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3D Play Fairway Analysis for Examining of Superhot Reservoir Production Scenarios

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ABSTRACT

The De-Risking Exploration for Geothermal Plays in Magmatic Environments (DEEPEN) project was an international, multi-laboratory effort to reduce uncertainty and improve resource characterization in superhot geothermal systems. Building on this foundation, our work advances open-source tools designed to lower the exploration risk and cost of superhot geothermal projects while promoting transparency, reproducibility, and efficiency in exploration workflows. These tools are being tested at two sites: (1) the Nesjavellir Geothermal Area in Iceland, where the Icelandic Deep Drilling Project will drill its third well, and (2) the Newberry Volcano in Oregon, United States, where Mazama Energy will pilot the first superhot enhanced geothermal system. A major outcome is the creation of a modular, open-source Python framework for play fairway analysis (PFA) in 2D and 3D, called geoPFA. The PFA workflow has been expanded to produce pseudo-conceptual models (e.g., models of favorable subsurface components but not geologic formations) and will soon be refined to assess reservoir components through integration with TReactMech, a thermal-hydrologic-mechanical-chemical simulator for coupled processes in porous and fractured media developed by Lawrence Berkeley National Laboratory. This expanded framework enables iterative coupling between PFA and thermal-hydrological-mechanical-chemical models, improving characterization of superhot systems. All three of the superhot reservoir production scenarios presented in Pálsdóttir et al. (2025) were analyzed via this framework: (1) a superhot deep injection well paired with conventional production wells at Nesjavellir, (2) a superhot deep production well at Nesjavellir, and (3) superhot enhanced geothermal system with a magmatic heat source at Newberry Volcano. This analysis provides useful insights into conceptual modeling of these production scenarios, helping inform decisions about which scenario is best suited for which types of environments.

1 INTRODUCTION

The De-Risking Exploration for Geothermal Plays in Magmatic Environments (DEEPEN) project was a transnational, multi-lab initiative funded in partnership with Geothermica that aimed to reduce exploration risk and improve characterization of superhot geothermal systems, particularly in magmatic environments (Hjörleifsdóttir et al. 2023; Kolker and Mibei, 2025). This paper describes follow-up work conducted by a subset of the original partners that is focused on integrating open-source play fairway analysis (PFA) workflows with TReactMech, a thermo-hydrological-mechanical-chemical (THMC) simulator for coupled processes in porous and fractured media developed by Lawrence Berkeley National Laboratory (LBNL). This integrated workflow will improve constraints on the reservoir component. Superhot geothermal has various definitions (e.g., Pálsdóttir et al. 2025; CATF 2025; Okamoto et al. 2019), but in the context of this paper, superhot geothermal systems are defined as those with temperatures exceeding 400°C. Pressure constraints are considered, but in a more nuanced manner; our exact pressure targets depend on the scenario. Superhot geothermal systems have much greater energy potential than conventional geothermal systems (Friðleifsson et al. 2014; Cladouhos et al. 2018; Feng et al. 2021), warranting the pursuit of solutions to the various challenges that come with the utilization of these fluids. One such challenge lies in reducing uncertainty around the resource through better exploration and site characterization (CATF 2025)—or, more specifically, developing the tools, data, and models needed to confidently identify, assess, and evaluate superhot resources before full-scale development.

The Icelandic Deep Drilling Project (IDDP) is one group working toward a superhot demonstration project. During the planning for the third IDDP well, or IDDP-3, Reykjvík Energy conceptualized three different superhot reservoir production scenarios (denoted Scenario 1, Scenario 2, and Scenario 3 throughout this work); these are depicted in Figure 1 (Pálsdóttir et al. 2025). The next IDDP well, drilled in Nesjavellir, will be a deep production well

(Scenario 2). In this work, these production scenarios serve as the underlying concepts for three distinct PFAs—one PFA per production scenario—to improve understanding of the most favorable locations for each superhot production scenario (i.e., wellbore configuration and/or technology used to produce the resource).If you use equations, define all symbols after the equation.

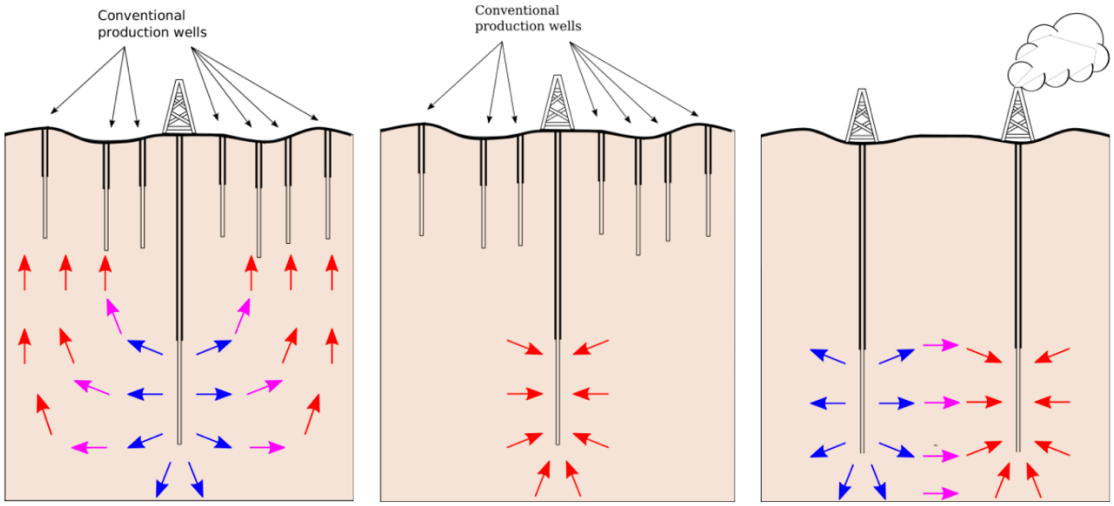


Figure 1. Considered superhot reservoir production scenarios from Pálsdóttir et al. (2025). (From left to right) Scenario 1: Deep injection well. Scenario 2: Deep production well. Scenario 3: Superhot enhanced geothermal system.

The DEEPEN project refined and applied PFAs in both 2D and 3D space to evaluate the viability of superhot geothermal systems at the Newberry Volcano for magmatic hydrothermal systems, superhot enhanced geothermal systems (EGS; Taverna et al. 2024), and supercritical geothermal systems. For the purposes of this study, we define a PFA as a method to combine diverse surface and subsurface data layers into favorability models. Limited constraints on the "producibility" component (the ability to create and sustain producible fractures in the context of superhot EGS or, in the context of "conventional" superhot systems, the proper pressure and permeability to support superhot fluid production) was noted as an area for future improvement in Taverna et al. (2024). In addition, the lack of accessible, open-source datasets and tools for conducting PFA limits reproducibility and scalability across different regions and project teams (Taverna et al. 2025b).

This work addresses these gaps by developing open-source PFA workflows tailored to superhot geothermal environments. Emphasis is placed on improving the representation of the "producibility" component, differentiating between the three IDDP production scenarios, promoting workflow transparency, and enabling extensibility to other geothermal applications. By advancing the tools and methods for PFA, the project contributes to reducing exploration risk, lowering development costs, and supporting broader adoption of superhot geothermal energy. This paper expands on the work published in Taverna et al. (2025b), examining production scenarios 1 and 3 and incorporating TReactMech THMC models to better constrain the reservoir producibility component.

1.1 Superhot Play Fairway Analysis Application Sites

IDDP's next well is planned to be drilled in the Hengill Volcanic Area in Iceland due to co-location with a known superhot resource (NJ-11) and three operating geothermal fields (Nesjavellir, Hellisheiði, and Hverahlíð), which will lead to a plethora of characterization and monitoring data (Gunnarsson et al. 2024). Nesjavellir was selected as the test site for two of the three superhot production scenarios considered by Reykjavík Energy, including (1) a deep injection well and (2) a deep production well in the Nesjavellir field, hopefully providing a means to validate the superhot PFA methodology in the future.

Nesjavellir is a well-characterized, producing hydrothermal field in the Hengill area (dashed blue box in Figure 2), located to the northeast fissure swarms of the Hengill Volcano, which is represented by the red star in Figure 2. Recent interpretations suggest that repeated shallow intrusions within the fissure swarms, identifiable as high-resistivity bodies in magnetotelluric models, may act as key heat sources for active production zones at Nesjavellir (e.g., Gunnarsson et al. 2011; Ragnarsson, 2022). Further supporting this concept, NJ-11 is a well that was unintentionally drilled into a superhot zone at Nesjavellir in 1985. The deepest part of the well had to be plugged with gravel due to superhot conditions, with temperatures exceeding 380°C at 2.1-km depth

(Steingrímsson et al. 1990). The current depth of the well is therefore 1.6 km, and the well is still producing and providing steam to the Nesjavellir power station.

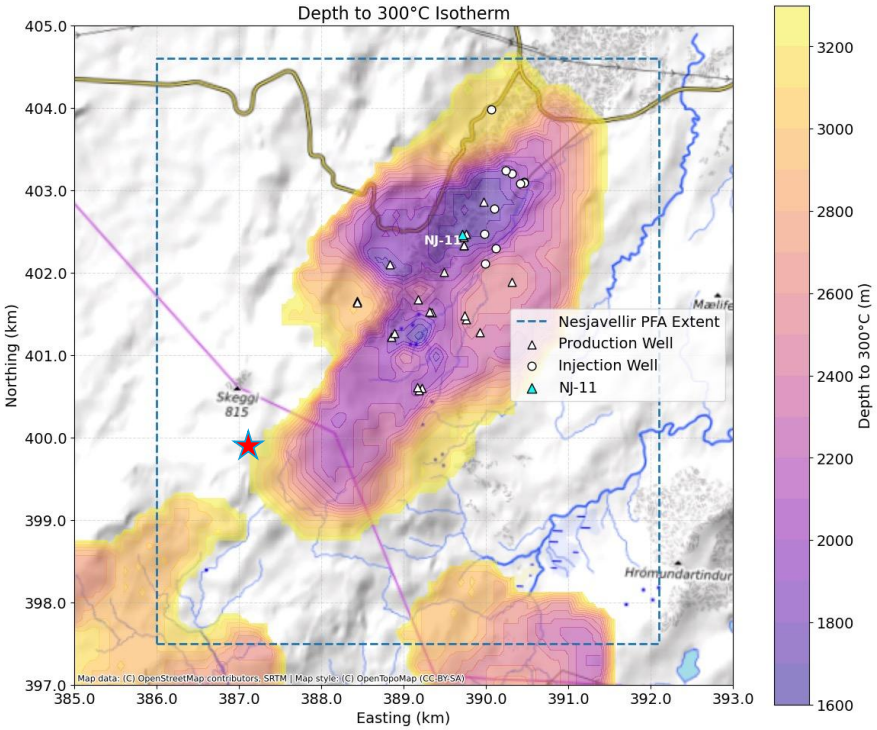


Figure 2. Map of the Nesjavellir Geothermal Field showing the estimated depth to 300°C (data from the Icelandic Geosurvey (ISOR) and Reykjavík Energy (OR), personal communication). Triangles represent production wells, and circles represent injection wells. NJ-11 is denoted with a green triangle. A dashed blue box has been added to delineate the study area for the Nesjavellir PFA. The red star indicates the surface location of the Hengill volcano.

The Newberry Volcano in Oregon, United States, is a well-studied, promising geothermal area with subsurface temperatures exceeding 320°C at 3 km and superhot zones over 400°C accessible within 5 km (Mazama Energy, n.d.). Its high thermal gradient and extensive geophysical characterization make it an ideal location for advanced geothermal development. Mazama Energy is leveraging this potential through the first superhot rock (SHR) EGS demonstration project, supported by the U.S. Department of Energy (DOE). The project involves reentering existing wells and drilling new ones to create a high-temperature reservoir capable of producing five to ten times more power than conventional geothermal systems using scalable methods (Mazama Energy 2025). Quaise Energy is also in the process of establishing new well(s) on the southern flank of the volcano to the south-southeast of the Big Obsidian Flow (Quaise Energy, n.d.). Given these unique geological and technological advantages, in combination with the fact that there are no near-term plans to develop an EGS at Nesjavellir, Newberry has been chosen as the application site for testing the PFA workflow targeting superhot production Scenario 3: superhot EGS.

There are multiple temperature models for Newberry. One such model is from Frone et al. (2015), which used a finite difference numerical heat conduction model for temperature modeling. Recent validation efforts have suggested that it does not match the temperature gradient observed in NWG 55-29, nor does it properly account for deep heat flux (i.e., Blackwell et al. (1981)). Therefore, we instead use the previously published DEEPEN thermal model (Pauling et al. 2023b) because it better reflects observed temperature values from wells in the area. This model was built by interpolating between observed BHTs and temperature profiles using Leapfrog Energy. Since temperature data are relatively sparse in the area and several of the temperature profiles are biased by meteoric water contamination (particularly GEO N-1 in the south), this model is also treated as fairly uncertain. To reflect this uncertainty, the temperature model is given a lower weight in the PFA. Figure 3 shows the depth to the 300°C isotherm based on each thermal model within the defined extent of the Newberry PFA. It is apparent that the two models are very different, and it is likely that neither is entirely correct; however, inclusion of measured temperature data is still useful for determining favorable areas where heat may exist. Additional work is needed to produce a high-confidence thermal model that matches the observed temperature profiles in the area and aligns with petrological constraints. Additional temperature data is expected to help

constrain the south-southeastern and western flanks through Quaise's and Mazama's drilling activities, respectively.

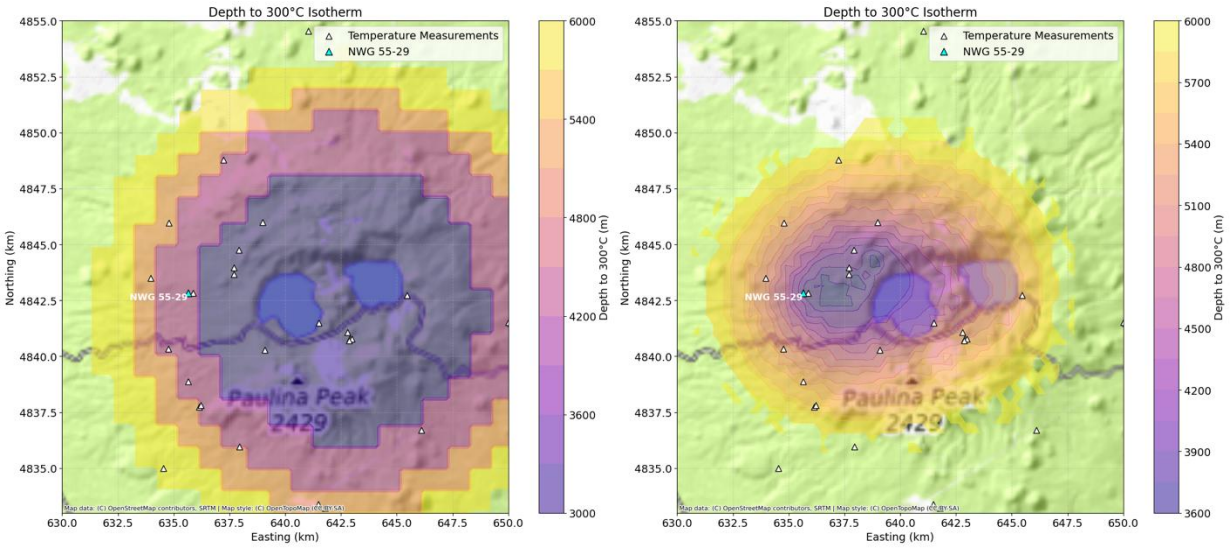


Figure 3. Depth to the 300°C isotherm based on two different thermal models within the PFA extent for Newberry Volcano, including Frone et al. (2015; left) and Pauling et al. (2023b; right). The Pauling model was selected for use in this study because it better matches the observed well profiles in the area, but both models have their own limitations.

1.2 Play Fairway Analysis

PFA offers a structured, systematic framework for integrating diverse surface and subsurface datasets to assess exploration resource potential and uncertainty, guiding early-stage development decisions. The methodology was originally developed for oil and gas exploration and has since been adapted to exploration for hidden hydrothermal resources (Pauling et al. 2023a). The exact methodology varies from project to project, but the general workflow follows the diagram in Figure 4, where data layers are organized according to which components (e.g., heat, permeability, fluid) of which criteria (e.g., geologic) they map to. Component favorability layers can be interpreted independently or weighted and combined once more into a criteria favorability layer—for example, a geologic criteria favorability layer that represents all geologic components. Taverna et al. (2025b) describe this process in more detail.

When working in 3D, weighting and combining geologic component favorability models into a combined geologic criteria favorability model is not recommended, because it greatly reduces interpretability, given that each component exists in a distinct location in 3D space, ideally stacked over one another. This means that the highest combined geologic favorability might indicate mild favorability for all components in an overlapping location, or high favorability for an individual component, with no way to differentiate. Either scenario could ultimately be? unfavorable for geothermal development; therefore, it is important to investigate geologic components separately in 3D space.

Kolker et al. (2022) developed indicators for superhot EGS and supercritical plays to inform a PFA applied to next-generation magmatic geothermal play types, expanding beyond the conventional hydrothermal PFA. These indicators and aspects from the methodology in Poux and O'brien (2020) were used as the basis for the superhot EGS PFA conducted at Newberry (Taverna et al. 2024). Taverna et al. (2025b) built on the workflow described by Taverna et al. (2024), developing an open-source Python library called geoPFA (Taverna et al. 2025a) to conduct customizable and reproduceable PFAs for any play type in both 2D and 3D, including expanded indicators for all three superhot production scenarios described in Figure 1.

In the work presented here, we conducted three different PFAs in both 2D and 3D, developing indicators for each scenario by combining those from Kolker et al. (2022) with the considerations for the superhot production scenarios laid out in Gunnarson et al. (2024) and Pálsdóttir et al. (2025). These indicators are as follows:

- **Scenario 1 – Deep Injection Well**: Target deep, superhot, thermally insulated (i.e., beneath conduction-dominated overburden) ductile rock at sub-supercritical pressures (i.e., less corrosive geochemistries), and low to high permeability (e.g., cold water injection may enhance permeability; Nesjavellir application).

- **Scenario 2 – Deep Production Well**: Target deep, superhot, thermally insulated, brittle permeable rock with existing fluid at sub-supercritical pressures (Nesjavellir application).
- **Scenario 3 – Superhot EGS**: Target superhot (magmatic heat source), thermally insulated, dry, more brittle, fracturable rock at sub-supercritical pressures (<22 MPa) and low permeability (Newberry application).

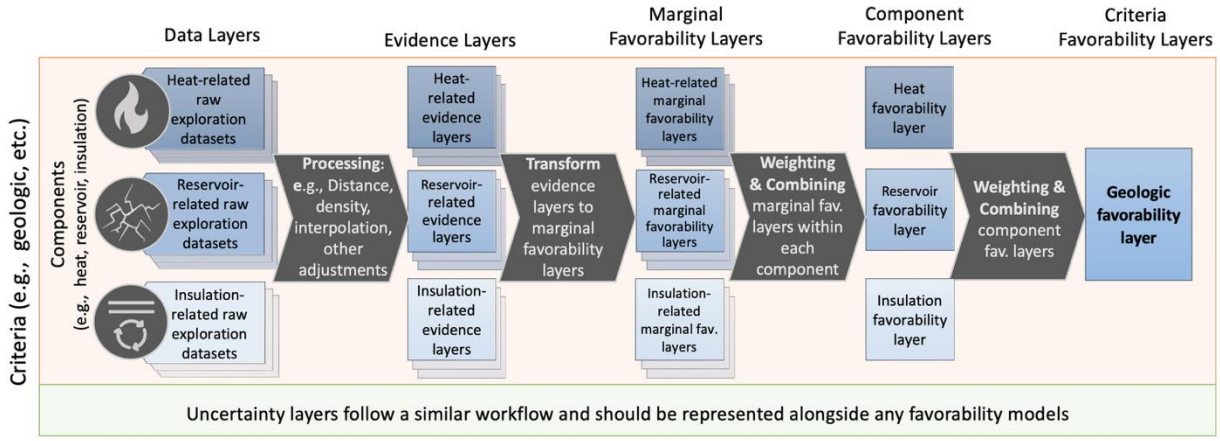


Figure 4. Flow chart outlining a generalized superhot PFA methodology. Adapted from Taverna et al. (2025b).

2 METHODS

The National Laboratory of the Rockies' (NLR's) geoPFA tool (Taverna et al. 2025a) was used to conduct 3D PFAs for each production scenario. The geoPFA tool is an open-source Python library for conducting PFA in 2D and 3D space, designed to reduce exploration risk by integrating surface and subsurface considerations into a single, transparent workflow. Built around NLR's Geothermal PFA Best Practices (Pauling et al. 2023a) and aligned with findable, accessible, interoperable, and reusable (FAIR) software principles, geoPFA provides modular, extensible tools for cleaning, processing, weighting, and combining diverse datasets into quantitative favorability maps. These datasets can include geological, geophysical, geochemical, and THMC simulation results, as well as surface-level factors such as energy demand, access to transmission lines, and natural hazard risk.

The framework is fully customizable, enabling users to define criteria, components, and indicators for any geothermal resource type, from low-temperature and conventional hydrothermal to superhot systems. The methodology can be extended to other subsurface applications if desired. The geoPFA tool supports multiple data processing approaches, including interpolation, density mapping, distance-based scoring, extrapolation, and thermal modeling, while allowing integration of user-defined weights (e.g., expert-derived, statistically generated, or otherwise assigned).

The geoPFA tool has been successfully demonstrated in diverse contexts: an initial 3D PFA for the Nesjavellir field in Iceland, where results aligned with known subsurface conditions and guided scenario-based development strategies (Taverna et al. 2025b), and 2D PFAs of the Denver Basin and Alaska for lower-enthalpy geothermal with greater emphasis on surface constraints (Davalos-Elizondo et al. 2025; Davalos-Elizondo et al. in press). By making advanced exploration workflows reproducible, transparent, and openly accessible, geoPFA enables research teams, developers, and agencies to make better-informed decisions through reducing the time required for developing workflows and allowing more time to be spent on feature engineering and interpretation of results.

2.1 3D Play Fairway Analysis

The general PFA workflow is described in Figure 4, but producing only component favorability models are produced. Raw data layers are cleaned and processed into evidence layers; evidence layers are transformed into marginal favorability layers; and marginal favorability layers are weighted and combined into component favorability models.

Data layers were cleaned so that all information was projected onto the same grid. To ensure information was presented continuously over 3D space, we used processing methods such as interpolation, density functions,

and distance functions. GeoPFA's implementation of these functions is described in more depth in Taverna et al. (2025b). Weights from the original DEEPEN project (Taverna et al. 2023; 2024) were reused in this study—particularly the expert-opinion-based weights generated from geoscientist interviews and combined via the analytical hierarchy process (AHP), where experts rank criteria based on importance.

Marginal favorability layers are produced by transforming continuous representations of each data layer based on the data layer's relative contributions to favorability using the transformation functions in Figure 5, followed by normalization on a scale from 1 to 5 (to avoid misleading readers into interpreting favorability as probability). For example, lower resistivity zones are more favorable for depicting a magmatic heat source. Figure 6 shows example marginal favorability models for Nesjavellir's Production Scenario 2 reservoir component.

Transformation functions are intentionally oversimplified in the current iteration of geoPFA since the goal is only to map data values to relative favorability values. These transformation functions currently include only relative relationships such as linear, inverse, radial basis function (RBF), and inverse RBF. A future release of geoPFA will ideally include more probabilistic transformation functions, leading to more quantitative and interpretable assessments of resource probability.

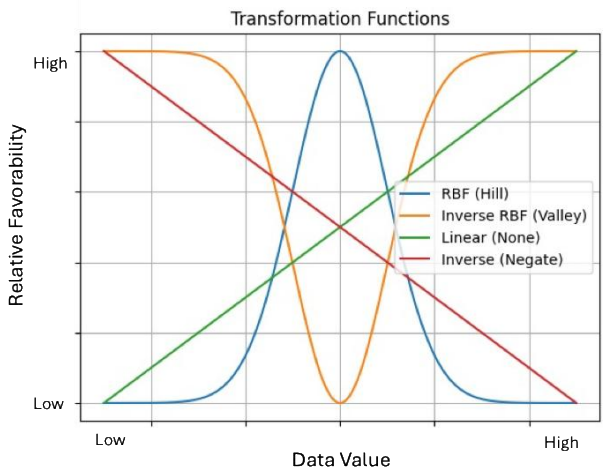


Figure 5. Functions used in this study to transform data values into relative favorability values.

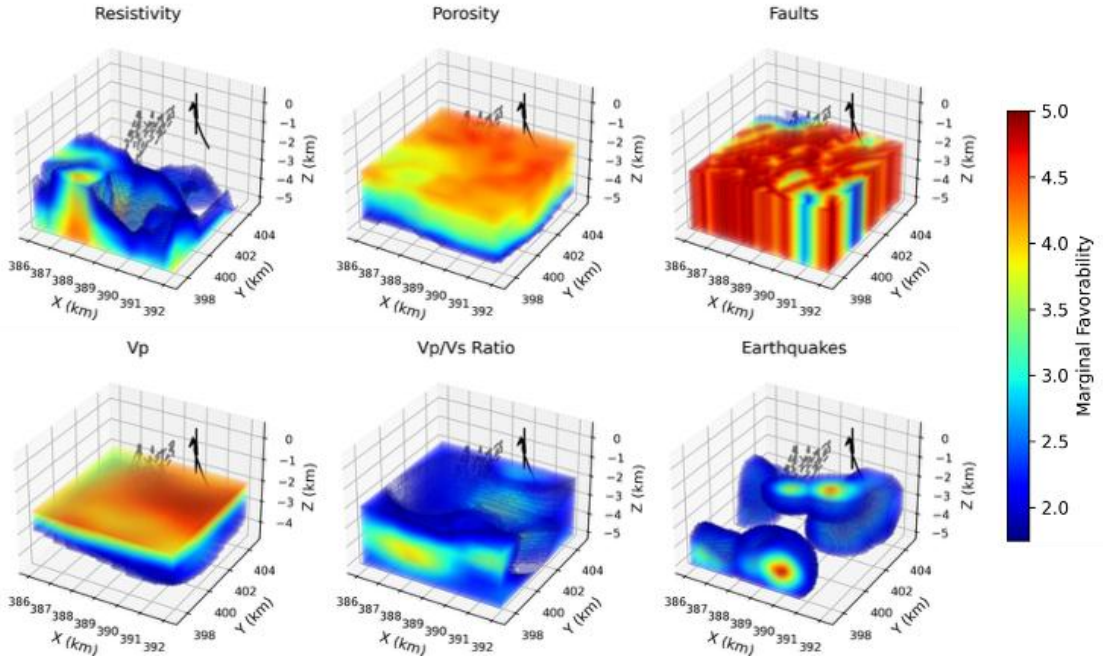


Figure 6. Example marginal favorability models for the reservoir component of Production Scenario 2 at Nesjavellir.

2.1.1 Production Scenario 1: Superhot Deep Injection Well

Production Scenario 1 (Figure 1) depicts a conceptual deep injection well completed into ductile SHR beneath a conventional production zone. This scenario targets zones of ductile SHR where permeability may not currently exist at sufficient quantities, but could potentially be created or enhanced through cold-water injection. The input data layers intend to identify elevated temperatures at depth, rock units with ductile behavior, indicators of low existing permeability, and conditions where permeability could be enhanced to connect the injection well vertically to the shallower production zone. The input data layers used in this PFA are summarized in Table 1, where each of the data layers for each component, their influence weights, and transformation methods applied are listed. In general, transformation methods and weights should be selected with geologic context in mind. Weights for the data layers and geologic components in this production scenario were generated using expert opinions, gathered through interviews of Icelandic geoscientists and combined via AHP. The seismic data collected and analyzed by Obermann et al. (2022) was considered, but ultimately not included. It is recommended that this data be used in future validation efforts for Nesjavellir.

Table 1. Components and associated data layers used in Production Scenario 1: superhot deep production well PFA at Nesjavellir, along with relative weights, transformation method applied (Figure 5), and reference for the dataset.

Play Type	Play Component	Data Layer	Relative Weight	Transformation Method	Reference
Production Scenario 1: Deep Injection Well at Nesjavellir	Heat Source	Temperature model	0.25	Linear	Hokstad et al. (2024) and ISOR & OR (unpublished data)
		Magnetotelluric resistivity	0.13	Inverse linear	Árnason et al. (2010)
		P-wave velocity	0.20	Inverse linear	Amoroso et al. (2022)
		Ratio of P- to S-wave velocity	0.20	Linear	Amoroso et al. (2022)
		Distance from surface fissures	0.048	Inverse linear	ISOR & OR (unpublished data)
		Magnetics	0.028	Inverse linear	Hokstad et al. (2024)
	Reservoir	Distance from earthquake clusters	0.15	Linear	NORSAR and ETH Zürich (unpublished data)
		Magnetotelluric resistivity	0.040	Inverse linear	Árnason et al. (2010)
		Distance from Faults	0.18	Inverse linear	ISOR & OR (unpublished data)
		TReactMech outputs (permeability)[1]	0.15	Inverse linear	LBNL (unpublished data)
		TReactMech outputs (pressure)[1]	0.15	RBF	LBNL (unpublished data)
		Multigeophysical inversion (porosity)[2]	0.15	Inverse linear	Hokstad et al. (2024)
		Magnetics	0.012	Inverse linear	Hokstad et al. (2024)
		Distance above earthquake cutoff	0.151	Inverse linear	Estimated from NORSAR and ETH Zürich (unpublished data)
	Thermal Insulation	Magnetotelluric resistivity	0.098	Inverse linear	Árnason et al. (2010)
		P-wave velocity	0.114	Linear	Amoroso et al. (2022)

[1] TReactMech modeling results are not ready at the time of publication. The workflow is described here, but results are saved for future publication.

[2] Dataset will be removed when TReactMech modeling results are incorporated to avoid multicollinearity.

		Ratio of P- to S-wave velocity	0.114	RBF	Amoroso et al. (2022)
		Magnetics	0.022	Inverse linear	Hokstad et al. (2024)
		Temperature model	0.283	Inverse linear	Hokstad et al. (2024)
		Earthquake density	0.124	Inverse linear	NORSAR and ETH Zürich (unpublished data)
		Multigeophysical inversion (porosity)	0.446	Linear	Hokstad et al. (2024)
		Depth	0.10	Inverse linear	N/A

The heat component maps the favorability of superhot temperature domains using a combination of temperature model outputs, structural information, and geophysical properties that can correlate with the thermal state. These layers provide indications of temperature-related behavior at depth. The favorability reflects both directly modeled temperatures and geophysical signatures that commonly correlate with high-temperature environments.

The reservoir component is designed around identifying where permeability is currently low, but stress conditions and lithology may allow permeability creation through injection. Specifically, data layers contribute to favorability in the following ways:

The insulation component represents both thermal insulation from overlying lithologies (reducing conductive heat loss) and fluid insulation caused by lower permeability in overlying lithologies (thus limiting upward heat fluid migration). The model relies on geophysical proxies that may indicate clay-rich, altered, or compacted lithologies capable of acting as effective barriers.

2.1.2 Production Scenario 2: Superhot Production Well

Production Scenario 2 (Figure 1) targets deep, superhot, brittle rock with existing natural permeability and active fluid circulation. Unlike Scenario 1, this scenario assumes that permeability must already be present and therefore emphasizes data layers associated with brittle behavior, structural pathways, and reservoir-quality rock. All data layers, weights, and references appear in Table 2. Weights for data layers and geologic components in this production scenario were again generated using expert input combined with AHP. The weights for Production Scenario 2 align with those in Production Scenario 1.

Table 2. Components and associated data layers used in Production Scenario 2: superhot deep production well PFA at Nesjavellir. Heat and insulation components are not listed here, as they are identical to those used in Production Scenario 1, along with relative weights, transformation method applied (Figure 5), and reference for the dataset.

Play Type	Play Component	Data Layer	Relative Weight	Transformation Method	Reference
Production Scenario 2: Deep Production Well at Nesjavellir	Heat Source	*See **Fehler! Verweisquelle konnte nicht gefunden werden.***			
	Reservoir	Distance from earthquake clusters	0.15	Linear	NORSAR and ETH Zürich (unpublished data)
		Magnetotelluric resistivity	0.040	Inverse linear	Árnason et al. (2010)
		Distance from Faults	0.18	Inverse linear	ISOR & OR (unpublished data)
		TReactMech outputs (permeability)[3]	0.15	Inverse linear	LBNL (unpublished data)
		TReactMech outputs (pressure)[3]	0.15	RBF	LBNL (unpublished data)

[3] TReactMech modeling results are not ready at the time of publication. The workflow is described here, but results are saved for future publication.

		Multigeophysical inversion (porosity)[4]	0.15	Inverse linear	Hokstad et al. (2024)
		Magnetics	0.012	Inverse linear	Hokstad et al. (2024)
		Distance above earthquake cutoff	0.151	Inverse linear	Estimated from NORSAR and ETH Zürich (unpublished data)
	Thermal Insulation	*See **Fehler! Verweisquelle konnte nicht gefunden werden.***			

Because the conceptual heat source and thermal insulation structures are the same at Nesjavellir regardless of the type of reservoir we are targeting, the heat and insulation components for Production Scenario 2 are identical to those described in the previous section for Production Scenario 1, and only the reservoir component changes here. The reservoir component for Scenario 2 emphasizes indicators of existing permeability in brittle, fluid-bearing units.

2.1.3 Production Scenario 3: Superhot EGS

Production Scenario 2 (Figure 1) targets superhot EGS, or dry rock. In this scenario, we target thermally insulated, dry, more brittle, fracturable rock at sub-supercritical pressures and low permeability at superhot temperatures. This scenario is applied to the Newberry Volcano, as it is the current target for the DOE-funded superhot dry rock demonstration project led by Mazama Energy. The input data layers and their associated weights for each component are outlined in Table 3. Weights for data layers and geologic components were generated using expert opinions gathered through interviews of U.S.-based geoscientists and combined via AHP. These weights were slightly modified to account for confidence in data inputs (i.e., temperature model weight was lowered due to uncertainty).

Table 3. Components and associated data layers used in the Production Scenario 3: superhot EGS well (with magmatic heat source) PFA at Newberry, along with relative weights, transformation method applied (Figure 5), and reference for the dataset.

Play Type	Play Component	Data Layer	Relative Weight	Transformation Method	Reference
Production Scenario 3: Superhot EGS at Newberry with Magmatic Heat Source	Heat Source	Density (joint inversion with MT resistivity)	0.20	Inverse linear	Schultz et al. (2023)
		Magnetotelluric resistivity (joint inversion with gravity)	0.20	Inverse linear	Schultz et al. (2023)
		Temperature model	0.05	Linear	Pauling et al. (2023b)
		Distance from earthquake clusters	0.05	Inverse linear	PNSN, USGS (2023)
		Fractional Velocity Perturbation	0.20	Inverse linear	Heath et al. (2015)
	Reservoir	Density (joint inversion with MT resistivity)	0.032	Linear	Schultz et al. (2023)
		Magnetotelluric resistivity (joint inversion with gravity)	0.044	Linear	Schultz et al. (2023)
		Distance from earthquake clusters	0.18	Inverse linear	PNSN, USGS (2023)
		Distance to ring faults	0.25	Inverse linear	Mark-Moser et al. (2019)
		Distance to lineaments	0.25	Inverse linear	NewGen (2016)

[4] Dataset will be removed when TReactMech modeling results are incorporated to avoid multicollinearity.

		TReactMech outputs (permeability)[5]	0.15	Linear	LBNL (unpublished data)
		TReactMech outputs (pressure)[5]	0.15	RBF	LBNL (unpublished data)
	Thermal Insulation	Density (joint inversion with MT resistivity)	0.11	Linear	Schultz et al. (2023)
		Magnetotelluric resistivity (joint inversion with gravity)	0.071	Inverse linear	Schultz et al. (2023)
		Temperature model	0.20	Inverse linear	Pauling et al. (2023b)
		Distance from earthquake clusters	0.049	Inverse linear	PNSN, USGS (2023)

The heat source is assumed to be magma in this PFA, although this is not always the case for superhot EGS. For example, the targeted heat source in the Mazama Energy project is a granodiorite pluton, which would appear much differently in the data (i.e., a more resistive, higher density body). The insulation component represents both thermal insulation over the caldera (reducing conductive heat loss) and fluid insulation (limiting upward fluid and heat transport). The model relies on geophysical proxies that may indicate clay-rich, altered, or compacted lithologies capable of acting as effective barriers (e.g., dikes or sills that are highly altered/impermeable or other altered older volcanic layers). The reservoir component for superhot EGS is hot dry rock, often without existing permeability, that can be hydraulically fractured.

2.2 Play Fairway Analysis Layer Combination

Marginal favorability layers are weighted and combined using a modified version of the Voter-Veto method developed by Ito et al. (2017) for the Hawaii PFA project. This method was chosen because it is the most probabilistic of the DOE-funded PFA projects' layer combination methods, described in Pauling et al. (2023a). To be truly probabilistic, significant effort is required to correlate probability density functions to each data layer to produce transformation functions. In the work presented here, we used simplified transformation methods to map data values to favorability values only in terms of general trends. The resulting values are normalized and presented as relative favorability on a scale from 1–5 to prevent misleading readers into believing they are looking at true probability. Additional work is needed to refine these results into more probabilistic representations of components.

2.3 TReactMech-Informed Play Fairway Analysis

One of the shortcomings identified in the Newberry superhot PFA conducted by Taverna et al. (2024) was the inability to model the reservoir (referred to as "producibility" in that study) component using the datasets at hand (primarily geophysical). Proposed solutions included incorporating stress data and downhole logging data, but these datasets are generally very limited in developing or undeveloped fields (i.e., stress data is often measured at a regional scale, and downhole logging data only exists where wells have been drilled and extensively documented). In an attempt to better model fracturability, permeability, ductility, and pressure in this work, we are exploring TReactMech outputs as PFA inputs and vice versa. These results were not ready at the time of submission and are therefore planned for future publication. In the interim, we substituted multigeophysical inversion (MGI) results by Hokstad et al. (2024) for porosity, but only for Nesjavellir. Such a study has not been published for Newberry thus far. When the TReactMech modeling results are obtained, the MGI results will be removed to reduce multicollinearity and limit the number of derivative models being used as inputs.

2.4 Conceptual Component Modeling

We converted the resulting 3D PFA models into pseudo-conceptual models (e.g., models of favorable subsurface components but not geologic formations) or conceptual component favorability models (e.g., individual heat, insulation, or reservoir favorability components of the pseudo-conceptual models) by filtering to the 85th percentile of favorability values for each component and visualizing them as 3D volumes on the same

[5] TReactMech modeling results are not ready at the time of publication. The workflow is described here, but results are saved for future publication.

model. This helps to analyze where each component lies in 3D space and to better conceptualize the system's layout. Given that the PFA process produces relative favorability values and that the exact magnitudes are based on subjective factors such as transformation and normalization methods, weights, and prior probabilities, the shapes and sizes of the features in conceptual component models likely vary, but the relative shapes and positions of each are informative.

3 RESULTS

Throughout this section, we show the component favorability models produced from each production scenario's PFA, along with a pseudo-conceptual model for each production scenario produced using the PFA outputs.

3.1 Production Scenario 1: Superhot Deep Injection Well

Figure 7 shows the component favorability models produced for the thermal insulation, reservoir, and heat source for Production Scenario 1 at Nesjavellir, displayed as 3D contours depicting the 85th percentile for interpretability. The colors in this depiction match the magnitude of the favorability for a given component. The NJ-11 well downhole temperature profile is plotted for context.

We can see a favorable layer for thermal insulation near the top of the model and a large favorable zone for heat beneath the Hengill Volcano, connected to a deeper, small-yet-favorable heat zone directly under NJ-11. The favorable zone for the reservoir is in between the favorable zones for heat and thermal insulation, overlapping with the heat source and loosely following the trends of the faulted zone. The heat source favorability model seems to support the preliminary hypothesis that the heat source for Nesjavellir is connected to a larger heat source beneath the Hengill Volcano (Gunnarsson et al. 2011; Ragnarsson, 2022).

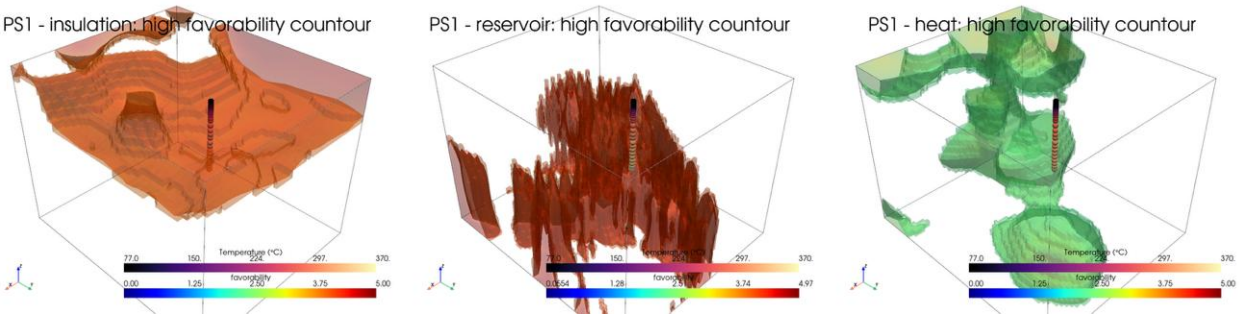


Figure 7. Component favorability models for thermal insulation (left), reservoir (center), and heat source (right) at Nesjavellir, produced from PFA for Production Scenario 1: Superhot Deep Injection Well and filtered to values greater than the 85th percentile. The NJ-11 temperature profile is included for context. The view is looking southwest. The top of the model is the surface (near 0-km elevation), and the bottom of the model is approximately -5-km elevation with respect to mean sea level.

Figure 8 shows the conceptual component model for Production Scenario 1 at Nesjavellir. This image better depicts the components' relative positions. Here, we can see that there are favorable reservoir zones intersecting with the heat source and rising slightly above it. This matches expectations for this production scenario, as we are targeting superhot ductile rock, meaning the line between heat source and reservoir is gradual and below the BDTZ.

3.2 Production Scenario 2: Superhot Deep Production Well

Figure 9 shows the component favorability models produced for the thermal insulation, reservoir, and heat source for Production Scenario 2 at Nesjavellir, displayed as 3D contours depicting the 85th percentile for interpretability. The colors in this depiction match the magnitude of the favorability for a given component. The NJ-11 temperature profile is once again plotted for context.

In this model, the thermal insulation and heat source favorability models are unchanged from those in Production Scenario 2 (i.e., the magmatic heat source and thermally insulating layers are still in the same locations). In this scenario, we can see that the reservoir is a bit higher above the heat source. This matches expectations, as we are targeting more brittle rock in this scenario so that the permeability propagates predictably.

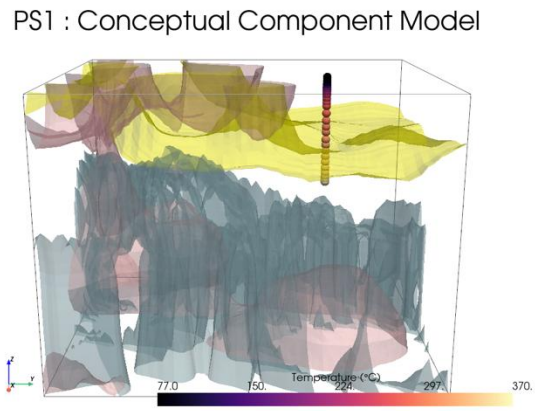


Figure 8. Conceptual component model depicting thermal insulation (yellow), reservoir (blue), and heat source (pink) at Nesjavellir, produced from PFA for Production Scenario 1: Superhot Deep Injection Well and filtered to values greater than the 85th percentile. The NJ-11 temperature profile is included for context. The view is looking west. The top of the model is the surface (near 0-km elevation), and the bottom of the model is approximately -5-km elevation with respect to mean sea level.

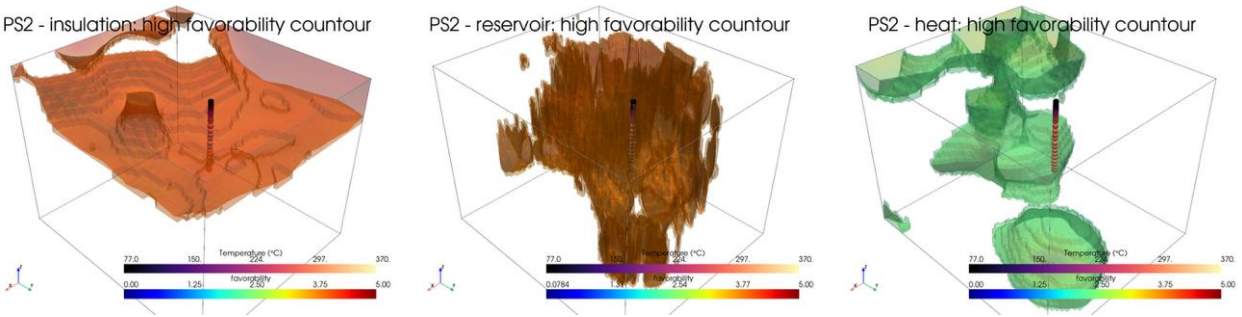


Figure 9. Component favorability models for thermal insulation (left), reservoir (center), and heat source (right) at Nesjavellir, produced from PFA for Production Scenario 2: Superhot Production Well and filtered to values greater than the 85th percentile. The NJ-11 temperature profile is included for context. The view is looking southwest. The top of the model is the surface (near 0-km elevation), and the bottom of the model is approximately -5-km elevation with respect to mean sea level.

Figure 10 shows the conceptual component model for Production Scenario 2 at Nesjavellir. Here, we can see more clearly that the reservoir has less overlap with the heat source and is nearer to the surface, more consistent with the depth that NJ-11 was drilled to.

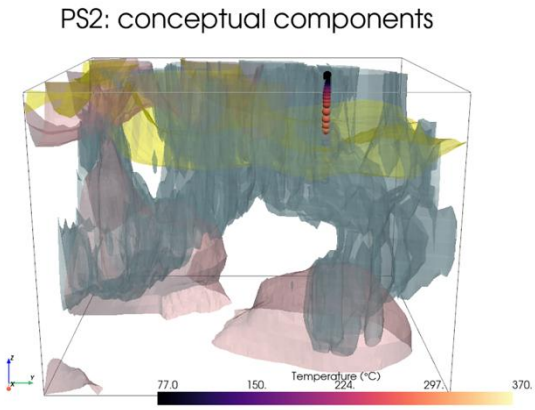


Figure 10. Conceptual component model depicting thermal insulation (yellow), reservoir (blue), and heat source (pink) at Nesjavellir, produced from PFA for Production Scenario 2: Superhot Production Well and filtered to values greater than the 85th percentile. The NJ-11 well downhole temperature profile is included

for context. The view is looking west. The top of the model is the surface (near 0-km elevation), and the bottom of the model is approximately -5-km elevation with respect to mean sea level.

3.3 Production Scenario 3: Superhot EGS

Figure 11 shows the component favorability models produced for the thermal insulation, reservoir, and heat source for Production Scenario 3 at Newberry, displayed as 3D contours depicting the 85th percentile for interpretability. The colors in this depiction match the magnitude of the favorability for a given component. The NWG 55-29 temperature profile is plotted for context, although it is hard to see given the larger extent of this model compared to Nesjavellir.

We can see a fairly consistent favorable layer for thermal insulation near the top of the model, with a gap to the north end of the caldera. As expected, the reservoir and heat source components look significantly different in this model. The reservoir favorability model highlights a large portion of the space beneath and directly outside of the caldera. The NWG 55-29 well intersects this favorable zone. The heat favorability model is more complex. A finger-shaped elevated favorability zone is observable for the heat source directly beneath the caldera, extending slightly to the south, in line with recent interpretations of gravity, resistivity, and density data (Schultz et al. 2024; Heath et al. 2015, 2018; Pang et al. 2025). We also see some elevated favorability zones to the north, northwest, and northeast of the caldera, but those are not associated with any expected anomalies documented in the literature. Notably, we do not see a high favorability zone for heat in the area where the NWG 55-29 well is located. This does not mean it is not hot in that region but is rather a factor of this PFA targeting magmatic heat source, whereas the Mazama Energy project is targeting a hot granodioritic pluton as its heat source, which has a significantly different geophysical signature than magma.

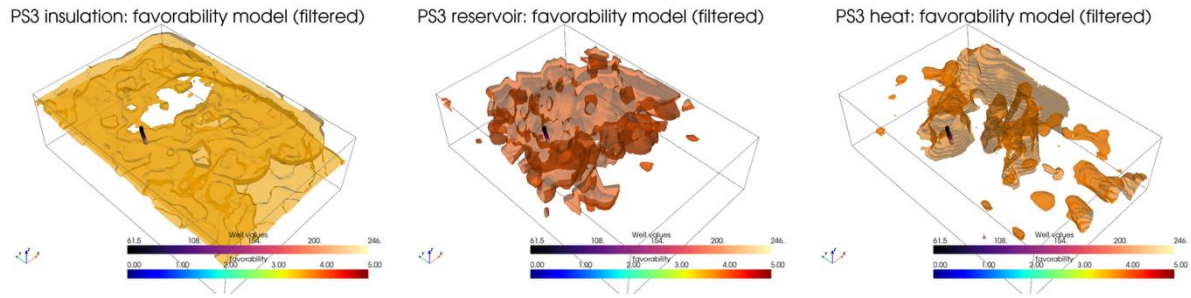


Figure 11. Component favorability models for thermal insulation (left), reservoir (center), and heat source (right) at Newberry, produced from PFA for Production Scenario 3: Superhot EGS and filtered to values greater than the 85th percentile. The NWG 55-29 temperature profile is included for context. Note that NWG 55-29 targeted a granodiorite plutonic heat source, hence its heat source is not identified here. The view is looking northeast. The top of the model is 1-km elevation with respect to mean sea level, and the bottom of the model is approximately -6-km elevation with respect to mean sea level.

Figure 12 shows the conceptual component model for Production Scenario 3 at Newberry. Here, we can see that the favorable reservoir volume significantly overlaps with the heat source favorable zone. For reference, NWG 55-29 was drilled into the highly favorable reservoir zone, beneath the lower bound of the favorable zone for thermal insulation and not intersecting with an identified favorable zone for a magmatic heat source (due to it instead targeting a granodioritic pluton heat source).

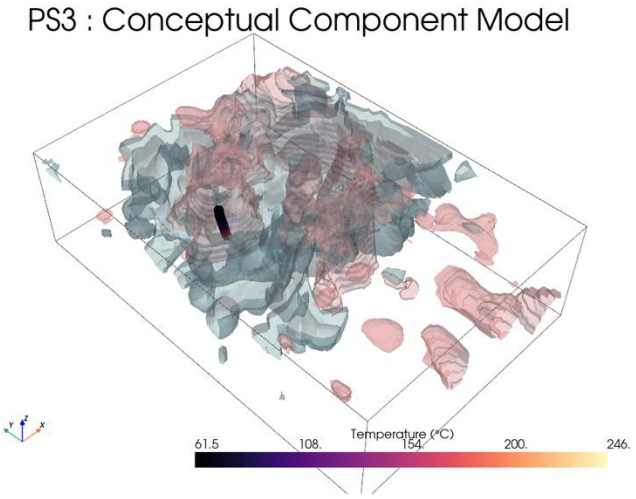


Figure 12. Conceptual component model depicting reservoir (blue) and heat source (pink) at Newberry, produced from PFA for Production Scenario 3: Superhot EGS (with magmatic heat source) and filtered to values greater than the 85th percentile. Note that NWG 55-29 targeted a granodiorite plutonic heat source, hence its heat source is not identified here. The thermal insulation component is not included in this visual because it is fairly consistent across the model area, and its inclusion impedes interpretation of the other two components. The NWG 55-29 temperature profile is included for context. The view is looking northeast. The top of the model is 1-km elevation with respect to mean sea level, and the bottom of the model is approximately -6-km elevation with respect to mean sea level.

4 DISCUSSION

It is important to consider that PFA is a purely analytical approach, and therefore these conceptual models are just to give a concept of how these systems might operate below the surface and to provide evidence to support or contradict geologically derived hypotheses. A more quantitative, or numerical methodology is needed to constrain the volumes of each component with more certainty. Additional limitations are introduced by the requirement of PFA to rigidly define target anomalies for each component. For example, Production Scenario 3 targeted a magmatic heat source in the work presented here, but other types of superhot heat sources exist, as is the case for the Mazama Energy project wherein the target heat source is a granodioritic pluton, which has a significantly different geophysical signature than a magma body. To capture plutonic heat sources, a separate PFA would need to be conducted with different targets, or a more flexible methodology would be needed. More generally speaking, in reality, any observable and favorability depends on local geology and on the goals of the project, so favorability is a complex functional of multiple geophysical and geological observables considered in aggregate rather than independently.

Despite these limitations, there is reasonable alignment between what we expect logically and the positions of each component with respect to each other and to existing wells. We have determined that the shape and depth of each component offer a useful inference for the favorability of the superhot resource position, given the following reasoning.

In the Hengill Volcanic Area, it has been hypothesized that a deep-seated heat source beneath the Hengill Volcano feeds one or more smaller heat sources (dike intrusions) at the Nesjavellir field (Gunnarsson et al. 2011; Ragnarsson, 2022). In the PFA model for Production Scenario 1, a complementary, large heat-favorability zone was inferred through this modeling effort beneath the Hengill Volcano, connected via a conduit to a smaller favorable zone for heat beneath Nesjavellir. The reservoir component overlaps with the heat source component, tying into the likelihood that the rock is more ductile without significant existing permeability, as it is hypothetically seated closer to molten rock. The shape of the reservoir loosely follows the faults, which is expected, given that some level of vertical permeability is needed to provide a preferential fluid pathway to create more significant permeability connecting the injected fluid from the ductile rock to the shallower hydrothermal reservoir feeding the active production field.

Production Scenario 2 at Nesjavellir targets brittle rock with existing permeability as the superhot reservoir. The favorable reservoir zone, though above that of Scenario 1, propagates along the fault zone. This aligns well with the modern understanding of fault systems and associated secondary permeability, supporting the hypothesized target for Production Scenario 2.

Production Scenario 3 at Newberry provided a model that indicated the presence of a shallower, finger-shaped, heat-component favorability volume beneath the caldera, and extending to the south. This coincides with multiple studies that have suggested that a magmatic heat source exists in that region (Schultz et al. 2024; Heath et al. 2015, 2018; Pang et al. 2025). There is a noticeable. lack of alignment between the Newberry thermal model and the heat component favorability model. While this misalignment requires additional effort to determine its route cause, it is likely a result of meteoric water contamination biasing temperature measurements, and therefore resulting temperature models, to the south of the caldera. The favorable reservoir zone is defined according to expectation, as the existing EGS well intersects that interval.

Although the results are promising, it is important to note that the exact shapes and sizes of individual components vary with subjective factors like weights, prior probabilities, and transformation functions. Additionally, it is possible that smaller magma chambers that could not be resolved confidently might exist in each of these models. A more probabilistic approach would enable uncertainty quantification and probabilistic intervals, allowing us to boost confidence in the conceptual component models.

This work in part aims to explore the trade-offs between analytical and numerical models and experiment with ways to integrate them. While we have yet to integrate numerical modeling approaches, the analytical approach shows significant promise, as it has a significantly lower computational cost and significantly fewer assumptions are required. When properly configured with an accurate geologic model and boundary conditions, numerical models are much more accurate. Analytical models, however, have the potential to provide information where the required existing data and modeling efforts are more sparse. While data is relatively abundant at most identified magmatic superhot systems, data is much more sparse when exploring non-magmatic superhot systems, a trend expected to accelerate as our understanding of superhot geothermal advances.

5 CONCLUSIONS AND FUTURE DIRECTIONS

This analysis provides useful insights around conceptual modeling of the superhot reservoir production scenarios, helping inform decisions around which scenario is best suited for which types of environments. With additional refinement, this methodology could be used to identify which zones of a play are good targets for specific types of superhot geothermal. The geoPFA library provides a reproducible tool set to carry out similar analyses on other superhot plays, other types of geothermal plays, or even other subsurface technologies.

Future work will include comparison to and integration of numerical modeling techniques, particularly TReactMech, to better constrain the reservoir component. The trade-offs between numerical and analytical modeling methods will be further explored in the context of magmatic and non-magmatic superhot systems.

To further investigate the discrepancy between the heat favorability model and the thermal models at Newberry, and to better understand the thermal resource there, a refined thermal model for Newberry is needed. A similar investigation would be useful for Nesjavellir, for which the MGI temperature model (Hokstad et al. 2024) is significantly hotter than the model used in this study (ISOR & OR, unpublished).

Lastly, more probabilistic transformation methods would enable more interpretable results with transparent uncertainty quantification, enabling more confident modeling and decision-making.

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