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Survey of Methods, Challenges, and Pathways Forward for Superhot Rock Characterization

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ABSTRACT

There is a growing governmental, commercial, and academic interest in high enthalpy, Superhot Rock (SHR) geothermal systems due to their high energy density and thus the potential for large-scale, economic electricity production. However, the highly site-specific aspects of geothermal power production introduce risks that can be a major obstacle to resource development. Geophysical methods must be optimized and adapted for SHR resource characterization to reduce exploration risk and improve reservoir monitoring techniques. Field-validation and laboratory facilities to measure geophysical properties at these conditions are limited, so it's important to best leverage the available information and target further data collection. This study examines the capabilities and limitations of geophysical methods that target subsurface features, identifies gaps in these methods for SHR characterization, and suggests strategies to close these gaps. We explore a range of geophysical-based methods that target key subsurface properties - temperature, stress state, structures and permeability - that are crucial to characterizing SHR resources.

1. INTRODUCTION

Superhot rock (SHR) geothermal reservoirs are defined as resources with temperatures above the supercritical point of pure water, ~375 ºC. These temperatures exist everywhere on Earth at sufficient depth but are more readily accessible in areas of active magmatism – subduction zones with volcanic arcs, extensional regions and rift structures, or hot spot mantle plumes (Manzella et al., 2019). To develop SHR resources beyond these geological domains, significant advances in reservoir permeability enhancement and ultradeep (>7 km) drilling into crystalline rock must be achieved (Cladouhos & Callahan, 2024). All SHR prospects, regardless of geological setting, must undergo extensive siting and characterization studies to assess the project's technical feasibility, risks, economic cost, and return on investment.

The site-specific aspects of geothermal resources introduce significant risk to developing SHR projects. Geothermal wells must be drilled into uncertain subsurface conditions at great expense, and their failure can terminate a project. While this challenge is not shared by modular renewable technologies such as wind and solar, other subsurface resources such as minerals and hydrocarbons face similar exploration risks. Techniques to mitigate these risks are well-developed by the mining, oil and gas, and conventional geothermal sectors, which can be leveraged and adapted for SHR siting and characterization procedures. This work reviews state-of-the-art geophysical, geochemical, and geological methods that can characterize SHR geothermal resources (Figure 1); identifies technical gaps in these methods for SHR characterization; and suggests potential strategies to close these gaps. The full report is one of a five-part series that analyzes technology gaps for SHR resource development (see companion reports on heat extraction, drilling, well completion, and surface equipment on the Clean Air Task Force (CATF) Superhot Rock Gap Analysis page: https://www.catf.us/superhot-rock/bridging-gaps/).

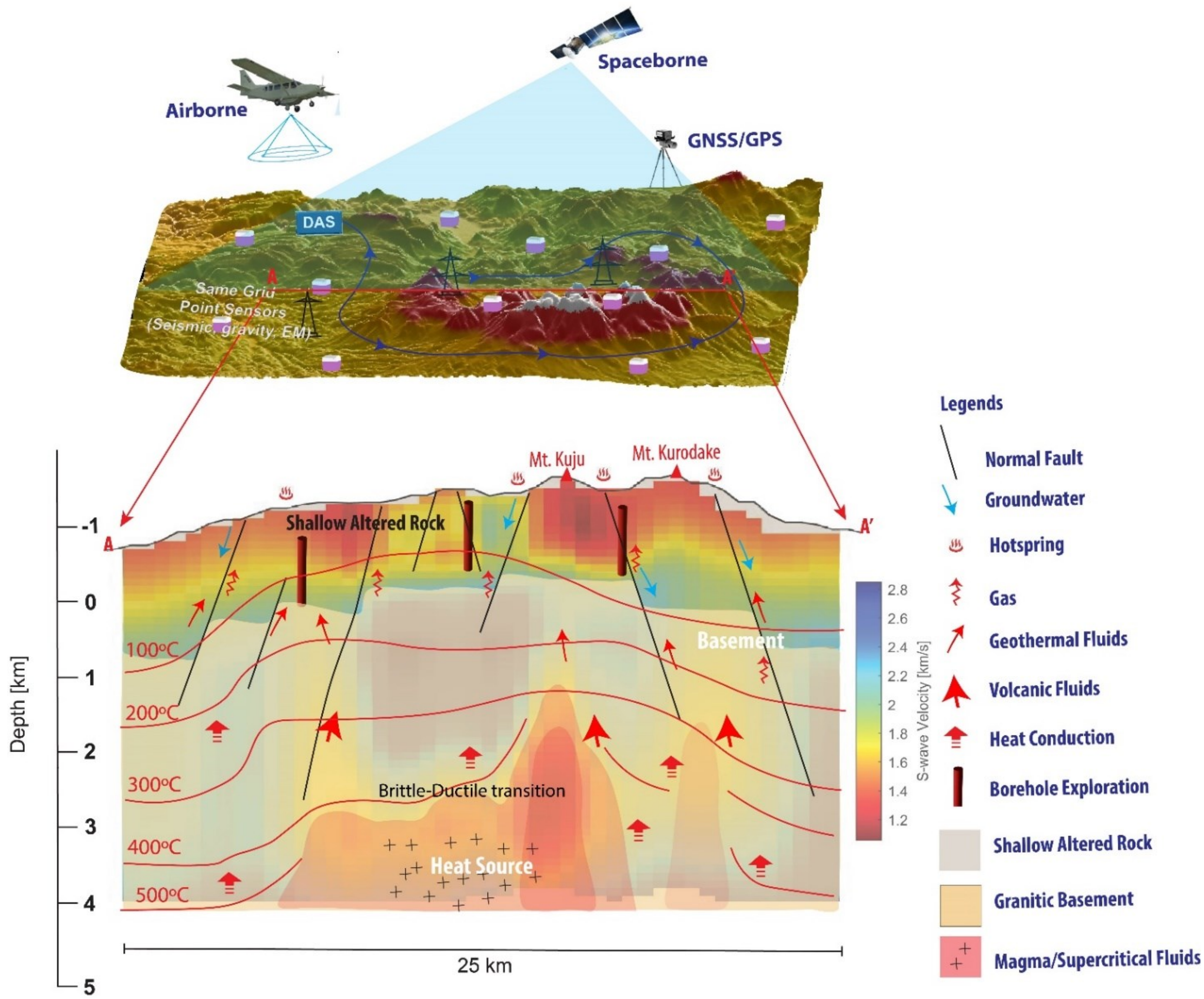

Figure 1: Conceptual representation of current technologies applied to SHR geothermal resource characterization and how these data of the subsurface are mapped and interpreted, modified from Chhun et al. (2024).

The deep subsurface is a complex system that offers limited directly observable evidence of conditions at depth. Geoscientific methods strive to illuminate these conditions with instruments that sense specific physical or chemical properties at depth. Sampling multiple properties and performing different types of geoscientific data analysis increases confidence in model outputs, iteratively reducing uncertainty and exploration risk. The properties targeted by an exploration program are specific to the prospected resource (Beardsmore & Cooper, 2009). In the case of SHR geothermal, the primary properties to constrain are heat, stress, permeability/fluid content and geological structures. These parameters are first-order controls of the commercial viability of a resource, as they inform: (1) the temperature and thermal transfer mechanism at depth; (2) the drilling program required to access the resource, including depth to target, well configuration and orientation; (3) requirements to enhance reservoir permeability; and (4) the risks of induced seismicity. It is, therefore, crucial to constrain the key properties to the highest degree of confidence or risk substantial project failures.

Exploration risks are particularly difficult to estimate and manage without costly exploration drilling, well-logging, and core analysis. Surface geophysics can indirectly estimate these properties at a broad range of scales with sufficient data coverage from coeval surveys; however, individual data source interpretations can be compromised by poor data quality or invalid assumptions. Lastly, there are only a handful of SHR resources (~20 wells have been drilled into SHR temperatures) that have been extensively characterized by geophysics and verified with exploration drilling, even laboratory facilities and results that simulate SHR conditions are severely limited. Therefore, it is not possible to conclusively determine best practices for SHR resource characterization yet, more laboratory and field validation is needed.2

2. KEY RESERVOIR PROPERTIES

In the following sections, the key geological/geophysical methods, gaps, and solutions are discussed for modeling the three critical parameters, heat/temperature mapping, stress and pore pressure at depth, and structure/permeability (Figure 2). These parameters are essential components of geological conceptual models and resource assessments, aimed at reducing risk and increasing the probability of success in selecting exploratory/development SHR sites.

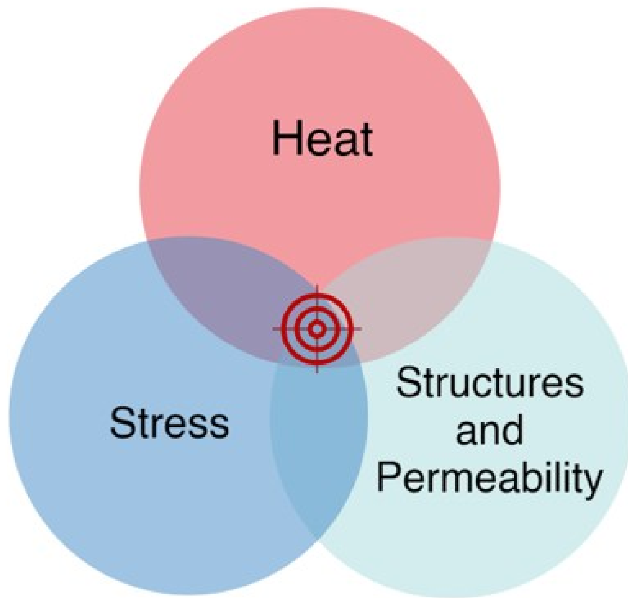

Figure 2: The three critical parameters for SHR characterization and siting, modified from Taverna et al. (2024)

2.1 HEAT/TEMPERATURE MAPPING

Heat mapping determines the thermal properties at depth for a prospective geothermal resource, commonly quantified as the geothermal gradient (°C/km), temperature at depth (T(z)), or heat flow (mW/m^2).,Geothermal heat flux is dependent on the conductive, convective and radiative heat transfer properties of the geological province (such as continental margin, sedimentary basins, shield-type cratons, or orogenic belts), geological properties (such as composition and porosity), and mantle dynamics that impact basal heat flow (Fullea et al., 2021; Grasby et al., 2011; Kirkby et al., 2024).

Before exploration drilling is able to provide direct but cost-intensive, relatively shallow, and highly localized measurements of thermal properties at depth, global-to-regional-scale heat flux values provide initial estimates. These indirect estimates are obtained by integrating a range of datasets including surface heat flow measurements, geological domain characteristics, electrical conductivity, gravitational and magnetic potential, seismic velocity, and other datatypes with sensitivity to temperature or structures associated with thermal properties (Kana et al., 2015). Thermal properties at depth are thus complex to resolve, yet essential for proposing and de-risking geothermal projects, including SHR plays.

2.1.1 Heat Mapping at the Exploration Scale (100's - 10's of km)

Two key challenges for heat mapping at the exploration scale are the inability to model convective heat transfer mechanisms, and lack of high-resolution data to inform thermal modeling algorithms. State-of-the-art mapping tools commonly demonstrate one or both of these technology gaps. For example, mapping the Curie Depth Point (CDP), the depth of the Curie temperature (~580 °C) where rocks become demagnetized, can provide a useful indication of temperature properties at the crustal scale. However, this measure is coarse (>90 km^2) and may not accurately determine the CDP thermophysical horizon if additional physical properties of the crust are unknown, such as rock composition. Conversely, surface heat flow mapping (Lucazeau, 2019; Fuchs et al., 2023) has a high thermal data density in the near-surface (<3 km), but extrapolating these temperature trends at depth can lead to inaccurate thermal models, to the order of 30 – 40% lower heat gradients when compared to other models that incorporate additional data (Batir & Richards, 2022). The crustal dynamics model LithoRef18 jointly inverts multiple geophysical datasets to improve model confidence, and can be used to estimate depth to the supercritical temperatures or other relevant isotherms (Figure 3) (Afonso et al., 2019; Ball et al., 2024; Sellars et al., 2023). However, LithoRef18 is also coarse grained (230 km^2), and only maps steady state – conductive – thermal transfer mechanisms. Researchers must integrate non-steady state – convective – heat transfer mechanisms into their modeling scheme to improve thermal mapping around volcanic domains, where early stage economically feasible SHR resources occur. The recently released Stanford Thermal Model integrates over twenty geophysical data inputs to map temperatures at depth with machine learning (ML) for the contiguous USA (Aljubran & Horne, 2024). The results are a high resolution (18 km^2) thermal model that extends 7 km deep, yielding an impressive temperature prediction accuracy of 6.4°C. However, the method also omits non-steady state thermal transfer mechanisms and only covers the contiguous USA. To improve accuracy in the US and extend the Stanford Thermal Model to a global scale, intensive data acquisition campaigns are needed.

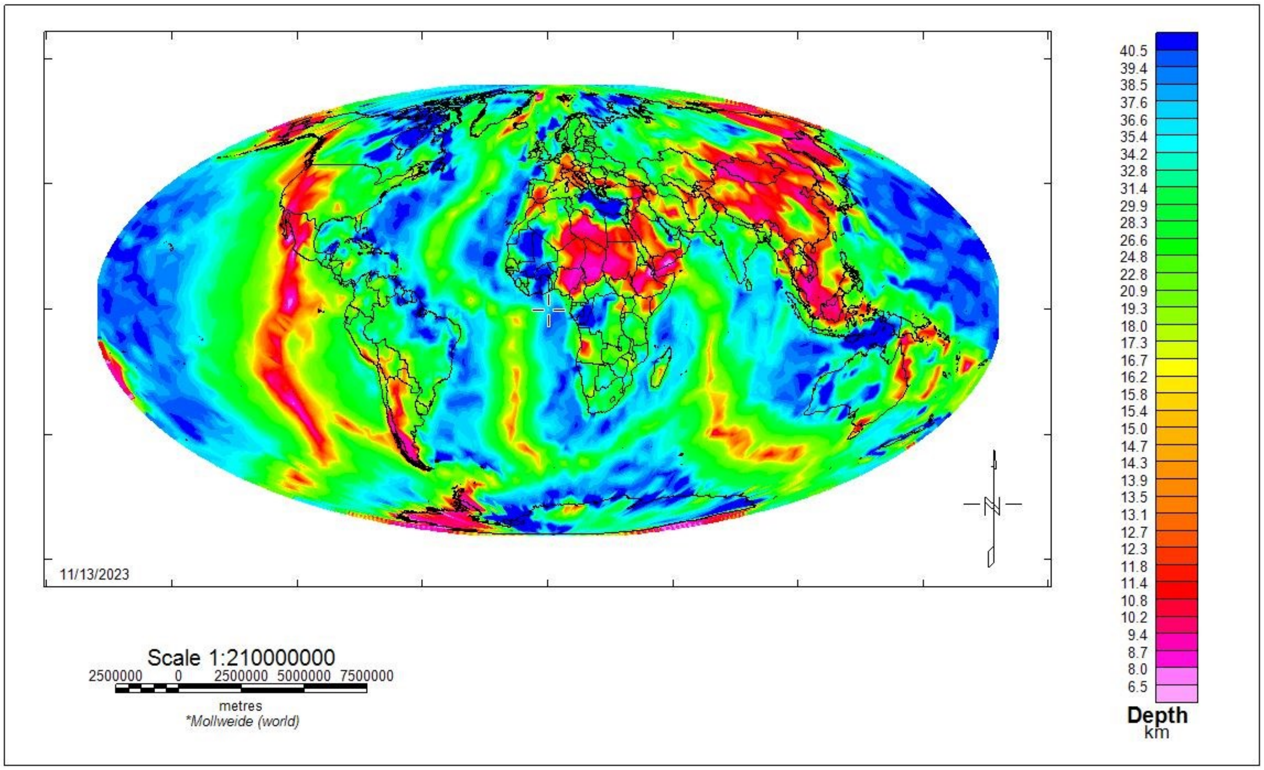

Figure 3: LithoRef18 computed 450°C isotherm calculated, Mollweide Projection. This is the first global representation of the 450°C steady-state conductive isotherm (Ball et al., 2024).

2.1.2 Heat Mapping at the Reservoir Scale (<10 km)

When a SHR geothermal project proceeds to planning and de-risking stages, additional strategies for subsurface heat mapping that rely on detailed borehole logs and geological models can be implemented. Temperature-depth (T(z)) estimations relate to lithological heat flow, thermal conductivity and heat generation. The petrophysical properties of core samples can be measured in laboratory facilities that measure thermal conductivity, thermal diffusivity, and heat capacity (Majorowicz & Grasby, 2010). When a sufficient distribution of exploration boreholes exists, thermal property measurements can be used to interpolate isotherms at varying depths. Where borehole data is not available, literature on thermal conductivity values from geological proxies can be incorporated into regional heat flow models, supplemented by geophysical information such as mantle seismic velocity, crustal geodynamics, and geological maps (Aghahosseini & Breyer, 2020; Majorowicz & Grasby, 2010). Incorporating downhole measurements into detailed geological models can lead to higher confidence, as described by Batir & Richards (2022).

Downhole temperatures can be measured with wireline tools and probes that come in direct contact with the borehole wall (Fuchs et al., 2023). The disturbance of in situ borehole conditions due to drilling must be considered when sampling temperature at depth, and measurements should only be taken after 10 – 20x the time spent drilling and circulating fluid to let the well thermally equilibrate (Blackwell et al., 2011; Fuchs et al., 2023; Shi et al., 2021). These tools must be adapted to be rated for SHR conditions, although some are nearing that threshold, such as the Kuster temperature mechanical gauge featuring a 360°C temperature rating (Shi et al., 2021), and Sensornet Distributed Temperature Sensing fiber with a 300°C temperature rating (Khankishiyev et al., 2024).

Challenges in heat mapping at the reservoir scale may occur as a result of sparse or incomplete datasets, leading to a misestimation of heat flow at depth. Where data is not available, statistical methods described by Aghahosseini (2020), Fuchs et al. (2023) and Lucazeau (2019) can be used to estimate regional to large-scale heat flow trends with the highest possible accuracy. Furthermore, measuring thermal conductivity requires laboratory processing of collected borehole samples, however, few facilities have the capacity to simulate in situ SHR pressures and temperatures. Otherwise, downhole measurements may be imperfect due to poor coupling or the presence of fluids and sediment that impair contact with the borehole. Improved downhole tools that can sample temperature and thermal conductivity properties must be designed to rapidly survey boreholes at SHR temperatures. Further work constraining radiogenic heat flow in the basement must be conducted, as this is a primary control on heat flow but is often oversimplified in heat flow modeling.

2.2 STRESS AND PORE PRESSURE AT DEPTH

Understanding the initial stress field is crucial for designing drilling and permeability enhancement strategies. Hydrofractures should be oriented perpendicular to the least principal stress, which the injected fluid pressure must exceed. Hydroshear can open existing fractures but requires detailed knowledge of the local stress field and natural fracture properties. Even with extensive characterization, meso-scale EGS experiments at conventional temperatures have found it difficult to increase permeability through hydroshear (Kneafsey,et al., 2024).

Another crucial parameter to estimate is the pore fluid pressure during drilling to reach the target reservoir (Figure 4b). Although many SHR scenarios may target areas with very low permeability, understanding pore pressure changes in the subsurface formation is significant for adjusting fluid drilling pressure when reaching different formations. If it is not properly predicted, for example, if mud/fluid drilling pressure is larger than pore pressure, it can result in induced fractures (e.g., fracture pressure), mud loss, or well instability (Zhang, 2011). Conversely, if the mud weight pressure is lower than the normal or hydrostatic pore pressure of subsurface formations, formation fluids can flow into the wellbore, causing drilling kicks/blow-out and wellbore instability.

2.2.1 Stress mapping at the exploration scale (100's - 10's of km)

The world stress map (e.g., stress field direction), refined over the last 40 years, shows the best estimated stress orientations and tectonic regimes globally (Heidbach et al., 2018). It compiles data on the present-day crustal stress field, including earthquake focal mechanisms, borehole data, in-situ stress measurements, and surface geological structures. However, the stress field is influenced by the natural state of stress in the crust, including overburden weight and tectonic forces, which vary regionally, locally, and with depth (Stephansson & Zang, 2014; Zang & Stephansson, 2009). The world stress map has limited resolution due to current data scarcity (with very limited data available in large areas) and scaling effects including limited exploratory borehole data and depth, which may not accurately represent the stress state at depth.

2.2.2 Stress mapping at the reservoir scale (<10 km)

A study of local 3D stress, based on a final rock stress model developed by Stephansson & Zang (2014) (Figure 4a), suggested a new approach through the joint stress data analysis using field, borehole, and seismic-based methods (e.g., stress inversion from focal mechanisms) and numerical modeling. This approach can produce a 3D stress model including the direction and amplitude in different local stress settings.

One example of a study on estimating pore fluid pressure in a reservoir was conducted in the St. Gallen Geothermal field (Switzerland) using earthquake hypocenters and focal mechanisms to estimate stress patterns and slip vectors and predicting excess pore fluid pressure (De Matteis et al., 2024). While this method focuses on how excess pore fluid pressure causes earthquakes/seismicity during fluid injection, applying it in SHR geothermal fields offers the possibility to predict pore fluid pressure excess during the SHR development, extraction, and monitoring.

Currently, advanced drilling technology (e.g., Managed Pressure Drilling as described in McCaskill et al. (2006)) can automatically adjust pressure and formation pore pressure at depth. However, reaching ductile SHR conditions still requires more field testing and validation, as well as logging and casing tools, at the high-pressure and high-temperature (HPHT) condition across various geodynamic settings. Most measurements of logging and casing tools can currently withstand temperatures of less than 250°C. Well logs, which are tools directly attached to the wellbore, can be influenced by casing or borehole breakout (e.g., fractures induced by drilling) and mud invasion.

Accurate pore pressure and stress field predictions are essential to ensure safe and smooth drilling operations, especially when encountering highly unexpected pressure/temperature differences (e.g., dikes, basements, gas, or magma pockets). Future research should focus on modeling accurate pore pressure distribution and in-situ 3D rock stress models, including stress magnitudes, regimes, and orientations in various SHR fields

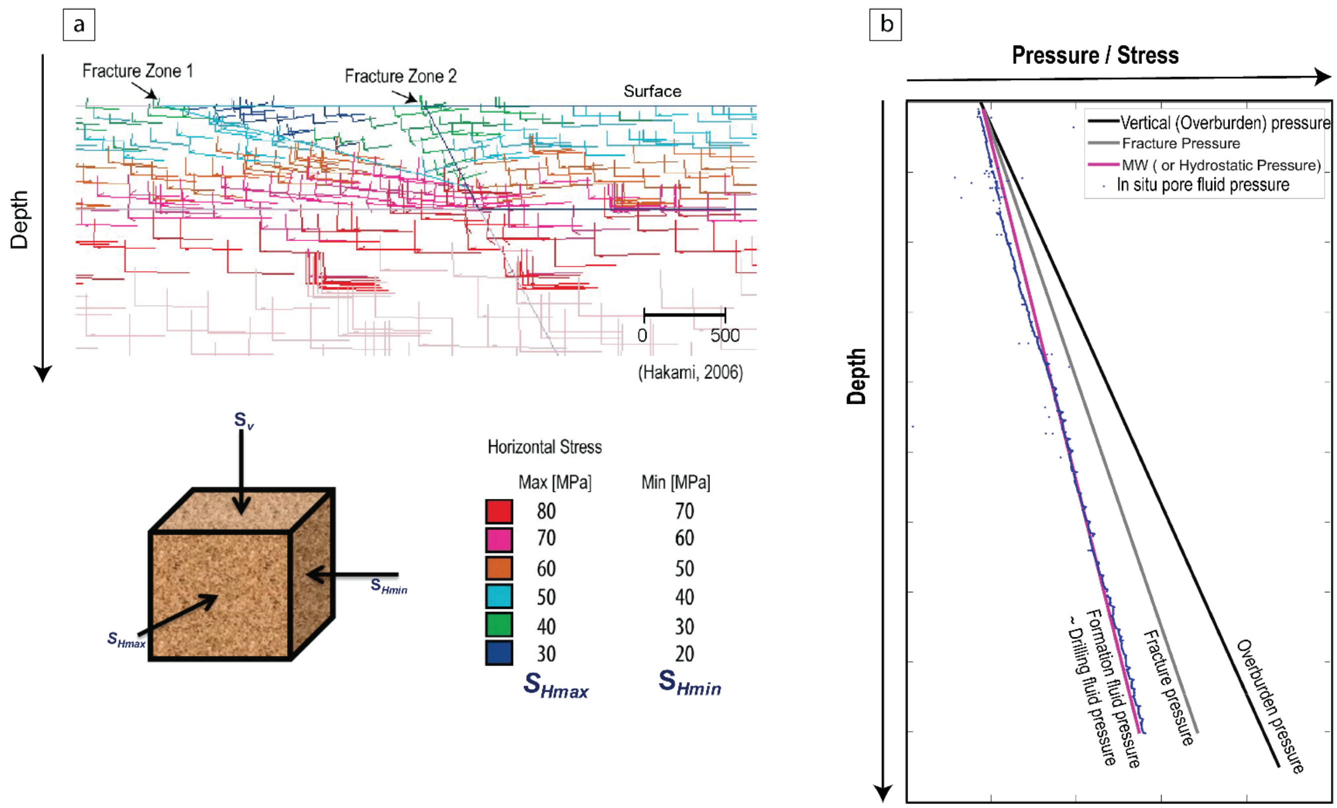

Figure 4: a). An estimated stress distribution of the orientation and magnitude of maximum and minimum principal (horizontal) stresses, (from Hakami, 2006); b) An example of balancing drilling fluid pressure and pore fluid pressure to prevent drilling risks, modified from Chhun & Tsuji, (2021).

2.3 STRUCTURES AND PERMEABILITY

In this section we focus on key methods for imaging structure/permeability, which is assumed to be dominated by fractures and faults in hydrothermal settings, while EGS or closed-loop systems might target non-fractured areas to limit potential drilling complications. High-resolution subsurface structure characterization from surface arrays and/or borehole measurements is a key input to conceptual models that inform many aspects of design and decision-making. Permeable fractures, faults, and other volcanic structures (such as magma chambers) can be mapped based on seismic reflection, fracture seismic imaging, seismic anisotropy, microseismic analysis, and other geophysical imaging. Although multiple geophysical methods could be relevant, here we focus on seismic methods.

Structural imaging can provide: (1) depth constraints for supercritical temperatures and Brittle-Ductile Transition (BDT) zone depths as well as magmatic heat sources; (2) high-resolution 3D velocity models to improve the absolute locations of induced seismic events; (3) maps of potentially active faults using microseismicity in the project area to avoid greater induced seismicity risk; (4) images of other structures or non-fractured zones (e.g., intrusions, dikes, basement depth) that would impact drilling and stimulation plans; (5) stress orientation and regime determination from the focal mechanism analysis and anisotropy (e.g., shear wave splitting or azimuthal anisotropic ambient noise); and (6) open fracture orientations.

2.3.1 Structure and permeability mapping at the exploration scale (100’s to 10’s of km)

Seismic reflection structures derived from active sources (e.g., high frequency sources at 5 – 500 Hz) are mostly applicable in sedimentary basins because high-resolution imaging is challenging in geothermal fields due to the complexities in obtaining P-wave or S-wave velocities and reflections. In the Larderello project, Italy (Bertani et al., 2018), the strong acoustic contrast (strong reflector or K-horizon) was interpreted to be caused by a supercritical fluid layer, but drilling did not encounter supercritical fluid there. This misinterpretation could be attributed to the complex structure/stratigraphy (e.g., contrast between hydrothermally altered rock vs. non-altered rock, basement-sediment layer, partial melt zones). A technique to overcome this issue is auto-correlation analysis using ambient noise data. This technique could retrieve P-wave or S-wave reflections using passive seismic sources (Sakagami et al., 2024; Viens et al., 2022). Successful application in SHR fields will require enhanced testing and advanced data processing methods to obtain and reveal the true subsurface structure in SHR reservoirs.

2.3.2 Structure and permeability mapping at the reservoir scale (<10 km)

Fracture seismic imaging based on microseismic events focuses on imaging fractures around the borehole. Fracture growth or fluid flow in fractures can provide a high frequency source band at 1 -100 Hz, which are recorded in dense passive nodal arrays and then processed using seismic reflection schemes to map hydraulically connected fractures (Sicking & Malin, 2019). Retrieving only fracture signals can be challenging due to noise from wave scattering and attenuation effects or other noise sources (e.g., from the well head). Interpreting fracture seismic maps can be complicated by amplitude artifacts and distortions. Therefore, advanced data processing, noise filtering, and new algorithms are required to remove amplitude artifacts and enhance signals for velocity and seismic attribute (fracture) analysis.

Anisotropy of geophysical properties provides important information about the orientation of stress and structures in the subsurface. Seismic anisotropy can be derived from the analysis of shear wave splitting tomography or azimuthal ambient noise tomography. Seismic anisotropy based on azimuthal ambient noise tomography can be derived from surface wave travel time analysis and inversion (i.e., ray paths relative to their direction) (Chhun et al., 2024). However, these techniques can be influenced by multiple modes of surface waves and varying velocities in different directions due to fluid, fracture, and litho-strata contrasts in rock. Therefore, dense ray paths, appropriate survey coverage (array spacing), and advanced velocity analysis are essential for reducing uncertainty and imaging SHR reservoir depths.

Microseismicity can be used to detect fracture activity within exploratory and producing fields (Bromley, 2020) and to trace fluid movement and fractures (Hartline, 2024). Thus, the boundaries or geometry of the reservoir and fractures/faults can be mapped using microseismic locations. However, high-resolution velocity models, dense sensors, and accurate seismic phase picking remain challenging for obtaining and estimating the absolute locations of seismicity/earthquakes. Many newly developed ML algorithms (e.g., pyOcto) are available for automated seismic modeling with high accuracy (Münchmeyer, 2024).

3. DATA INTEGRATION FOR RESOURCE ASSESSMENTS

Data integration refers to the process of unifying various sources of heterogeneous data. In geothermal resource assessment, the data integration process includes a mix of geological, geophysical, and geochemical evidence from which various techniques can be applied.

The Geothermal Play Fairway Analysis (GPFA) methodology integrates various datasets to find favorable intersections of the required elements (e.g., presence of fluid, heat source, and reservoir permeability in conventional geothermal resources) (Kolker et al., 2022; Pauling et al., 2023; Taverna et al., 2024; Trainor-Guitton et al., 2024) for a geothermal system, which can guide initial exploration efforts. The traditional GPFA approach considers conventional geothermal systems and therefore is typically applied to identify areas where fluid and permeability are already present. Nevertheless, Taverna et al. (2024) successfully modified the approach to target superhot EGS systems in a case study in the Newberry Volcano, OR. Aspects of the data integration include the use of a joint inversion (magnetotelluric and gravity) with many other datasets (e.g., digital elevation model, earthquake catalogs, seismic velocity, geothermal well data, and geological modeling) for resource favorability evaluation. SHR resources are believed to exist in various geodynamic environments and consequently, the use of Taverna et al. (2024) GPFA may lack the flexibility to identify all the subsets of SHR plays.

Artificial Intelligence (AI) and machining learning (ML) are utilized in a wide range of applications, including predictive and classification modeling for enhanced geophysical data processing (Misra et al., 2021), resource exploration (e.g., Brown et al., 2020; Mordensky et al., 2023a), and reservoir characterization (e.g., Zhang et al., 2020). Chhun et al. (2024) extended their work by incorporating multi-modal data to estimate the 3D temperature model of Mt. Kuju, Japan. The 3D temperature of the Kuju reservoir (10 x 10 sq. km) was estimated using various ML models using eight temperature well logs, 3D S-wave velocity, 3D resistivity, 3D gravity, and 3D seismic anisotropy to serve as proxies for fracture orientations (Figure 5). The application could also be extended to include other borehole data such as stress, permeability, and porosity. Since geothermal well data is limited to depths of less than 2 km, temperature varied up to 250°C within the identified geothermal reservoirs. As a deeper, exploration-scale case study, Aljubran & Horne (2024) used a graph-based ML approach to create thermal models across the US regions up to 7 km of depth.

The aforementioned studies demonstrate that AI/ML is a powerful tool to predict physical rock properties and conditions that can support the exploration and development of SHR. However, these methods are sensitive to the volume and quality of the input data, so the limited number of examples of superhot conditions, and non-standardized exploration approaches, data collection and processing are major current limitations. It's important to note that the addition of new datasets may not lead to better model performance (Mordensky et al., 2023b). Thus, increasing the quality of the data using better data processing techniques, collecting higher resolution data and identifying input data that enhance the model predictive skills may be required for the ML algorithms to identify meaningful patterns. This process would benefit from the decision analysis field to quantify how relevant a source of information is (i.e., Value of Information; Trainor-Guitton et al., 2013) to reduce uncertainty and decrease economic risks. Effective resource modeling approaches lead to improved resource characterization, more accurate assessments, and optimized development strategies, increasing the probability of project success across SHR fields.

Despite limitations, the existent data assimilation techniques are readily available to SHR. Further studies are needed to relate geophysical, geochemical, and geological observations (and potential signatures) to rock properties at SHR conditions. In that sense, field-validation in superhot fields is fundamental, while laboratory experiments at these conditions can also improve confidence in interpretations.

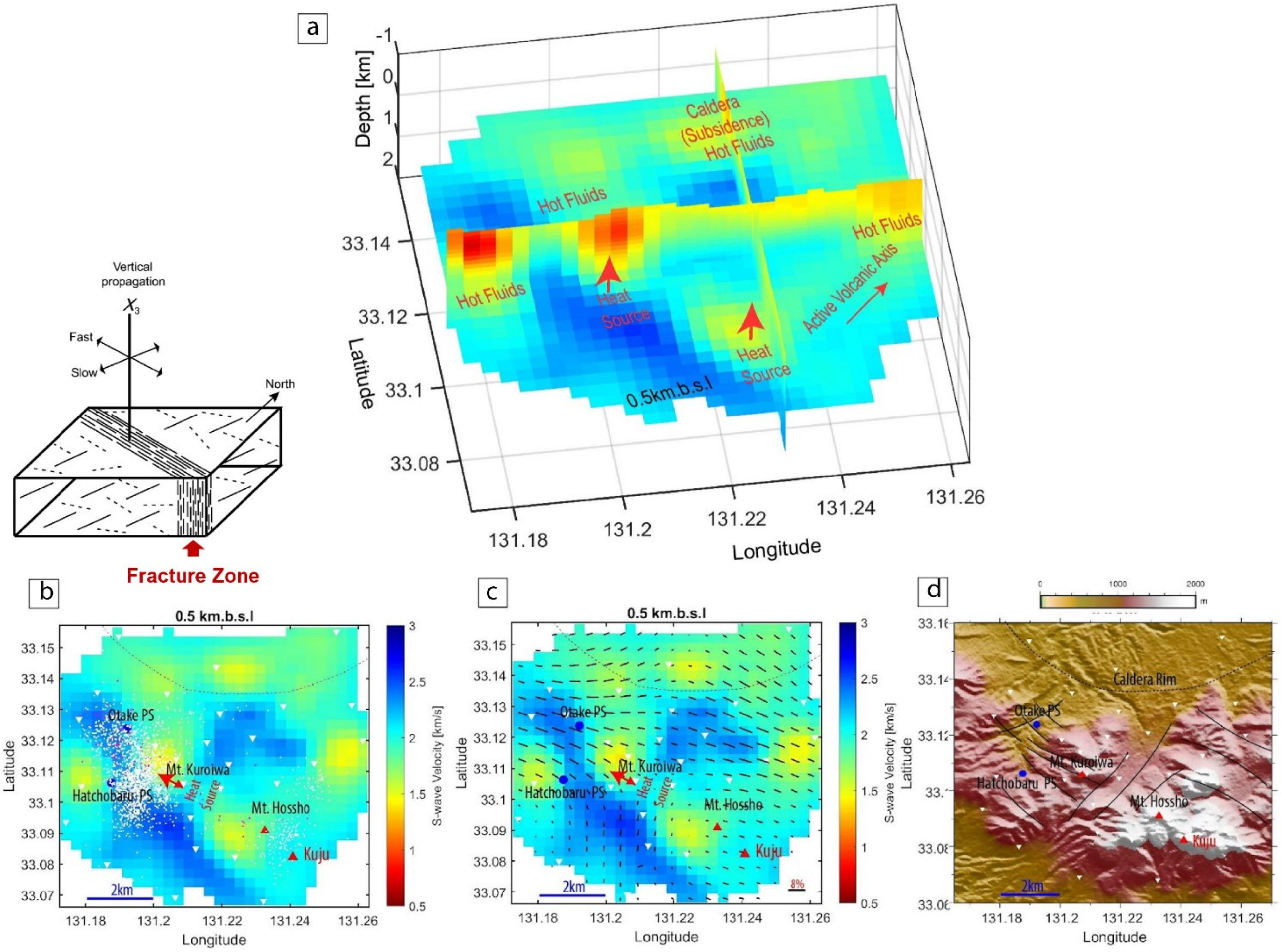

Figure 5: An example of multiple geophysical results extrapolated using ML to determine siting (Chhun et al., 2024) a) 3D S-wave velocity model, b) a velocity slice at a depth of 0.5 km below sea level or ~1.5 km below surface, c) the anisotropic structure (fast polarization axis) overlaid on the velocity model, and d) the structural (faults/fractures) interpretation derived from (c).

4. SUMMARY

Many geophysical methods required for SHR exploration are developed and ready for application, but limited validation in relevant locations hampers robust conclusions. Data-driven analysis methods, including PFA and ML, show potential but are constrained by a lack of sufficient data. More field-validation datasets and laboratory experiments are needed to establish robust connections between geophysical observables and the key rock properties and conditions (namely temperature, stress, structures, and permeability/fluid content). By addressing the following challenges/gaps and advancing the necessary technologies, SHR geothermal systems can become a viable and significant source of clean electricity:

- Expand and integrate superhot rock data to enhance models: Integrate diverse datasets to achieve high-resolution models and identify optimal locations for demonstrating SHR reservoir development within areas of sustained elevated heat flow.
- Standardize shared data collection and analysis: Establish a sharing approach of SHR site characterization to de-risk exploration (e.g., PFA) and improve extrapolation of lessons learned between projects. Conduct retroactive studies with archival datasets to identify optimal geophysical techniques and lessons learned from existing geothermal/SHR reservoirs.
- Increase investment and policy support: Substantial subsidies, tax incentives, research funding, and company investment are needed to support the development of next-generation technologies, leading to increased field data deployments, applications, and exploratory boreholes for SHR resource development.

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