DFN models. By holding all physical properties and operational parameters constant, the analysis highlights how differences in fracture representation alone affect flow partitioning, thermal breakthrough, long-term heat recovery, and numerical performance during sustained circulation. Figure 3 illustrates the evolution of production (bottomhole) temperature over a 10-year circulation period for the idealized and geologic DFN representations. Both models begin with similar initial production temperatures (210°C), indicating comparable early time access to reservoir heat and similar startup behavior. During the first year, thermal decline is modest in both cases, reflecting dominant advective heat transport within fractures and limited thermal depletion of the surrounding matrix.

**Figure 3: Production Temperature Evolution for Idealized and Geologic DFN Models**

Beyond approximately after a year of operation, the temperature trajectories diverge. The idealized DFN exhibits a more rapid decline in production temperature, reaching approximately 130°C at year 10. In contrast, the geologic DFN sustains higher production temperatures throughout the simulation, remaining near 141°C at year 10. This represents an approximately 11°C ($\approx 2.7\%$) higher production temperature relative to the idealized case at the end of the simulation. The delayed thermal drawdown in the geologic DFN indicates improved thermal sweep efficiency and enhanced fracture–matrix heat exchange, consistent with more spatially distributed flow paths and reduced channeling.

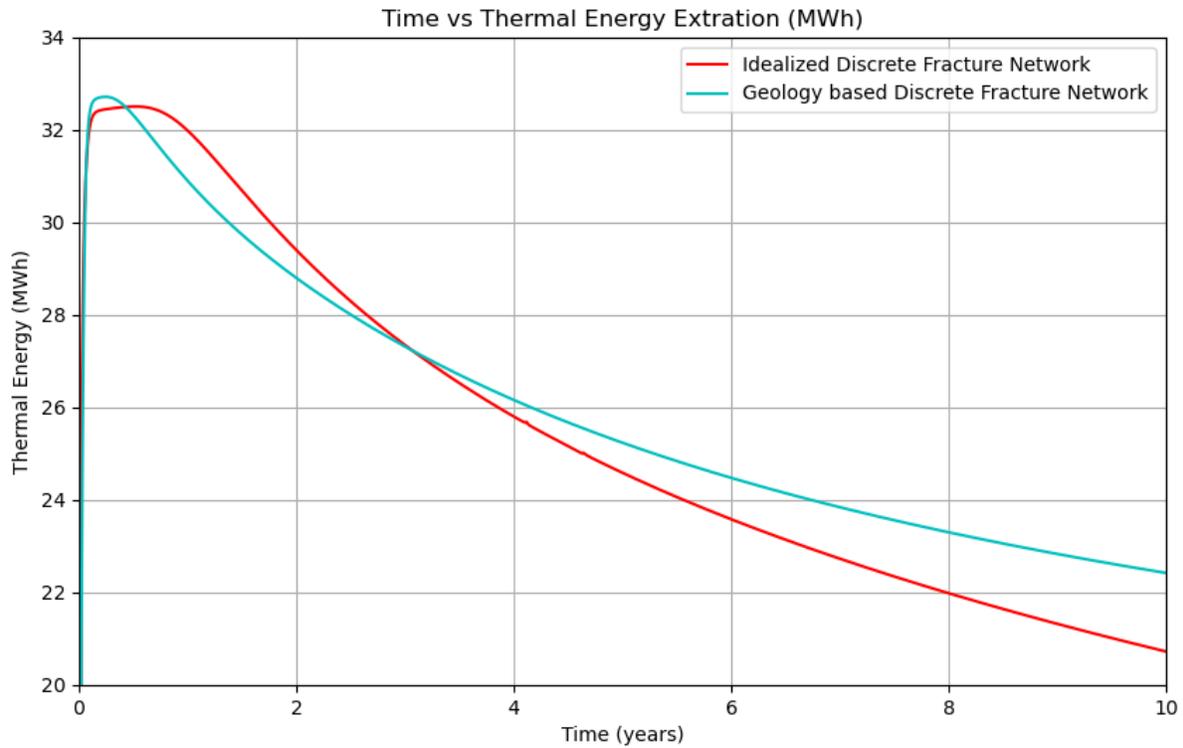


Figure 4: Thermal Energy Extraction Comparison Between Idealized and Geologic DFNs

The temporal evolution of thermal energy extraction is shown in Figure 4. Both DFNs representations display a rapid increase in thermal power during the initial phase of circulation, reaching peak values slightly above 32 MWh within the first year. This early-time behavior reflects high production temperatures and efficient heat extraction under near-initial reservoir conditions.

Following peak output, thermal energy extraction declines steadily in both models as cooling progresses. However, the rate of decline differs markedly. The idealized DFN experiences a more pronounced reduction in thermal output, decreasing to approximately 20.8 MWh by year 10. In contrast, the geologic DFN maintains higher thermal power, producing approximately 22.4 MWh at the same time. This corresponds to a $\sim 7.7\%$ increase in sustained thermal output relative to the idealized DFN at the end of the simulation. Over the full production period, this difference translates into higher cumulative energy recovery for the geologic DFN, underscoring the importance of fracture network complexity for long-term thermal sustainability.

The observed differences in temperature and energy production can be attributed to fundamental differences in flow distribution between the two DFN representations. The idealized DFN promotes more direct and channelized flow between injection and production wells, resulting in rapid thermal breakthrough along dominant fractures. While this configuration supports efficient short-term heat extraction, it limits thermal interaction with the surrounding rock matrix and reduces effective reservoir volume.

In contrast, the geologic DFN incorporates a more heterogeneous fracture network with varied orientations and connectivity. This complexity promotes flow partitioning across multiple fractures, increasing residence time and enhancing conductive heat transfer from the rock matrix. It should be noted in this work all initial apertures and conductivity are not function of dips, and normal stress. The resulting distributed flow regime delays thermal breakthrough and sustains higher production temperatures over longer time scales.

Figure 5 compares computational time as a function of simulated reservoir time for the two DFN representations. The idealized DFN completes the full 10-year simulation in approximately 52 hours of wall-clock time, whereas the geologic DFN requires approximately 95 hours. This represents nearly a twofold increase in computational cost associated with the geologic DFN.

Both simulations exhibit an approximately linear relationship between wall time and simulated time, indicating stable numerical performance. However, the increased fracture density and geometric complexity of the geologic DFN introduce greater numerical stiffness and higher computational overhead. These results highlight a key practical consideration for reservoir modeling at Utah FORGE: while geologic DFNs provide improved physical realism and predictive capability, they significantly increase computational demand, which may limit their use in large parametric or uncertainty studies.

The combined thermal and computational results demonstrate that DFN conceptualization strongly influences predicted reservoir performance and modeling efficiency. The idealized DFN captures first-order trends in pressure response, temperature decline, and energy

extraction at substantially lower computational cost. As such, it is well suited for early-stage screening, sensitivity analysis, and rapid evaluation of operational scenarios.

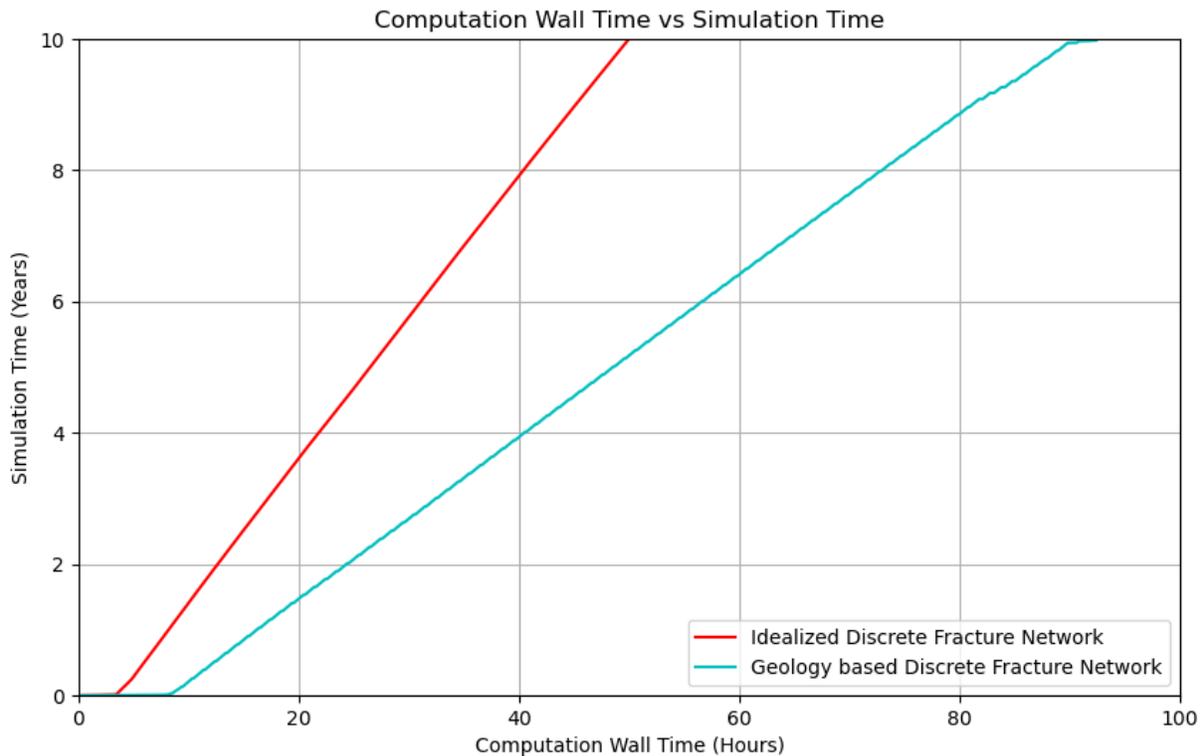


Figure 5: Computational Wall Time as a Function of Simulation Time for DFN Models

However, the idealized DFN systematically underpredicts long-term production temperature and thermal energy recovery due to enhanced flow channeling and premature thermal breakthrough. The geologic DFN, while more computationally expensive, produces more optimistic and potentially more realistic projections of reservoir longevity by better representing fracture heterogeneity and distributed flow. This suggests that geologic DFNs are better suited for detailed performance forecasting, interpretation of long-duration circulation tests, and assessment of commercial viability at Utah FORGE.

These findings support a tiered modeling strategy for EGS development at Utah FORGE. Idealized DFNs can be used efficiently to explore operational design space, assess sensitivity to injection rates and well configurations, and guide experimental planning. Geologic DFNs should be reserved for focused analyses where accurate prediction of thermal sustainability and long-term energy recovery is critical. By quantifying the performance gains and computational costs associated with increased DFN complexity, this study provides actionable guidance for selecting appropriate modeling approaches to support stimulation design, circulation testing, and long-term reservoir management at Utah FORGE.

Conclusion

The simulation results demonstrate that DFN representation strongly influences predicted thermal performance in the Utah FORGE reservoir. Although both DFN models exhibit similar early-time behavior, their long-term responses diverge significantly. The idealized DFN produces more direct and channelized flow paths between the injection and production wells, leading to earlier thermal breakthrough and a faster decline in production temperature. In contrast, the geologic DFN sustains higher production temperatures throughout the 10-year simulation, with an approximately 11°C higher outlet temperature at year 10. This difference reflects more distributed flow and enhanced fracture–matrix heat exchange in the geologic DFN, which increases the effective heat-swept reservoir volume and delays thermal depletion. Thermal energy extraction results further highlight the impact of fracture network complexity. While both models achieve comparable peak thermal power during early circulation, the idealized DFN experiences a more rapid decline in thermal output, reaching approximately 20.8 MWh by year 10. The geologic DFN maintains higher sustained power, producing approximately 22.4 MWh at the same time, corresponding to approximately 7.6% improvement in long-term energy production. These results indicate that fracture connectivity and flow partitioning, rather than fracture count or uniform geometry, exert the strongest control on long-term heat recovery in EGS reservoirs. The improved thermal performance of the geologic DFN comes at a substantial computational cost. The geologic DFN requires nearly twice the wall-clock time of the idealized DFN to simulate the same 10-year period, reflecting increased fracture density and geometric complexity. These results emphasize a practical tradeoff: simplified DFNs are efficient and suitable for rapid scenario

testing, whereas geologic DFNs provide more realistic and optimistic predictions of thermal sustainability and should be reserved for detailed performance forecasting and interpretation of long-duration circulation tests.

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