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DErisking Exploration for geothermal Plays in magmatic Environments – Results and Perspectives from the DEEPEN Project

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ABSTRACT

High resource risk and upstream exploration costs are key barriers to scaling up of geothermal energy development globally. Reducing the upstream risk has, for a long time, been a priority area of the sector on several fronts. The DEEPEN project was intended to contribute to this goal through increasing the probability of success when drilling for geothermal fluids in magmatic systems.

Advancement on several fronts is required for improved de-risking and in this project we address them in a targeted manner.

First, there is limited understanding of the details of the interaction between the heat source, i.e., magmatic intrusions, and the geothermal system and what happens in the region between them. In this project, we develop THMC Native-State models and use them to evaluate supercritical reservoir performance.

Second, many of the tools and techniques that we use for imaging geothermal systems and estimating their potential have been used for decades, with limited development. Part of this project focuses on tool development, particularly for near magmatic or super-hot resources. We develop novel geothermometers to detect whether fluids from the geothermal reservoir have at some point reached very high (>380°C) temperatures. We also explore how to best use magnetotelluric methods to image deep heat sources.

Seismology, in particular seismic reflection methods, are a staple of oil and gas exploration. Unfortunately, the method is much less effective in geothermal environments. However, several seismological methods have been used in volcanology to study volcanoes and magmatic reservoirs, with some success at regional scales. For de-risking geothermal exploration, however, reservoir scale is required. As part of the DEEPEN project, we collected new seismic data to explore the feasibility of using a dense nodal network (500 nodes) together with 2 DAS units connected to

fibre optic cables to image the high-temperature geothermal systems of Hengill, SW Iceland. We also collected extensive seismic and magnetotelluric data at Newberry volcano, Oregon, USA.

Finally, we explore methods to jointly interpret geological, geochemical and geophysical datasets for resource estimation. This includes the development of a Play Fairway Analysis (PFA) methodology for geothermal systems in magmatic environments, with multiple plays such as conventional hydrothermal, supercritical or super-hot geothermal, and superhot Enhanced Geothermal Systems (EGS). We furthermore explore the use of multi-geophysical inversion for joint interpretation. The expected outcomes include:

- a suggested site for the next super-hot well in the Iceland Deep Drilling Program series; IDDP-3, which is to be sited in one of the geothermal fields operated by OR – Reykjavík Energy in Hengill, SW Iceland
- PFA method for multiple plays in magmatic environments
- identification of geoscientific datasets for further research of geothermal exploration
- generalized methodology for assessing supercritical resources in magmatic plays

1. Introduction

The DEEPEN project focuses on advancing the exploration for different geothermal play types in magmatic reservoirs: (1) conventional hydrothermal plays; (2) super-hot plays that may be found near or underneath conventional hydrothermal systems; and (3) EGS plays that may require enhanced fracturing and/or addition of fluids (see Figure 1 for a schematic overview).

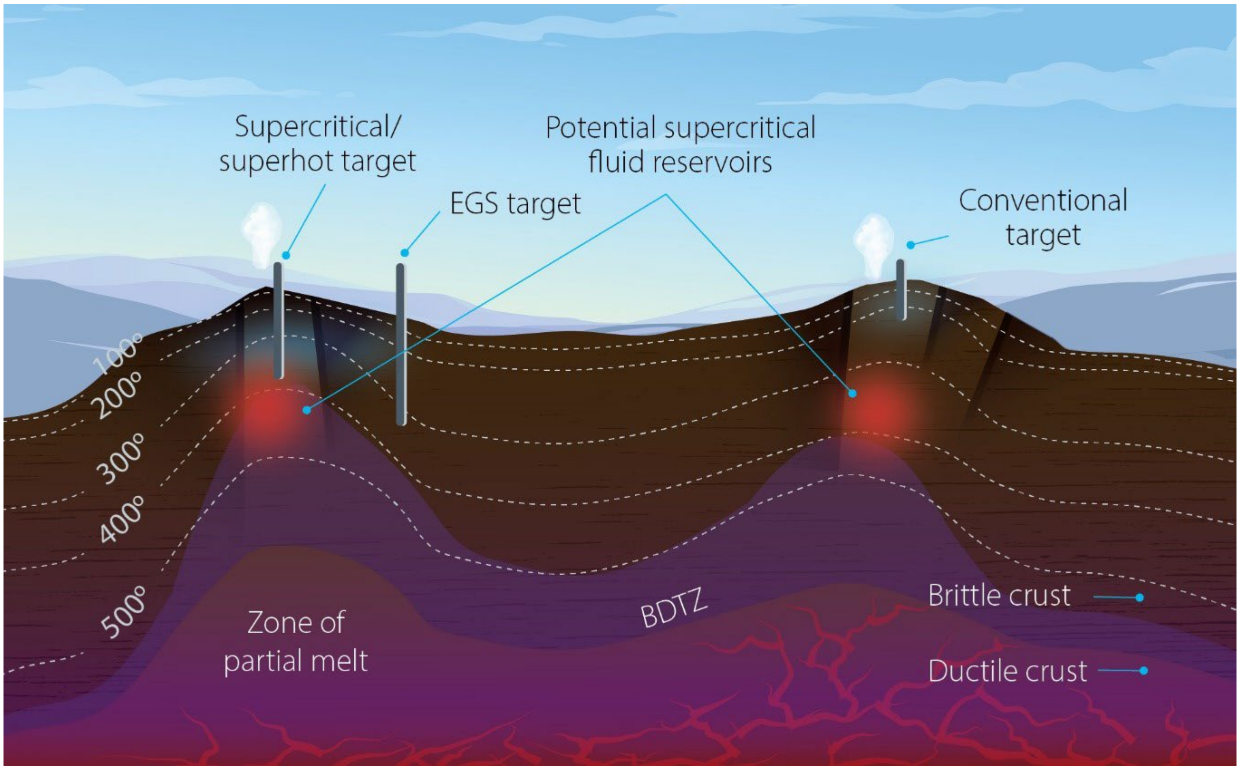

Figure 1. Schematic view of several plays (i.e., subsurface resources) in the same region.

Locating reservoirs and placing wells represent some of the highest risk elements of geothermal operations. The most sophisticated techniques for imaging reservoirs have predominantly been tailored to meet the requirements of oil and gas exploration. However, oil and gas resources are primarily found in sedimentary environments, whereas many of the world's geothermal fields are situated within magmatic systems, which are geologically very different. For this reason, a different "tailoring" of methods is needed to locate and image magmatic geothermal reservoirs. We divide the procedure that aims at estimating the *favorability* for encountering geothermal resources into five main phases, and attempt to make progress on each of the phases, to create a more efficient and lower risk process. These phases are:

1. Develop conceptual models for geothermal systems in magmatic settings
2. Obtain relevant measurements
3. Interpret measurements in terms of variables
4. Interpret variables in terms of reservoir properties
5. Interpret reservoir properties in terms of favorability

For the conceptual models we focus on understanding the geologic elements for the "root zone" of magmatic hydrothermal systems based on results from numerical models, experimental results, and geologic models of active and fossil superhot systems (e.g., ore deposits formed in supercritical conditions). Geothermal conceptual models generally depict magmatic sources of heat, the resulting thermal regime (with isotherms), directions and sources of circulating fluids, zones of fluid-rock interaction with differing types of hydrothermal alteration, and characteristic surface thermal features. These systems evolve over time, influenced by processes such as water-rock interactions neutralizing acidic volcanic fluids, interactions between the intrusive magmatic body and the overlying hydrothermal system involving fluxes of fluid and heat from the underlying magmatic system, and episodic periods of self-sealing related to retrograde solubility of silica at elevated temperatures (Saishu et al., 2014). Conceptual models can be used to investigate dominant heat transfer mechanisms, the role of structure and lithology in permeability, and to hypothesis-test key unknowns (e.g., location of magmatic intrusion(s)) against existing data and models.

One of the main objectives of the DEEPEN project is to use novel seismological measurements to better image geothermal reservoirs in magmatic systems, with special focus on superhot sections. Seismic reflection methods used in oil and gas are not well suited to magmatic regions, as they depend on regular layering of geological units with contrasting seismic velocities, that are present in sedimentary environment, but typically absent in magmatic regions. Furthermore, traditional tomographic methods lack the high resolution needed for targeting within a reservoir. However, recent advances in seismology, brought on by method development as well as increasing computing power, may open up new possibilities. We focus on three newly established methodologies; the use of high number of nodal seismometers, noise tomography, distributed acoustic sensing through fibre optic cable together with more traditional micro-seismicity analysis.

In addition to improving the seismological tools, we focus on geochemical and resistivity methods.

Another main focus of the DEEPEN project to jointly interpret many variables or observations, in terms of favorability for geothermal resources. We use two parallel or complementary methods; Joint Geophysical Inversion and Play Fairway Analysis.

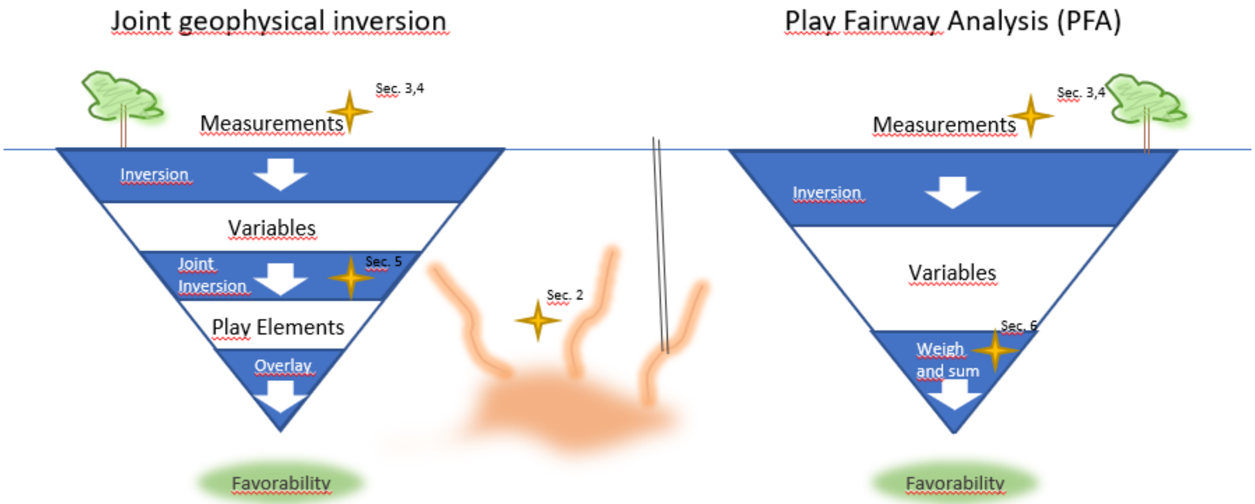

Figure 2. A schematic view of the process of estimating the favorability for encountering a geothermal resource, through either Joint geophysical Inversion or Play Fairway Analysis.

2. **Obtaining a better understanding of superhot geothermal systems**

Exploration for superhot geothermal resources requires understanding of signals from transient and complex systems in dynamic volcano-magmatic environments (Kolker et al., 2022). A team of geophysicists, data scientists, and geoscientists from the National Renewable Energy Laboratory (NREL) and the Lawrence Berkeley National Laboratory (LBNL) evaluated conceptual models of active and fossil superhot geothermal systems, including hydrothermal ore deposits. Based on the conceptual model and literature review, the team determined the following:

First, the longevity of the geothermal resource is dependent on repeated magmatic intrusions, which provide additional heat and fluids to the system. Once magmatic inputs cease, the related hydrothermal system will wane as the system cools, resulting in an inactive, fossil system over time. Examples of such systems, described by Mercer and Reed, 2013, have also been used to characterize the spatial and temporal evolution of supercritical geothermal systems (e.g., Tsuchiya et al., 2016). Episodic breaching of a self-sealing zone driven by upward moving magma or increasing fluid pressure locally increases strain rate and induces shear failure to increase fracture permeability. Increased temperature and pressure associated with pulses of ascending magma and/or buildup of magmatic volatiles drive further fracturing, brecciation, and increased hydrothermal fluid flow. Given the transitory nature of the conditions, there are typically repeated cycles of breaching, mineral deposition and plastic healing, and re-breaching until magmatism wanes, the 400°C isotherm descends, and magma-driven mineralization is overprinted by meteoric-dominated, hydrostatic hydrothermal mineralization and alteration (Kolker et al., 2022).

Second, key geologic components of hydrothermal systems (heat, fluid, permeability) are not directly transferable to supercritical and superhot targets. The conceptual model analysis and literature review suggested a different set of key geologic components for these new types of targets. For supercritical targets, four key geologic components may be required: (H) Heat; (SF) Supercritical fluid; (S) Seal; and (P) Producibility. For superhot EGS targets, only two to three key geologic components may be required: (H) Heat; (I) Insulation; and (P) Producibility. These key components were used as the basis for a Play Fairway Analysis (PFA) methodology development for multiple plays in magmatic settings.

Lastly, a thermo-hydraulic-mechanical-chemical (THMC) model for the Newberry Volcano magma-hydrothermal system was developed by Lawrence Berkeley National Laboratory (LBNL). This model extended a native state model of the volcano to 3D and coupled it with local geochemical and geomechanical parameters. Geochemical parameters for Newberry included: basaltic-granodioritic mineral assemblage, +calcite & pyrite, measured groundwater recharge chemistry. Geomechanical parameters for Newberry included initial anisotropic stress ratios, shear failure, Linear thermal expansion coefficient, Young's Modulus from an updated TReactMesh model. The THMC model found the following: (1) permeabilities near the contact of magma body decrease drastically as rock temperatures increase to near 1000ºC due to thermal expansion-induced porosity loss leading to permeability decrease, and mineral dissolution/precipitation effects. (2) Shear failures initiate at tip of magma body and migrate upward over 2km at about 60 degrees by 200 years. (3) The volume of shear failures is dynamic, with dilation and contraction occurring with effective stress changes. (3) Fracture permeability is controlled by the Cubic Law (effective continuum with fracture and matrix porosities/permeabilities for geomechanics). (4) Permeabilities increase in fracture zones as they decrease outside due to rock thermal expansion. (5) Temperatures are mostly conductive after 200 years because of overall permeability decrease. (6) Fluid fluxes and pore velocities show flow focusing in fracture zone and above temperature-induced porosity-reduction zone. (7) Deviatoric stresses are compressive and reflect the large-scale perturbation of the crust, with the large deformation zone ahead of the fracture zone "tip" (8) MEQs (shear failures) show some migration over top of magma body, and failure volumes (shear dilation) are highest near fracture zone center with weaker changes at the margins (9) Porosities and permeabilities decrease as a function of temperature through changes in effective stress owing to thermal expansion and fracture closure, without a specific "stress-permeability law." (10) Broad zones of chlorite alteration occur around the magma body, and concentrate at the fluid upflow zone at the magma body corner; whereas a narrow region of epidote alteration occurs around the magma body, and is concentrated in fluid upflow zone. (11) Strong calcite dissolution occurs around the magma body with weak far-field precipitation. (12) Permeability contours reflect greater shear dilation in the fracture zone core (Sonnenthal, 2022).

Taken together, the THMC modeling results combined with the conceptual model analysis and literature review suggest that a "goldilocks" environment will likely be required for the conditions to be just right for power production from naturally occurring supercritical fluids. The longevity of superhot resources is dependent on repeated magmatic intrusions providing additional heat and fluids to the system.

3. Extending existing exploration tools to deeper and hotter resources

The University of Iceland (UoI) has worked towards of assessing supercritical hydrothermal fluid composition and development of new type of geochemical geothermometry to identify deep supercritical fluids. The work involves setting up a framework of thermodynamic modeling of fluid-rock interaction and fluid composition at supercritical water and superheated vapor at temperatures of 400-600°C and pressures below 300 bar. The modeling involves development of Equation of State (EoS) based on molecular gas species hydration originally proposed by Pitzer and Papalan (1986) and parametrization the EoS based on available data in the literature. The development of new geothermometry is based on temperature dependent volatility of non-reactive elements like boron and chlorine. The geochemical work has been targeted against Nesjavellir (Iceland) among other geothermal fields.

At IFPeN, we proposed a **continuous approach** based on i) a Cubic Plus Association equation of state to model phase equilibria between a gas and an associative compound such as water (Kontogeorgis et al. 1996); ii) a reactive flash tool treating NaCl salt dissociation reaction and iii) an electrostatic term integrated into the equation of state and considering solvated Na^+/Cl^- ions (Courtial et al. 2014). Such model (eCPA) is capable to correctly describe the dissociation of the NaCl salt over a wide range of conditions (Fig. 1, left) and it can be effectively applied to systems containing H_2O, NaCl, CO_2 and CH_4 in a wide range of conditions ($T = 273K - 823K$, $P \leq 200$ MPa, salinity up to saturation). It perfectly reproduces a strong dependence of solution density, vapor pressures, liquid and vapor phase compositions with molality (Fig. 1, middle and right, respectively). So called "salting-out" effect when the addition of salts in an aqueous solution reduces the gas solubility is correctly described. The model can include other compounds after additional regressions of the relevant parameters. Such a tool will give real benefits for situations in magmatic environments by enabling High Pressure / High Temperature and surface situations to be handled with the same tool.

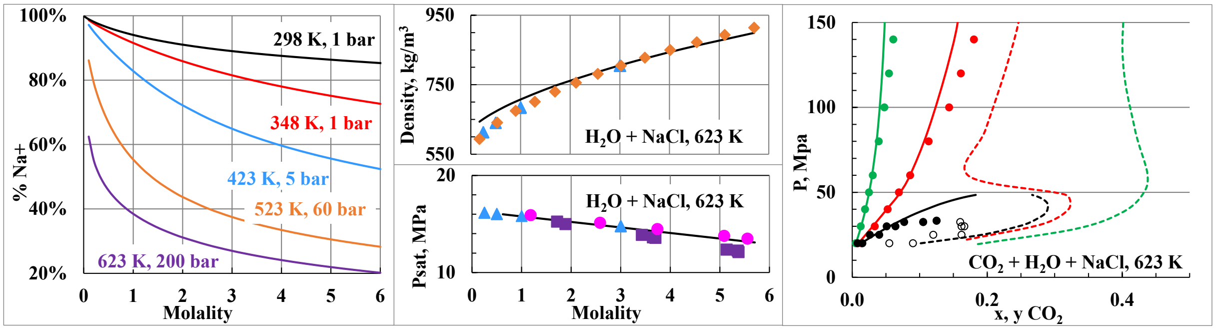

Figure 31. Left: Predicted Na^+ ions distribution in aqueous solutions as a function of molality, T and P. Middle: Experimental data for density and saturation pressures [in symbols: orange, Potter et al. 1977; blue, Crovetto et al. 1993; magenta, Mashovets et al. 1973; violet, Urusova et al. 1971] vs. the model (in lines). Right: VLE experimental data [in symbols for NaCl molality = 0.0M, black, Todheide et al. 1963; Takenouchi et al. 1964; 1.09M red and 4.28M green, Takenouchi et al. 1965) vs. the model [continuous lines for the liquid and dash ones for the gas].

ÍSOR is working on network design of resistivity measurements (MT & TEM) for targets at the deeper end of the depth range, i.e., 2-5 km, by extensive numerical modelling of existing data. Furthermore, ÍSOR is exploring, with synthetic numerical modelling, where additional soundings should be placed to get a better image within this depth range. These results can eventually be used to suggest locations of additional MT/TEM soundings in previously imaged areas, to better detect structures in the 2-5 km depth range.

Wells in high-temperature geothermal areas in Iceland are frequently drilled down to 2-3 km depth, and lithological logs are measured in most of them. These include resistivity, gamma and neutron (NN) logs, and in rare instances there are sonic logs available. Both NN and sonic measurements have been correlated with porosity, and it has also been suggested that NN logs could be correlated to sonic velocity. ÍSOR is now working to extend this approach, by comparing NN and sonic logs from existing geothermal wells in Iceland, e.g., the Hengill area, to construct velocity models of the uppermost crust where data exists. Expected results are a calibration between sonic log velocity and NN logs that can be applied in magmatic geothermal areas to infer seismic velocity through NN logs. Results will be presented in upcoming publications.

4. Recently developed exploration methods applied to super-hot reservoirs

Hengill Volcano, Iceland

From June to August 2021, ETHZ, GFZ and OR deployed a dense seismic nodal network across the Hengill geothermal area in southwest Iceland to image and characterize faults and high-temperature zones at high resolution (Fig. 4, Obermann et al. 2022a). The nodal network comprised 498 geophone nodes spread across the northern Nesjavellir and southern Hverahlíð geothermal fields and was complemented by an existing permanent and temporary backbone seismic network of a total of 44 short-period and broadband stations. In addition, we recorded distributed acoustic sensing data along two fiber optic telecommunication cables near the Nesjavellir geothermal power plant with commercial interrogators. A vibrating source was employed along two road segments for imaging in collaboration with the SUCCEED project (Durucan et al, 2021).

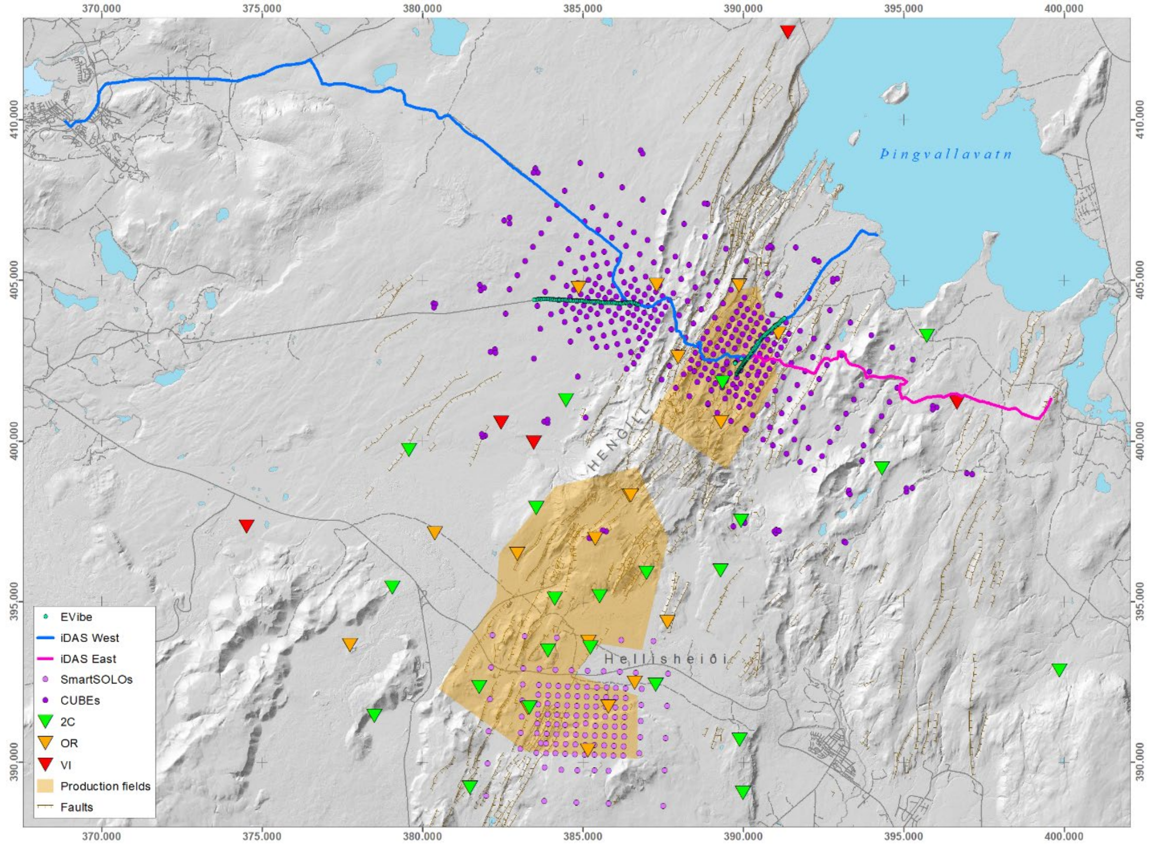

Fig 4. Overview map of the seismic network installations across the Hengill geothermal field during the DEEPEN project

Seismic imaging of the Hengill area was performed using various methods; Body-wave tomography using earthquakes (Obermann et al, 2022b), ambient noise surface wave tomography (Sanchez-Pastor et al. 2021) and high-resolution seismic isotropic and anisotropic imaging using the nodal array data (Wu et al., in prep). The seismic velocity models are in good agreement, allowing us to image the seismic structure of the Hengill geothermal area with an excellent resolution in the uppermost 4-6 km of the crust. In particular, with the dense arrays, localized low-velocity anomalies could be resolved and linked to powerful wells in the area.

Detailed seismicity analysis around Nesjavellir shows that seismic events mostly occur in spatial clusters that delineate vertically dipping planar structures. Some clusters develop in bursts of only a few days, corresponding to the creation or reactivation of fault segments, sometimes in areas where no previous seismic activity has been recorded and no faults have been mapped. Moreover, events within each cluster exhibit similar focal mechanisms. Through the denser coverage they provide, both nodal and DAS data contribute to better constraint the mechanisms. Most of them are strike-slip with their orientation consistent with the maximum stress field. Finally, the dense spatial sampling provided by DAS data allows to observe fine perturbations of the wavefield that may be related to the presence of faults while the delays observed in phase arrivals fit velocity anomalies identified in the tomographic models.

Newberry Volcano, USA

As part of the Newberry application, a team from NREL and Oregon State University collected additional gravity and MT data to fill in station coverage along the south rim and south flank of Newberry volcano, where the magmatic plumbing system has been modeled to reach shallower depths. Single and joint inversions of new gravity and MT data were undertaken to yield final 3D density and resistivity structure models. Existing datasets were acquired from the Geothermal Data Repository (GDR). New data collection during the summer of 2022 was designed to improve the spatial resolving power of the subsurface electrical resistivity and density structure as determined by inversion of MT and gravity data, with particular focus on the poorly covered south part of the volcano. This enables better understanding and distinction between deep magmatic sources, permeable pathways, and conditions at depths (3,000–5,000 m) that span the brittle-ductile transition and where supercritical conditions are believed to exist.

Previous work at Oregon State University (Bowles-Martinez and Schultz, 2020) indicated that there was a likely an electrically conductive target that shallowed near South rim and extended to depths that were previously associated with partial melt beneath the caldera. By expanding the station coverage in this area, the conductive feature and its relationship to geothermal targets could be better assessed. 233 gravity stations were acquired, and 43 wideband MT stations were installed and operated. For inverse modeling of the resistivity and density structure of the volcano, these data were combined with legacy wideband MT data and gravity data from previous work. Following the individual inversion of the gravity and MT data, joint inversion of these data was carried out to yield final 3D density and resistivity structure models using a set of inverse modeling codes developed for this project.

The 3D MT inversion employed an integral equation forward solver that allowed for topography at the surface. The 3D gravity inversion, also allowing for topography, solves for the variation in density around an average value. The joint inversion approach identified structural features that are common between the density and electrical resistivity distributions in the models, using

Gramian structural coupling. While there is no requirement, from the perspective of equations of state, for the variations in density and the variations in electrical resistivity to be strictly coincident, experience has shown that coupling the two solutions together through gradient-based approaches helps to stabilize the solutions and to identify real structural boundaries that might otherwise be poorly resolved or missed when inverted for single with only a single type of dataset.

5. Joint inversion of geophysical data

Joint inversion of geophysical data comes in comes in many flavors. So-called simultaneous joint inversion focuses on structural imaging and obtaining geometrical similarity of shape between different geophysical models. This can be achieved by means of a cross-gradient term in the objective function (De Stefano et al., 2011). The cross gradient of two geophysical models, $\nabla m_i \times \nabla m_j$, where × denotes the Cartesian vector product, is zero if the two models have the same geometrical shape. Alternatively structural similarity of geophysical models can be obtained using Gramian constraints (Tu and Zhdanov, 2020), which can be shown to be equivalent to cross gradients. In the DEEPEN project, simultaneous joint inversion of MT and gravity data is demonstrated on the Newberry Volcano in Oregon, and then used as part of the input to PFA.

The joint inversions carried out at Newberry suggested a highly conductive low-density zone near the Big Obsidian Flow along the southern caldera rim area, deepening to the south and not connecting with the seismic feature beneath the caldera. This raised the question of whether the current volcanic center of the volcano has migrated south of the caldera and is now beneath the south rim or south flank, which requires further investigation.

Alternatively, multigeophysical inversion can be used to assess information about one or more properties of interest (Hokstad et al., 2017). Multigeophysical inversion is a statistical method using a Bayesian network (Figure 5) where various geophysical models from single domain inversion are coupled through common parameters that we want to estimate by inversion. This leads to conditional independence of the geophysical models if the noise in the different types of geophysical data is independent. In the geothermal application of multigeophysical inversion, the properties of interest are temperature and porosity. Permeability cannot be estimated directly from geophysical data and must be obtained by porosity-permeability relationships. In the DEEPEN project, multigeophysical inversion is demonstrated in the Hengill area, Iceland, with the goal of contributing to the siting of the IDDP-3 well (Hokstad, 2023).

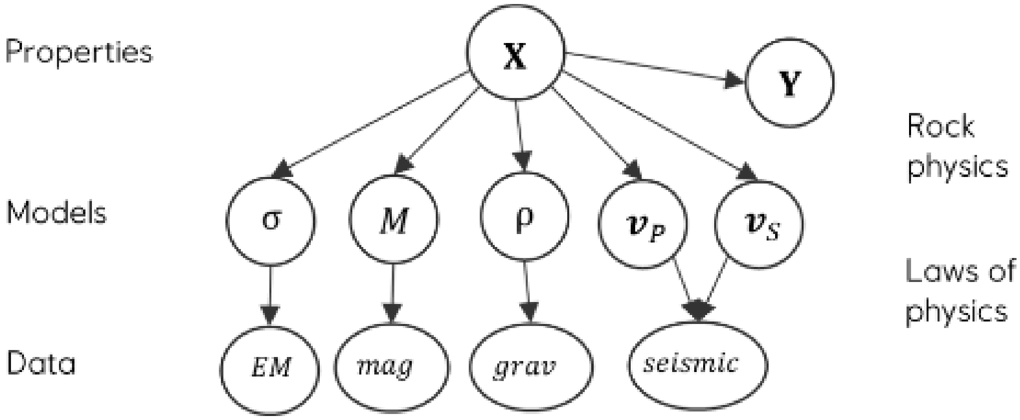

Figure 5: Bayesian network representing geophysical data, geophysical models, and properties of interest. σ is electric conductivity, M is magnetization, ρ is density, v_P is seismic P-wave velocity, and v_S is seismic S-wave velocity. X represents properties of interest, temperature and porosity in the geothermal case, and Y may represent geological and geochemical information.

6. PFA methodology for magmatic plays

To de-risk exploration for hidden geothermal systems in magmatic settings, a Play Fairway Analysis (PFA) approach was developed, wherein training data were compiled, weights assigned to various exploration datasets, and input into a 3D PFA workflow that combines multiple exploration datasets to generate 3D geothermal favorability models (Kolker et al., 2022).

6.1 Extension of PFA methodology to magmatic plays

The DEEPEN PFA approach is based on a 3D method proposed by Poux (2021), which uses the Leapfrog Energy software with the Edge extension to conduct PFA in a 3D environment. This method uses all available data to build a 3D geodata model which can be broken down into smaller blocks and analyzed with advanced geostatistical methods. Each data set is imported into a 3D model in Leapfrog and divided into smaller blocks. Conditional queries can then be used to assign each block an index value which conditionally ranks each block's favorability, from 0-5 with 5 being most favorable, for each model (e.g., lithologic, seismic, magnetic, structural). The values between 0-5 assigned to each block are referred to as index values. The final step of the process is to combine all the index models to create a favorability index. This involves multiplying each index model by a given weight and then summing the resulting values.

6.2 Application of PFA methodology to Newberry volcano

The application of the PFA methodology to Newberry Volcano will be documented in detail in a forthcoming publication by NREL. In brief, the PFA methodology successfully identified known areas of interest for conventional hydrothermal and superhot EGS resources at Newberry, and identified a few areas warranting additional exploration, while highlighting the importance of uncertainty modeling and demonstrating the impact that different sets of weights can have on the resulting maps and models.

7. Conclusions - Recommendations for exploring and assessing super-hot geothermal systems

Different magmatic supercritical and superhot geothermal play types were discussed by Kolker et al (2022). The key play elements of conventional PFA are heat source, permeability and presence of fluids. A magmatic heat source is always needed. However, depending on the presence of fluids and permeability, the play types are characterized as hydrothermal or EGS, respectively. In the DEEPEN project, both play types have been addressed and investigated, at Hengill, Iceland (hydrothermal) and Newberry, Oregon (EGS).

For hydrothermal magmatic systems, the depth of the intrusions is important. Reactive transport simulations presented by Scott et al., (2016) indicate that shallow intrusions ($z<2$km) leads to hypersaline brines, poor heat transfer, and low-enthalpy geothermal fluids. For intrusions at depths greater than 4 km, phase separation of hypersaline brine occurs, and the mass and heat fluxes from superheated steam are enhanced. Hence, we may expect that attractive supercritical/superhot hydrothermal resources will be associated with magmatic intrusions deeper than 4km. At temperatures above the brittle-ductile transition, porosity and permeability vanish rapidly, and heat transfer from a magmatic source to fluids relies on conduction.

Challenges related to supercritical plays include derisking of the heat source, permeability and presence of fluids. Supercritical geothermal systems are usually blind systems underneath a conventional geothermal system. The surface exposures will mainly reflect the properties of the conventional system above. Multiple plays in coinciding geographical locations (stacked plays) are common in petroleum exploration (e.g. Cretaceous stratigraphic trap above Jurassic structural trap above Permian carbonate play).

Mapping and imaging of blind geothermal systems rely on the use of geophysical data and methods. In the DEEPEN project we have investigated the use of seismic, electromagnetic and magnetic data, as well as the integration of geophysical data using joint inversion and multigeophysical inversion (Tu and Zhdanov, 2020; Hokstad, 2023).

Seismic v_p/v_S ratio and MT resistivity may be used to image an intrusive magmatic heat source. The v_p/v_S ratio increases with increasing melt fraction (Obermann et al., 2022). Seismic P-wave velocity is a good indicator of porosity which has a first order effect. Effective stress dominates the temperature effects.

The electric resistivity of basalt and granites decreases slowly with increasing temperatures below ~150 °C, and then decreases rapidly at temperatures above ~150°C (Mostafa et al., 2003). The resistivity of porous and fractured rock is also sensitive to the presence of saline fluids occupying the void space (Archie equation, Mavko et al., 2009).

Magnetization from magnetic inversion is sensitive to temperature and hydrothermal alteration and oxidation of magnetic minerals. The Curie depth associated with magnetite can be used as an isotherm in old continental crust. However, for young magmatic systems, it is more complex, since multiple Curie temperatures associated with exsolution and magnetization of titanomagnetites is encountered (Oliva-Urcia et al., 2011).

Other interesting geophysical methods that have not been investigated in the DEEPEN project are elastic full waveform inversion of seismic data and muon tomography, which can be used to assess density variations in the subsurface (Olah et al., 2022).

Detection of a deep magmatic heat source may be challenging but is still the "easier" problem. Very little is known about the properties of super critical fluids in general. Samples of such fluids are mostly obtained from fluid inclusions (Bali et al., 2020). Theoretical studies are limited because thermodynamic equations for the supercritical domain are not known.

Elements and isotopes from degassing of magmatic fluids are channeled through hydrothermal pathways and vents. Hence, geochemical signatures observed in boreholes and at the surface, and supported by numerical modeling, may be used to assess information about the nature and origin of the fluids (Renta et al., 2026). Isotope fractionation can possibly be linked to temperature of the geothermal reservoir. In natural waters from Iceland, Cl and B acts as incompatible elements. The concentrations of Cl and B may be used to assess information about the origin of geothermal waters (Stefansson and Barnes, 2016).

Finally, this project benefits in an important way from the possibility of collaboration between continents, through the GEOTHERMICA initiative. Similar collaborations, including additional regions, could accelerate the research of hot and superhot resources, resulting in faster uptake of new technologies.

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