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Enhanced Geothermal Systems (EGS) Modeling with Volsung: Evaluating System Design Geometry and Stimulation Spacing

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Keywords

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ABSTRACT

The viability and performance of Enhanced Geothermal Systems (EGS) depend heavily on well architecture, stimulation spacing, and the spatial dimensions of the stimulated reservoir volume. In this study, the Volsung geothermal reservoir simulator was used to evaluate the thermal recovery potential of several EGS configurations, with a focus on sensitivity to geometry and fracture layout.

To validate Volsung for high-resolution EGS modeling, we first replicated the temperature decline curves presented by Gringarten et al. (1975) using a 400 m × 1000 m × 1000 m domain with 1 m grid cells. The analytical solution, based on an assumption of constant-temperature orthogonal to the flow direction, predicted thermal breakthrough at year 10. This result was replicated in Volsung with a 2D grid and constant vertical temperature. In contrast, a 3D model grid, allowing temperature variation in all directions, predicted breakthrough approximately 7 years earlier. This underscores the limitations of the constant-temperature assumption imbedded within EGS type-curve solutions and highlights the importance of explicitly modeling thermal gradients within fractures over time.

Building on this validation, we simulated the geometry proposed by Fercho et al. (2025) for the Project Cape site (1650 m × 300 m × 150 m). Results showed thermal decline starting within the first year of production, raising concerns about long-term sustainability at this scale. A full-scale EGS system (3000 m × 500 m × 500 m) was then modeled, demonstrating that 20 years of sustained generation could be achieved with 10 m fracture spacing. Further modeling showed that even with 100 m fracture spacing and fracture heterogeneity, the system-maintained production with modest thermal decline over two decades.

This work demonstrates Volsung's ability to capture detailed heat and fluid dynamics in EGS reservoirs and overcome key limitations of traditional analytical approaches. It offers a fully integrated platform for evaluating, designing, and optimizing future EGS developments.

1. Introduction

Enhanced Geothermal Systems (EGS) represent a transformative opportunity to unlock geothermal energy in regions without naturally permeable reservoirs. Unlike conventional hydrothermal systems, EGS relies on engineered fracture networks to circulate fluid through hot rock, enabling heat extraction at depth. As the industry transitions from concept to commercialization, accurate performance forecasting becomes essential for investment decisions, well design, and long-term field planning.

Analytical models, such as those derived from Gringarten et al. (1975), have played a foundational role in early EGS evaluations. These solutions offer insights into idealized thermal decline behavior but rely on simplifying assumptions that may not hold in real 3D systems, including constant temperature along the fracture orthogonal to the flow direction. This assumption in particular, eliminates the ability to resolve spatial flow heterogeneity and can lead to overly optimistic projections of thermal breakthrough and long-term heat recovery.

To improve our predictive capability for EGS systems, reservoir simulation tools must resolve fine-scale thermal processes within complex, heterogeneous domains. Volsung is an integrated simulation platform designed for the geothermal industry that includes a reservoir, wellbore and surface network simulator (Franz et al. 2019). Previous applications of Volsung have focused on modelling conventional geothermal systems, but the capability to do high-resolution, fully coupled thermal-fluid modeling make it well suited for modern EGS design evaluation. This study uses Volsung to assess the performance of multiple EGS configurations, with a focus on how geometry and fracture spacing influence thermal sustainability.

We begin by validating Volsung against the Gringarten analytical solution for 10 fractures with 40m spacing. From there, we evaluate the EGS system design proposed by Fercho et al. (2025) and compare performance against a full-scale commercial layout. The results reveal critical dependencies on resolving the temperature variation across the fracture plane, fracture spacing, and system scale, highlighting the importance of 3D modeling during the EGS system design and planning phase.

2. Modeling Framework

Numerical simulations were performed using Volsung. Volsung supports both 2D and 3D simulations using a finite-volume approach with fully implicit time-stepping, allowing users to define permeability, porosity, thermal conductivity, and other rock and fluid properties at the cell level (Franz et al. 2019). For this study, all simulations were conducted with water as the working fluid, and injection/production rates were set to initially approximate 10 MW of gross electricity production per fracture array.

2.1 Gringarten Model Validation

To validate Volsung's ability to reproduce analytical EGS model results, an initial simulation was constructed to match the assumptions and geometry of the Gringarten et al. (1975) example solution provided in their paper. To replicate the analytical assumption of constant temperature orthogonal to the flow direction, the model was configured without vertical discretization. The simulation domain measured 400 m × 1000 m × 1000 m, with 1-meter grid resolution applied parallel to the fracture plane.

The validation model consisted of 10 vertical fractures spaced 40 m apart. Figure 1(a) shows the configuration used to match the analytical solution. This 2D model successfully reproduced the temperature decline behavior presented by Gringarten, with a close match illustrated in Figure 2, where Volsung results (black triangles) closely follow the analytical solution (green line).

A second model using the same geometry introduced vertical discretization, allowing temperature to vary across the height of the fractures (Figure 1(b)). As shown in Figure 2, the 3D Volsung model with vertical temperature variation predicted thermal breakthrough approximately 7 years earlier than the analytical solution. This demonstrates that Gringarten's assumption of constant Z-temperature can underpredict early thermal decline. The result underscores the importance of explicitly modeling the thermal profile within fractures when evaluating EGS system performance over time.

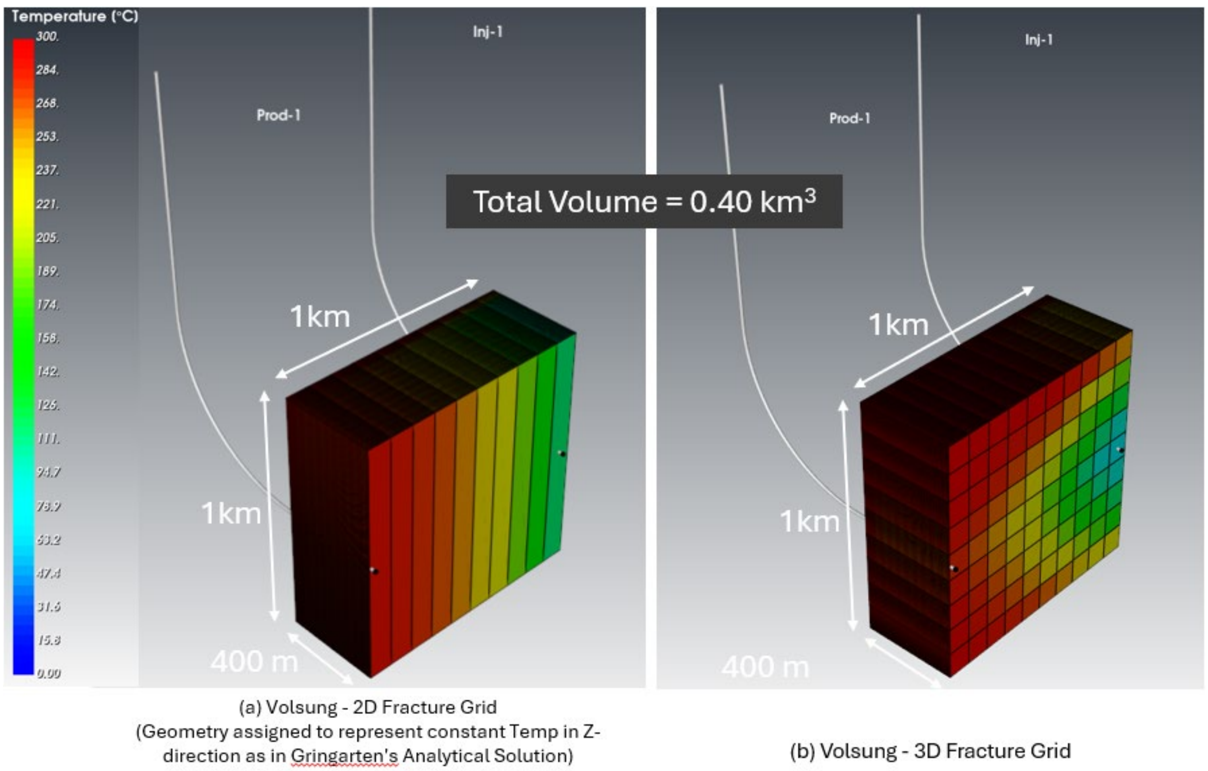

Figure 1 – (a) 2D fracture grid consisting of 400 cells in the x-direction, 10 in the y-direction, and 1 in the z-direction. (b) 3D fracture grid consisting of 400 cells in the x-direction, 10 in the y-direction, and 9 in the z-direction. Both grids simulate 10 uniformly spaced vertical fractures with homogeneous permeability and 40 m spacing.

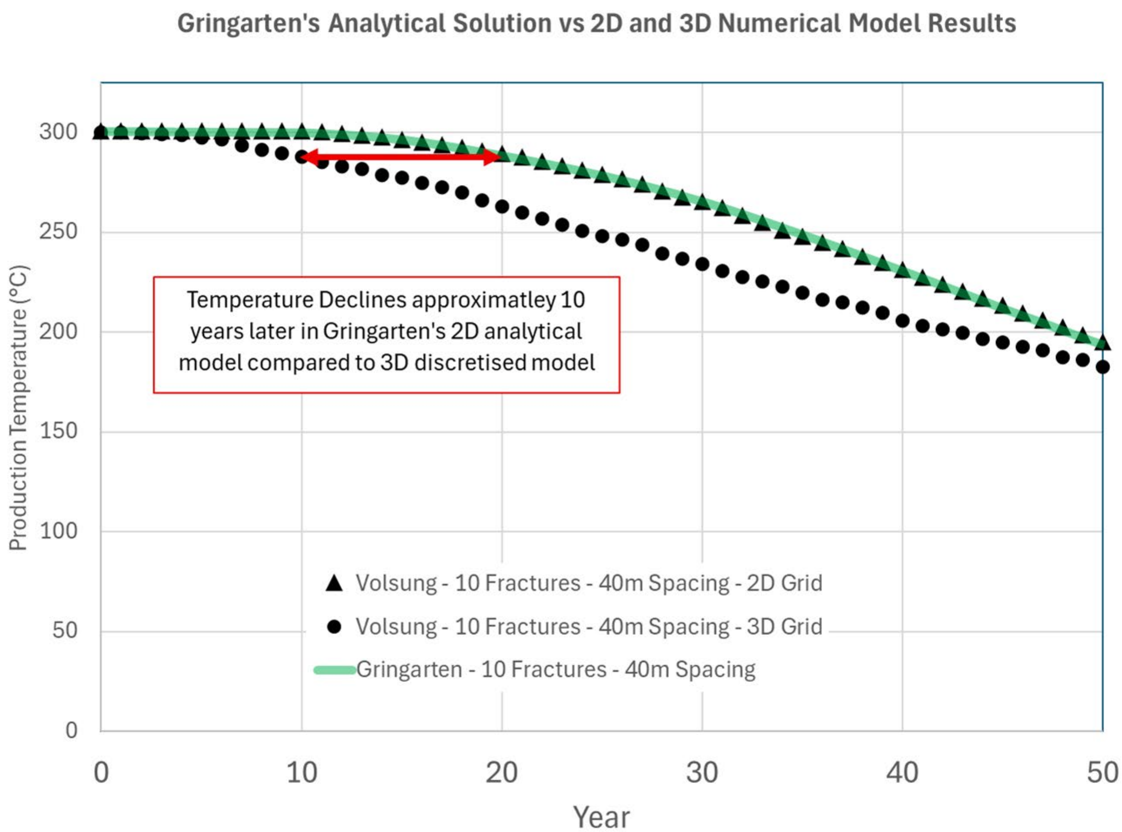

Figure 2 – Comparison of temperature decline curves from Gringarten's analytical solution and Volsung simulations. The 2D Volsung model closely matches the analytical prediction, while the 3D model predicts earlier thermal decline, highlighting the limitations of the constant temperature assumption in the analytical model.

2.2 Fervo 2025 Geometry

The next scenario simulated the EGS system design proposed by Fercho et al. (2025). This configuration, hereafter referred to as the *Fervo 2025 Geometry*, consists of an EGS layout with two injection wells and one production well. The design utilizes 1650 m well laterals, with 50 vertical fractures spaced 33 m apart, each fracture measuring 300 m wide by 150 m tall.

The reservoir was initialized at a temperature of 220 °C, with injection fluid entering at 80 °C. A total injection rate of 360 ton/hr was applied and a matching production rate of 360 ton/hr was targeted. The production equivalent to approximately 7 MW-gross power generation. The grid geometry for this system is shown in Figure 3.

This geometry was implemented in a 3D Volsung model using discretized fracture zones with homogeneous permeability. The surrounding host rock was modeled as impermeable, with heat transfer occurring via conduction only. The simulation measured the production temperature at the central production well.

Figure 4 presents the temperature results, which show thermal breakthrough occurring late in the first year, followed by continued temperature decline over the remainder of the simulation at approximately 4 °C/year. These results contrast with the expectations based on the Gringarten type curve analysis predicting delayed breakthrough, highlighting the importance of 3D modeling in capturing thermal depletion dynamics that may not be evident in simplified analytical frameworks.

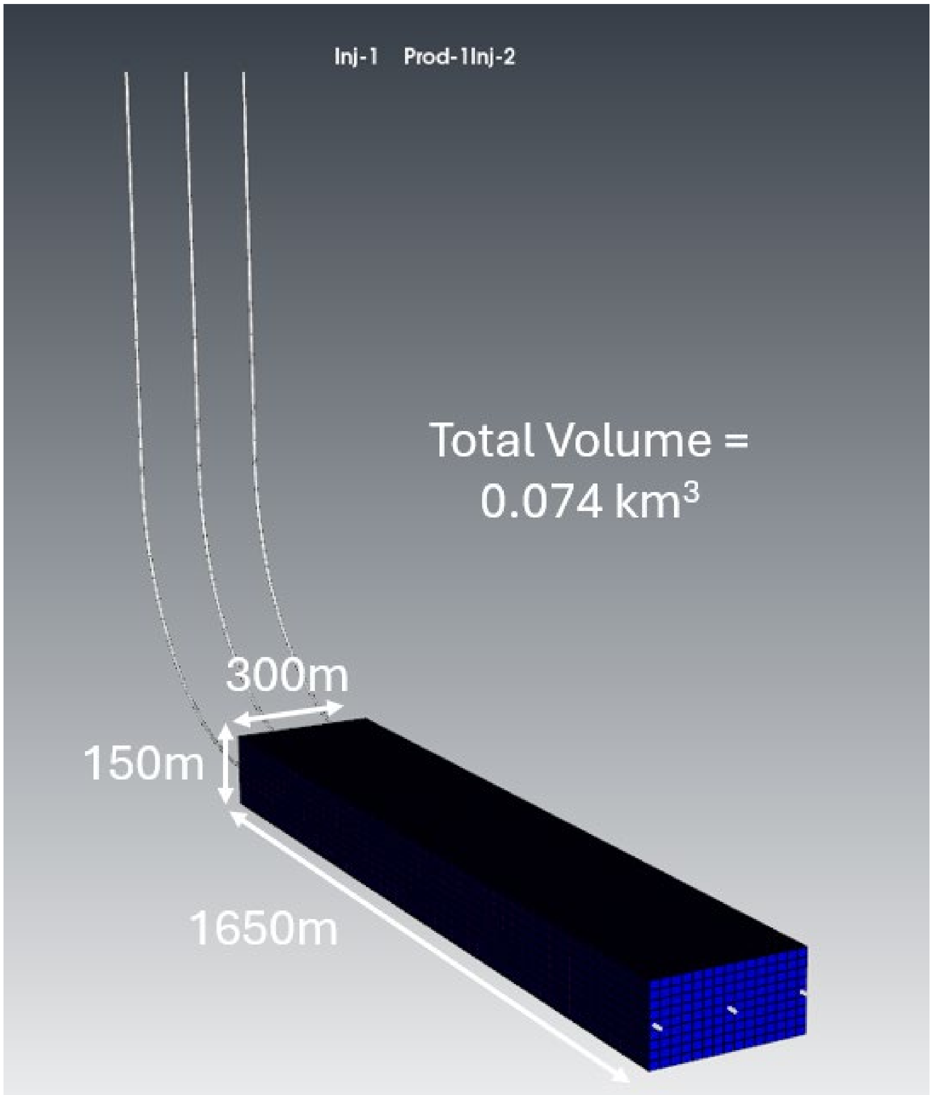

Figure 3 - The EGS system design proposed by Fercho et al. (2025), referred to here as the Fervo 2025 Geometry. The model represents an EGS doublet with two injection wells and one production well located between them. The stimulated reservoir volume measures 1650 m in length, 300 m in width, and 150 m in height, and contains 50 uniformly spaced fractures at 33 m intervals.

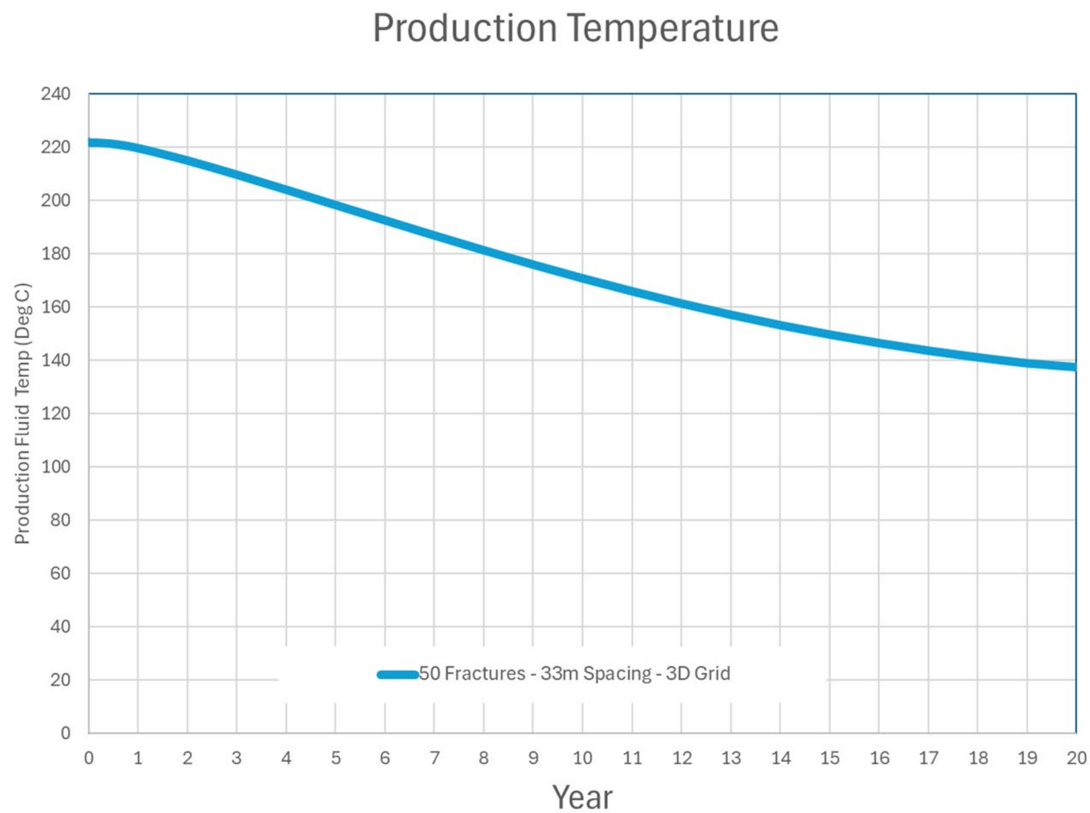

Figure 4 – Production temperature predicted by the 3D Volsung simulation of the *Fervo 2025 geometry*, with 360 ton/hr injection and production. Thermal breakthrough occurs at the end of the first year, followed by continued temperature decline of approximately 4°C per year.

2.3 Full-Scale System Models

To evaluate the performance of larger, full-scale EGS development targeting 10 MW-gross generation, a final set of simulations was conducted using a domain size of 3000 m × 500 m × 500 m. This configuration represents a larger stimulated reservoir volume than the Fervo 2025 Geometry and was designed to assess long-term thermal sustainability under varying fracture spacings and degrees of heterogeneity.

Two primary fracture configurations were evaluated:

- 10 m fracture spacing, representing tightly spaced stimulation zones with a high density of fluid pathways.

- 100 m fracture spacing, representing a more widely spaced design with fewer fracture planes intersecting the reservoir.

In both cases, the total injection and production rate was maintained at 500 ton/hr, with an injection temperature of 65 °C and an initial reservoir temperature of 220 °C. Simulations were run for 20 years, and production temperature was measured at the production well. All fractures were embedded within a 3D grid, while the surrounding host rock remained impermeable, with heat transfer occurring solely through conduction.

To assess the impact of fracture heterogeneity on system performance, additional simulations introduced variations in fracture flow across the domain. These scenarios evaluated the system's resilience to non-uniform stimulation and preferential flow effects.

Figure 5 presents the 3D grid layout used in the full-scale model. Figure 6 shows the production temperature results measured at the production well for all fracture spacing scenarios. In the case with 10 m fracture spacing, no thermal decline was observed, production temperature remained stable for the full 20-year simulation. With 100 m spacing, a modest decline in production temperature was observed at approximately 1.5 °C/year.

For the 5× and 10× heterogeneity scenarios, fracture flow rates varied such that the most permeable fractures accepted 5 to 10 times more fluid than the least permeable ones within the same well. Figure 7 presents the resulting temperature distributions, illustrating how permeability contrasts between fractures affect localized cooling and reduce thermal sweep efficiency. In these heterogeneous cases evaluated, the average rate of temperature decline increased slightly to approximately 2.0 °C/ year. This suggests that flow nonuniformity contributed an additional 0.5 °C/year of thermal decline for the given well configuration.

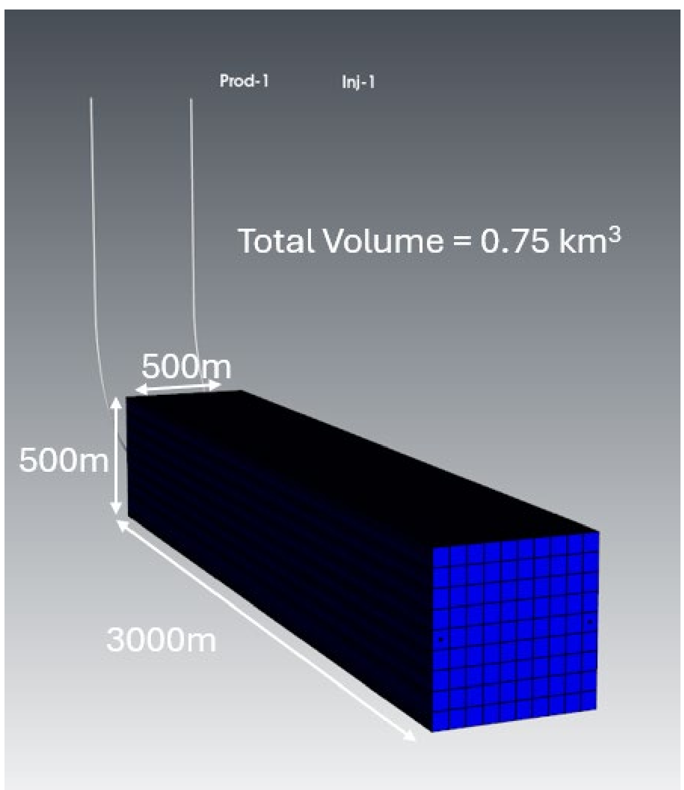

Figure 5 - Grid layout for the full-scale EGS simulation domain measuring 3000 m × 500 m × 500 m. The model includes embedded vertical fractures with either 10 m or 100 m spacing, and simulates injection and production through a central well pair. The host rock is impermeable, with heat transfer occurring through conduction into the fracture network.

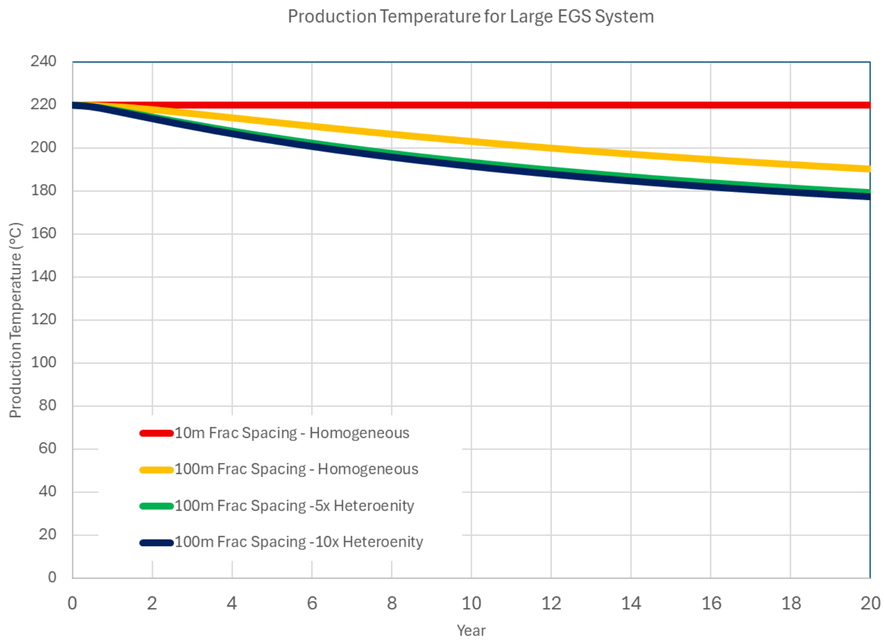

Figure 6 – Production temperature results for the full-scale EGS system over a 20-year simulation period. The case with 10 m fracture spacing maintained stable production temperatures with no measure thermal decline. In contrast, the 100 m spacing case with homogeneous permeability exhibited a temperature decline of approximately 1.5 °C/year. Introducing flow heterogeneity between fractures increased thermal decline slightly to 2.0 °C/year for both the 5× and 10× heterogeneity scenarios .

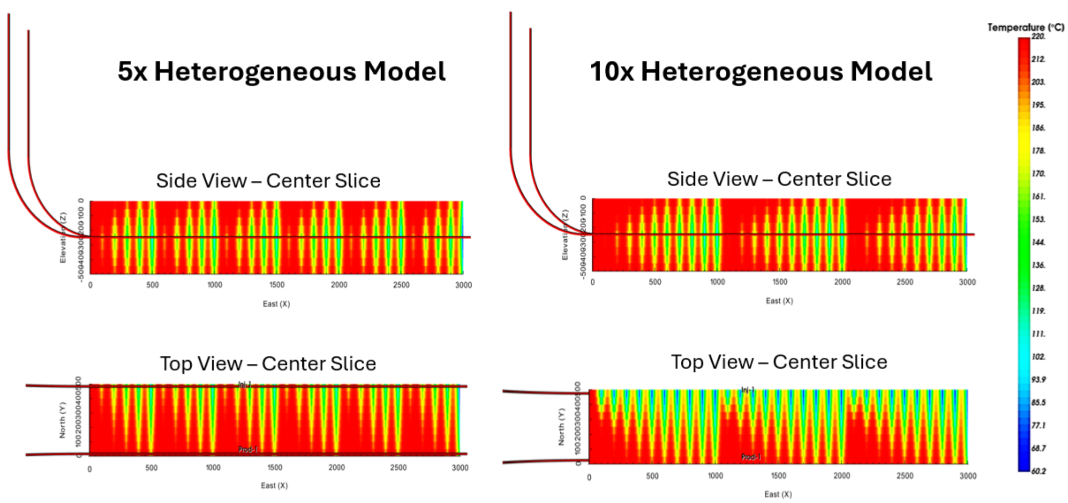

Figure 7 – Top and side view slices of the EGS reservoir after 20 years of simulation, showing temperature distribution for fracture networks with 5× and 10× permeability heterogeneity. These scenarios represent flow variability across fractures, where the most permeable fracture conducts 5 to 10 times more flow than the least permeable one. The images illustrate the influence of heterogeneity on thermal sweep efficiency and localized cooling.

3. Results and Discussion

The simulations performed in this study reveal how key design parameters (vertical grid resolution, fracture spacing, and fracture flow distribution) impact the thermal sustainability of Enhanced Geothermal Systems (EGS). Results from three primary model scenarios were presented: (1) validation against the analytical Gringarten solution, (2) simulation of the Fervo 2025 geometry, and (3) evaluation of a larger full-scale EGS system under varying conditions.

3.1 Comparison with Gringarten's Analytical Solution

The 2D Volsung model, configured to replicate the assumptions of Gringarten et al. (1975), closely matched the predicted thermal decline curve for a system with 10 vertical fractures spaced 40 m apart. However, once the model was discretized vertically, allowing temperature to vary along the fracture height, breakthrough occurred approximately 10 years earlier than predicted by the analytical solution. This discrepancy highlights a critical limitation of the constant temperature assumption used in Gringarten-type curves and underscores the value of full 3D modeling to improve the performance of the EGS system during the design and planning phase.

3.2 Performance of the Fervo 2025 Geometry

The simulation model of the EGS system design proposed by Fercho et al. (2025) revealed the risk of injection fluid returns impacting production early in the life of operation. Despite the use of 50 fractures with 33 m spacing, thermal breakthrough is predicted to occur in the first year of operation. The forecast predicted temperatures to continue to decline at approximately 4 °C/year beyond that point. These findings suggest that although the design meets the surface area targets outlined in the original paper, the confined vertical extent of the stimulated reservoir (150 m) may not provide sufficient reservoir volume to sustain long-term energy production.

3.3 Impact of Scale, Spacing, and Heterogeneity in Large-Scale Models

The full-scale EGS model (3000 m × 500 m × 500 m) exhibited improved thermal sustainability due to the greater reservoir volume available for heat extraction. With 10 m fracture spacing, the system maintained stable production temperatures throughout the 20-year simulation, highlighting the design's ability to access sufficient rock volume to support long-term power generation. When fracture spacing was increased to 100 m, temperature declines of approximately 1.5 °C per year were observed.

Introducing fracture flow heterogeneity had a modest effect on thermal performance. In the 5× and 10× heterogeneity cases—where the most permeable fractures accepted 5 and 10 times more flow, respectively, than the least permeable—temperature decline rates increased modestly to around 2 °C per year. The similarity in decline between the 5× and 10× cases suggests a potential threshold beyond which additional heterogeneity yields diminishing impacts on thermal drawdown.

These results underscore the importance of both fracture spacing and flow uniformity in governing EGS performance. While tighter fracture spacing enhances thermal sweep efficiency, effective flow distribution across fractures is essential to sustaining long-term reservoir productivity. The comparison between uniform and heterogeneous flow scenarios suggests that flow nonuniformity contributed an additional ~0.5 °C per year of thermal decline for the given well configuration.

4. Conclusions

This study used Volsung, a high-resolution geothermal reservoir simulator, to evaluate the thermal performance of multiple Enhanced Geothermal System (EGS) configurations. The results demonstrate both the strengths and limitations of analytical methods and highlight the of 3D modeling during the EGS system design and planning phase.

Key conclusions from this work include:

- **Validation Against Analytical Models:** Volsung was able to closely replicate the temperature decline curves predicted by Gringarten's analytical solution for a system of 10 vertical fractures spaced 40 m apart using a 2D model. However, when the model was extended to 3D to allow vertical temperature variation, thermal breakthrough occurred roughly 7 years earlier than the analytical model suggested, exposing a important limitation in the assumption of constant temperature orthogonal to the flow direction in the analytical model.
- **Limitations of the Fervo 2025 Geometry:** The simulation of the EGS design proposed by Fercho et al. (2025) (1650 m × 300 m × 150 m) revealed early thermal breakthrough followed by temperature decline of approximately 4°C per year.
- **Benefits of Scale and Fracture Density:** A larger EGS system (3000 m × 500 m × 500 m) with 10 m fracture spacing was able to sustain power-grade outlet temperatures for 20 years. When fracture spacing was increased to 100 m, thermal decline became more pronounced at 1.5°C per year.
- **Effect of Fracture Heterogeneity:** Flow heterogeneity between fractures accelerated thermal decline. In these cases, where the most permeable fractures carried 5 to 10 times more flow than the least permeable, temperature declines increased from 1.5 °C/year (uniform flow) to approximately 2.0 °C/year. This suggests that flow nonuniformity contributed an additional 0.5 °C/year of thermal decline for the given well configuration.

Overall, this study demonstrates the value of using high-resolution 3D simulation tools like Volsung for evaluating, designing, and optimizing EGS designs. These models can reveal critical insights that are not captured by simplified analytical approaches. Volsung provides a foundation for advancing EGS development by providing a fully integrated platform for evaluating, designing, testing, and optimizing designs for EGS developments

Overall, this study demonstrates the value of high-resolution 3D simulation tools like Volsung for evaluating, designing, and optimizing Enhanced Geothermal Systems (EGS). These models can reveal critical insights that are often overlooked by simplified analytical approaches. Volsung provides a fully integrated platform for evaluating, designing, testing, and optimizing layouts for EGS developments.

Acknowledgement

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REFERENCES

Franz, P., Clearwater, J., & Burnell, J. (2019). *Introducing The Volsung Geothermal Simulator: Benchmarking and Performance*. Proceedings 41st New Zealand Geothermal Workshop.

Fercho, S., Norbeck, J., Dadi, S., Matson, G., Borell, J., McConville, E., Webb, S., Bowie, C., & Rhodes, G. (2025). *Update on the Geology, Temperature, Fracturing, and Resource Potential at the Cape Geothermal Project Informed by Data Acquired from the Drilling of Additional Horizontal EGS Wells.* Proceedings, 50th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 10–12, 2025, SGP-TR-229.

Gringarten, A. C., Witherspoon, P. A., & Ohnishi, Y. (1975). *Theory of Heat Extraction from Fractured Hot Dry Rock.* Journal of Geophysical Research, 80(8), 1120–1124. https://doi.org/10.1029/JB080i008p01120