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Prospecting for superhot rock energy

Summary of a technology gap analysis for siting and characterizing superhot rock energy resources

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Introduction

Superhot rock energy is attracting growing interest from governments, energy suppliers, and energy transition researchers due to its high energy density and potential for large-scale, always-on electricity production. To improve our understanding of the geological conditions where superhot rock energy is found, further technical advances are required. Research initiatives must target specific technology gaps for characterizing superhot rock resources in order to improve our ability to harness this resource. After conducting a substantial review of existing methods for subsurface resource characterization, we recommend specific areas to focus future research efforts for superhot rock energy prospecting. The findings of our detailed analysis are summarized here.

Superhot rock geothermal systems access rock that is hotter than the supercritical point of pure water, ~375° C. Superhot rock energy can be found anywhere in the world, in a diverse range of geological settings and subsurface conditions, but nearly always at depths greater than five kilometres. These findings are, therefore, applicable to both superhot and ultradeep geothermal systems. Because of the range of settings, subsurface conditions, and depths involved, each superhot rock project must undergo extensive siting and characterization studies to reduce drilling risk, improve project cost projections, and secure financing by proving the economic viability of the resource.

The Earth's crust is a complex system that offers little observable evidence of subsurface conditions. Geoscientific methods strive to illuminate these conditions with instruments that sense specific physical or chemical properties at depth. In the case of superhot rock geothermal, the primary properties are heat, stress, permeability, fluid content, and geological structures. These parameters determine 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 these key properties to the highest degree of confidence or risk project failures.

The mining, oil and gas, and conventional geothermal sectors have developed significant expertise in mitigating exploration risks, and this expertise can be leveraged and adapted for superhot rock siting and characterization procedures. The report summarized here identifies technical gaps in these methods, and suggests strategies to close these gaps for superhot rock characterization. The full paper, *Bridging the gaps: A survey of methods, challenges, and pathways forward for superhot rock siting and characterization*, is one report of a five-part series that analyzes technology gaps for superhot rock resource development (see companion reports on heat extraction, drilling, well completion, and surface equipment on the Clean Air Task Force's website).

In the following sections, we review methods for characterizing the subsurface with mature geophysical, geochemical and laboratory techniques, identifying the strengths and limitations of each for superhot rock energy applications. We follow this with a review of technologies that can best measure the key properties of superhot rock energy—heat, permeability, stress, and structure—from the exploration scale (greater than 10 kilometres spatial coverage), reservoir scale (less than 10 kilometres spatial coverage) and monitoring scale (less than one kilometre spatial coverage). These scales broadly follow the stages of project planning, from the siting stage (exploration) to the feasibility stage (reservoir), and finally the production stage (monitoring).

Geophysical, geochemical, and laboratory methods

Surface and downhole geophysics provide valuable insight into subsurface conditions, such as the density, magnetic susceptibility, electromagnetic conductivity, and elasticity or anelasticity of the surveyed rock formations. These data can be used to infer the composition, temperature, stress state, basement geometry, and other subsurface properties that characterize a superhot rock resource. These geophysical data can be collected on the global, continental, or local scale, increasing resolution as the spatial coverage decreases. The methods involved are mature and widely used by academics and industry, and the required instruments, processes, and modelling software are readily available. The applicability of these methods to conventional geothermal systems is well-documented, though some gaps remain when applying them to superhot rock resources.

Potential field methods such as gravimetry and magnetic surveys that lose resolution with depth can present challenges when accessing deep superhot rock resources in near-homogeneous basement rock, where faults or other seismic hazards may occur. Researchers must perform forward modelling experiments to identify the limitations of these methods. Magnetotellurics is the leading electromagnetic method for geothermal exploration due to its sensitivity to fluids and minerals, which are indicators of temperatures at depth. Challenges remain in detecting small resistive features and imaging beneath conductors, and distinguishing ambiguous temperature indicators, such as the high resistivity signatures of both cold crystalline rock and superhot fluids. Laboratory experiments at superhot rock conditions may help to differentiate these temperature signatures.

Seismology reveals the elastic properties of rocks, including rock hardness, fluid content, fracture density, stress orientation, and tectonic structures. Seismic reflection methods can be challenged by complex hard-rock environments at depth due to acoustic signal interference. Adapting processing schemes may improve deep hard-rock structure resolution. Surface wave and ambient noise tomography is sensitive to fractures—although not fluids—and is best coupled with a seismic velocity model. Advances in attenuation and anisotropy tomography show promise for high-resolution imaging of fault or fracture zones, but this technology faces complications with wave scattering in complex geology.

Geochemical data on superhot rock conditions are limited. Data scarcity is further challenged by a lack of laboratory facilities with superhot rock capacity or downhole tools that can withstand these environments. Supercritical fluid geochemistry resulting from reservoir stimulations of well-completion technologies requires further study, which in turn requires in situ experimentation at existing superhot rock sites. Researchers must quantify the relationship between electrical resistivity (measured with electromagnetics) and temperature and seismic velocity ratios (measured with seismic tomography) to fracture density in controlled laboratory conditions. Further research must address the mechanics of ductile deformation into superhot rock reservoir stimulation modelling and seismic risk assessment.

Data integration methods

The integration and interpretation of data is a rapidly evolving field with the advancement of computational power and artificial intelligence. Regions with sparse or no datasets can be modelled with machine learning or value-of-information methods. Advanced joint-inversion techniques yield higher confidence in models relative to single property inversions. Comprehensive assessments of a geothermal play can be guided by *play fairway analysis*, a subsurface resource categorization method established by the oil and gas industry that has been adapted for conventional geothermal resources. Limitations for adapting these methods for superhot rock purposes include the lack of superhot rock data, low data granularity, and a lack of open-source software.

Exploration scale

At the exploration scale, from tens to hundreds of square kilometres, existing methods to estimate temperature, stress, structures, and permeability at depth can be applied for superhot rock resources, although some technology gaps remain. Heat mapping at the exploration scale is best achieved by integrating a range of geophysical datasets with modern joint inversion or machine learning. Thermal models will become more accurate with higher data density and the capacity to model convective heat flow. The 3D in situ stress state at depth can be captured by detailed stress maps, but they require better data resolution. Further research is needed into improved data resolution and mapping pore fluid pressures at depth. Structures and permeability at depth indicate fluid transfer mechanisms and the ambient stress fields. Seismic methods such as fracture imaging and focal mechanism analysis show promise for mapping these structures, but these methods are currently unable to characterize hard-rock and heterogeneous superhot rock geothermal fields.

Reservoir and validation scale

At the reservoir scale of less than ten kilometres, project proponents can better estimate temperature at depth through direct measurements from exploratory boreholes and integrating detailed 3D geological models with thermal conductivity data or a proxy. A higher density of thermal data improves thermal model accuracy, elevating the need for high-resolution well-log sampling and other geophysical data at superhot rock sites. Stress measurements and pore fluid pressure estimation are essential for designing reservoir boreholes to prevent drilling complications and successfully stimulate the reservoir. Anisotropy in geophysical data, as well as techniques from the oil and gas sector, can indicate stress and pore fluid pressure at depth. Crosswell seismic/electromagnetic tomography and logging show promise for the high-resolution mapping of structures and permeability in the vicinity of the boreholes.

Monitoring

Monitoring induced seismicity provides detailed information about the reservoir state and mitigates reservoir development and extraction risks. Adaptive Traffic Light Systems need to be developed for superhot rock fields to limit the intensity of seismicity, particularly in ductile regimes, as the deformation mechanisms of ductile rock are poorly understood. Real-time microseismic monitoring arrays, temporal gravity and geodesy can also map (sub)surface deformation due to changes in reservoir mass balance and fluid injection. There are a few cases where electromagnetic methods have detected reservoir changes due to stimulation, but these studies require further validation. Long-term lifecycle analysis (for example, numerical reservoir simulation, tracer, and transient tests) is necessary to track heat depletion, mass balance, and fluid-rock interaction geochemistry, which requires more field demonstration sites and long-term production data, supported by numerical modelling experiments.

Conclusions

Many of the geophysical methods needed to identify viable sites for superhot rock energy are developed and ready for application, but these methods have yet to be tested and validated in superhot environments. Data-driven analysis methods, including machine learning, show potential but are constrained by a lack of data. More field-validated datasets and laboratory experiments would help establish connections between geophysical observables and the key rock properties and conditions.

Project proponents and researchers should take the following actions to advance key technologies:

1. **Expand and integrate superhot rock data to improve models.** Integrate datasets to identify favourable conditions for superhot reservoirs within sustained elevated heat flow areas. Develop new models based on both data and expert-driven analyses.
2. **Standardize and share data.** Establish a sharing approach to superhot rock site characterization to de-risk exploration (for example, Play Fairway Analysis) and improve the communication of lessons learned between projects. Conduct retroactive studies with archival datasets to identify optimal geophysical techniques.
3. **Increase investment and policy support.** Subsidies, tax incentives, research funding, and private investment are needed to support the development of next-generation technologies and promote public understanding and acceptance of superhot rock geothermal energy.

Read the full series of reports.

Citation

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