Exploring for Superhot Geothermal Targets in Magmatic Settings: Developing a Methodology

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ABSTRACT

This paper presents preliminary results from a subset of work carried out as part of a multinational research project entitled DErisking Exploration for multiple geothermal Plays in magmatic ENvironments (DEEPEN). One objective of DEEPEN is to develop a customized approach to exploration for superhot geothermal plays in magmatic systems. This paper summarizes key geologic components, risk factors, and exploration methods for geothermal plays in magmatic settings based on a review and comparative analysis of international training sites. As part of a Play Fairway Analysis (PFA) approach to exploring for multiple play types in a single magmatic system, training data were compiled and weights assigned to various evidence layers. Two different approaches for weighting exploration datasets are described in this paper – one based on expert opinions and the other using statistical learning. Weights produced by both approaches will be input into a 3D PFA workflow that combines multiple exploration datasets to generate 3D geothermal favorability models, which will be applied to two international demonstration sites.

1. Introduction

Supercritical geothermal resources are defined as systems where the reservoir fluid is assumed to be in the supercritical state (temperature in excess of 374°C and pressure in excess of 221 bar for pure water). Producible geothermal energy could be increased significantly by exploiting the bottom of convective geothermal reservoirs where supercritical conditions prevail. However, no geothermal well has successfully exploited supercritical fluids. The energy potential of supercritical resources has been estimated at the gigawatt scale for at least one resource area (Okamoto et al., 2019), or 5 to 10 times more energy per well relative to a conventional geothermal system (Friðleifsson et al., 2014; Cladouhos et al., 2018; Feng et al., 2021). Similar increases in well productivity have been estimated for superhot enhanced (or engineered) geothermal system (EGS) wells relative to regular EGS (Bonneville et al., 2021). This makes the risk/reward picture for superhot resources more like petroleum than conventional geothermal. Given the much larger estimated resource base of EGS versus conventional hydrothermal systems (e.g., Williams et al., 2008), application of EGS technology in superhot conditions could additionally broaden and improve the geothermal resource base substantially.

The Iceland Deep Drilling Project (IDDP) is a long-term research and development project with the ultimate aim of successfully drilling well(s) capable of producing 400-600°C supercritical fluid. Two wells have been drilled thus far as part of IDDP and a third is planned for the 2025 timeframe. The first IDDP well (IDDP-1) was drilled at Krafla volcano and encountered magma. The high enthalpy fluids it produced were very corrosive and abrasive (Reinsch et al., 2017). The IDDP-2 well at Reykjanes drilled into an active supercritical hydrothermal environment analogous to black smoker systems. That well suffered from integrity problems and was not able to be sampled or accurately logged, but the highest measured temperature and pressure were 426°C and 340 bar (Friðleifsson et al., 2021). These experiences show that in order to successfully produce supercritical fluids, the methodology for defining well targets needs to be improved. The last of the three IDDP wells is planned be drilled in the Hengill geothermal field. The DEEPEN project aims to develop a methodology for targeting this and other superhot wells.

2. Magmatic geothermal systems and multiple play types

Magmatic geothermal systems, in the context of DEEPEN, refers to geothermal systems formed in volcanic and/or plutonic settings. Magmatic geothermal plays occur in rift settings, subduction settings, and in hotspot settings. The three general geothermal play types that may develop in magmatic environments include:

1. Conventional convective hydrothermal reservoirs,
2. Supercritical fluid and/or superheated steam reservoirs
3. Hot rocks suitable for development through EGS technology.

Nearly 75% of productive and prospective geothermal power plants worldwide are associated with subduction zone volcanoes (Moeck, 2014). Plutonic settings, such as Larderello and The Geysers, tend to have the highest temperature geothermal fluids and have therefore been studied extensively over the past century, though major questions about the subsurface (e.g., relative degree of conductive and convective heat transfer) remain (Büsing et al., 2018). The hottest geothermal fluids exploited for power typically have temperatures between 350°C and 365°C. Wells drilled to temperatures greater than 370°C have historically encountered little permeability, suggesting that the brittle-ductile transition commonly occurs at 370°C to 400°C within active hydrothermal systems in magmatic settings (Fournier, 1999). However, experimental data suggests that the temperature at which the transition to ductile behavior occurs is dependent on rock composition and stress conditions, and can vary significantly (e.g., Watanabe et al., 2017; Parisio et al., 2019).

Supercritical geothermal systems require conditions that, depending on rock and magma type, may correspond with the transition from brittle to ductile behavior of rocks. The brittle-ductile transition zone (BDTZ) occurs in relatively shallow crustal depths in some magmatic settings (Stimac et al., 2017). Ogawa (2014) hypothesized that large amounts of crustal fluid may be trapped in the supercritical state in places like Japan, where intrusive rocks of very high temperatures (> 400°C) are widely distributed at shallow depths (< 5 km).

EGS has been broadly defined as engineered reservoirs that have been created to extract heat from low permeability and/or porosity geothermal resources (Tester et al., 2006). Hot, low-permeability rocks are prevalent at depth, but the challenge of extracting thermal energy depends on the ability to create and sustain open fracture networks (e.g., Dobson et al., 2021). Superhot EGS targets (> 375°C) are more energy dense than conventional EGS targets.

3. Developing training sites for DEEPEN PFA

For shallow high-temperature systems, substantial experience exists on acquiring and interpreting surface datasets to reduce the risk related to encountering high-temperature fluids in the subsurface. Nonetheless, exploration of those fields remains a high-risk activity. Exploring and producing from deeper and even higher-temperature plays, where even higher-energy resources can be encountered, carries even higher risk – but potentially a much higher reward, as the power output from each well can be significantly higher.

To de-risk exploration for superhot resources, the DEEPEN team draws from the Play Fairway Analysis (PFA) method for exploration, developed to identify blind resources (meaning “hidden” at the surface by lack of surface manifestations). PFA methodology involves quantitative integration of geoscientific data which are used to produce evidence layers to identify prospective geothermal trends at various scales for further exploration. The method uses training sites to determine key components of a subsurface resource (e.g., favorable intersections of heat, permeability, and fluid) and identifies exploration approaches likely to lead to successful identification of a geothermal resource. Part of the method involves assembling exploration datasets from “training sites” to train the user on the relative significance of each evidence layer.

3.1 DEEPEN training site selection

More than 25 deep wells drilled in geothermal fields have encountered temperatures in excess of 374°C, such as The Geysers (USA), Kakkonda (Japan), Larderello (Italy), Krafla (Iceland), Los Humeros (Mexico), and Menengai (Kenya). In some cases, these wells have also encountered magma (Reinsch et al., 2017). We collected data from a subset of those systems as training sites, and from the DOE-funded geothermal PFA projects in magmatic settings in the United States. Data and models from the following categories of projects were compiled and reviewed: Geothermal PFA projects targeting hydrothermal resources located in magmatic settings in the US; Developed geothermal fields where wells have encountered temperatures in excess of 374°C; and superhot/supercritical geothermal exploration projects (Table 1).

Table 1. Training sites used in DEEPEN analysis

Training site	Tectonic setting	Magmatic system type
Aleutians/Cascades PFA	Subduction-related island arc	Arc stratovolcanoes
Hawaii (PFA & Kilauea)	Hotspot island arc	Shield volcanoes, fissure eruptions
OR/CA Cascades PFA	Subduction-related continental arc	Arc stratovolcanoes
Snake River Plain PFA	Hotspot trace and backarc extension	Continental hot spot (silicic volcanism + flood basalts)
Washington State PFA	Subduction-related continental arc	Arc stratovolcanoes
Newberry Volcano, OR	Continental arc and backarc extension	Shield volcano
Coso	Transtensional basin / Shear zone	Bimodal; rhyolitic magma ~5.5 km
The Geysers	Triple junction	Silicic volcanism and intrusions
Snake River Plain PFA	Hotspot trace and backarc extension	Basaltic volcanism
IDDP-1 (Krafla), Iceland	Mid-ocean rift	Basaltic volcanism
IDDP-2 (Reykjanes), Iceland	Mid-ocean rift	Basaltic volcanism
Los Humeros, Mexico	Subduction-related continental arc	Silicic caldera
Taupo VZ, New Zealand	Arc rift	Intermediate to silicic volcanism
Kakkonda, Japan	Subduction-related island arc	Intermediate to silicic volcanism
Larderello, Italy	Subduction-related continental arc	Silicic volcanism

3.2 Data used in DEEPEN training sites

We developed a list of common exploration data types used to produce evidence layers based on a comprehensive review of literature and data from the training sites listed above. Table 2 shows the full list of evidence layers in DEEPEN training sites. A catalog of identified exploration data for training sites can be found at https://gdr.openei.org/submissions/1332. All datasets were processed, formatted, and imported into Leapfrog Geothermal, a 3D subsurface modeling software.

3.3 Epithermal ore deposits as supplementary DEEPEN training sites

Hydrothermal ore deposits are well studied and provide abundant physical and chemical data to characterize fossil supercritical systems. Understanding the controls on and processes at these transitions is explored by Fournier (1999) with particular focus on pressure, temperature, and rock mechanics. The porphyry mineralizing environment, and potentially exploitable supercritical geothermal resource, is associated with emplacement of shallow intrusions (2-6 km depth) that heat a large volume of rock to temperatures > 400°C, inducing plastic behavior at normal strain rates ~$10^{-14}$$sec^{-1}$. Where least principal stress is lithostatic load, brine and gas exsolved from magma accumulate in plastic rocks at lithostatic pressure, separated by a self-sealing zone above which meteoric-water-dominant hydrothermal fluids circulate in brittle rocks at hydrostatic pressure. Episodic breaching of the self-sealing zone is likely driven by upward moving magma or increasing fluid pressure that 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. Associated magmas are typically water-rich and felsic ± intermediate composition (Tosdal and Richards, 2001). Recent work by Tosdal and Dilles (2020) reviews a long history of porphyry mineralization research and focuses on permeability. High fracture permeability is typical of crust above a brittle-ductile or brittle-plastic transition at temperatures below 350° to 400°C, whereas fracture permeability is commonly low at greater depth and higher temperature.

Table 2. Evidence layers in DEEPEN training sites

Evidence Layers				
Geological Features	**Geophysics and Remote Sensing**	**Chemistry and Geochemistry**	**Mapping and Modelling**	**Direct Observations**
Faults and fractures (density, age, intersections, aperture)	MT/AMT (resistivity)	Geothermometry (indicators of high temperatures)	Geologic maps and cross-sections (reservoir host rock, faults)	Well lithology and alteration data (cuttings/cores, fluid inclusions)
Dikes and intrusions (presence, density)	InSAR and GPS data (deformation)	Rock geochemistry (mineralization)	Geologic and conceptual models (reservoir host rock, faults, fractures)	Downhole temperature measurements (bottom hole temperature, temperature gradient)
Rifts (presence, proximity)	Gravity (density)	Gas geochemistry (H_2S, CO_2, helium)	Digital elevation models (fault traces)	In-situ rock properties (sigma1 direction, fracture propagation, permeability, porosity, stress, alteration, flow rate, specific heat)
Volcanic vents (presence, proximity, age)	Magnetics (total magnetic anomaly, susceptibility)	Alteration mineralogy (presence, type, grade)	Heat flow (extrapolated)	
Thermal springs and fumaroles (presence, temperature)	Seismic (Vp, Vs, b-value, attenuation)			
Tectonic/structural setting (magmatic setting, tectonic setting, stress setting)	Earthquake locations (cutoff depth, density)			
Groundwater data (presence, temperature, thermal masking)	Well logs (gamma, neutron, induction, density, sonic, etc.)			

4. Observations from training sites

4.1 Key components of conceptual models from DEEPEN training sites

Generic conceptual models for volcanic-hosted geothermal systems have been developed by many studies (e.g., Henley and Ellis, 1983; Cumming, 2009). These 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 as water-rock interactions tend to neutralize acidic volcanic fluids over time. The interactions between the intrusive magmatic body and the overlying hydrothermal system involve fluxes of fluid and heat from the underlying magmatic system, and may involve episodic periods of enhanced flow up through the brittle-ductile regime. The longevity of the geothermal resource is dependent on repeated magmatic intrusions, which provide additional heat and fluids to the system. Table 3 summarizes the key geologic components depicted in conceptual models for DEEPEN training sites.

Table 3. Geologic components used in conceptual models for DEEPEN training sites

Conceptual model	Key Geologic Components	Data types depicted
Hydrothermal systems hosted by stratovolcanoes (Bogie et al., 2005)	Volcanic edifice, magmatic heat source, isotherms, geochemistry of magmatic/geothermal fluids/gasses, meteoric recharge, mixing paths and phase changes of upwelling geothermal fluids, faults/structure	Geochemistry of surface and subsurface fluids, magmatic gas input
Epithermal systems hosted by stratovolcanoes (Fournier, 1999)	Volcanic edifice, zoned magmatic heat source, isotherms, arrows for upwelling geothermal fluids, phase separation, alteration patterns	Epithermal
Mt St Helens (Forson et al., 2017)	Heat source, predicted fluid flow paths	Vp/Vs and MT
Immature hydrothermal systems hosted by stratovolcanoes (Bogie et al., 2005)	Volcanic edifice, magmatic heat source, isotherms, geochemistry and mixing paths of upwelling geothermal fluids, meteoric recharge, faults/structure, phase separation	Geochemistry of different fluids and magmatic fluids
Newberry Volcano (Sonnenthal et al., 2012 ; Mark-Moser et al., 2016)	Volcanic edifice, several distinct magma bodies and partial melt zones, faults/structure	Geologic and geophysical data (resistivity)
Yellowstone (Fournier et al., 1994)	Surface expressions, geochemistry of magmatic/geothermal fluids and gasses and mixing processes therein, meteoric recharge, basal magmatic heat sill	Geochemistry
Mountain Home, ID (Nielson et al., 2017; 2019)	Depictions of continued intrusion of mafic magma into shallow magma chambers – these lead to the creation of sills and feeder dikes.	Geology
The Geysers (Schmitt et al., 2003; Norton & Hulen, 2001).	Detailed geometry of the plutonic complex with well constraints, isotherms	Well logs
Los Humeros (Arzate et al., 2018; Deb et al., 2021)	Magma bodies and partially molten rocks, regional groundwater flow directions, paths for upwardly migrating hot fluids. major faults, volcanic deposits, alteration patterns	Well data, resistivity profiles
Reykjanes (Nielsson et al., 2021; Weisenberger et al., 2021; Barton & O'Sullivan, 2021)	Regional stratigraphy, shallow structures, the volcanic heat source, isotherms, fluid pathway	Geology (stratigraphy) with well constraints

4.2 Geologic characteristics of geothermal plays in magmatic systems

4.1.1 General geologic elements of magmatic geothermal systems

Thermal energy in the earth is distributed between the constituent host rock and natural fluids contained in permeable formations (such fractures and pore spaces). Thermal energy is extracted from the reservoir by coupled transport processes (convective heat transfer in porous and/or fractured regions of rock and conduction through the rock itself). Typically, hot water or steam is produced, and its energy is converted into electricity or used directly as heat (Tester et al., 2006). Figure 1 presents a schematic view of the key components of magmatic geothermal systems, as well as the three geothermal targets or "plays" described above. Key components include: the heat source (magma, zone of partial melt, or conductively heated rocks), the BDTZ, reservoir targets, and temperature isotherms (measured from wells and extrapolated; or estimated from chemical geothermometry methods and extrapolated). Figure 1 shows a schematic of a magmatic system with multiple geothermal plays, including a conventional hydrothermal target, supercritical fluid reservoir target, and superhot EGS target. Note: this schematic does not include flow paths for hydrothermal fluids, which are key components for conventional hydrothermal plays.

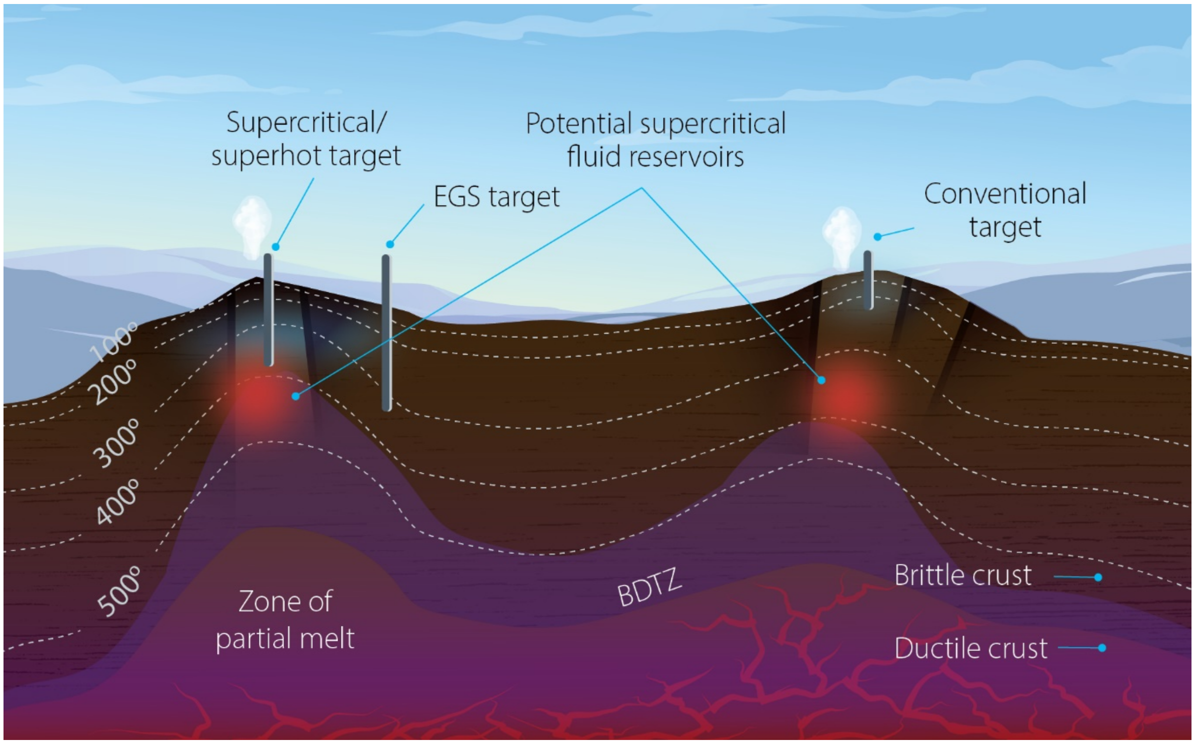

Figure 1: Schematic view of several plays (i.e., subsurface resources) in the same region.

The BDTZ is defined as the depth at which rock is just as likely to undergo ductile deformation as shear failure (Scholz, 2002). This transitional boundary between brittle and ductile crust is marked by a sharp decrease in seismic activity (Ágústsson and Flóvenz, 2005) as faulting and fracturing gives way to plastic deformation. The depth where the rock transitions from brittle to ductile depends on the local temperature gradient, rock composition, stress conditions, and other factors such as magmatic activity (Ágústsson and Flóvenz, 2005). In general, continental crust transitions from brittle to ductile at 250-450°C while the BDTZ in oceanic crust occurs at 600-800°C (Chen and Molnar, 1983). Except in locations close to shallow magma bodies and intrusions in the upper crust (< 5 km), the BDTZ is often at depths > 8 km. While supercritical resources may be located at depths near or below BDTZ in the crust (Reinsch et al., 2017;

Stimac et al., 2017), it is not well understood how fluids and permeability behave near the BDTZ.

4.3 Common exploration methods for magmatic systems

Of the many datasets used in geothermal exploration, most are indirect measurements of subsurface properties and thus are applied with a high degree of uncertainty. There are two major risk factors in exploring for superhot geothermal resources: imaging magma and characterizing permeability. Fundamental assumptions about imaging magma may warrant re-examination based on recent observations from drilling into magma in geothermal settings. Eichelberger et al. (2021) noted the following in such wells: (1) There is an unexpectedly short transition from solid rock to molten rock. A "mush zone" of partially crystallized magma – seen in lava lakes and expected thermodynamically – is missing. (2) Magma was controlled through normal geothermal engineering practice (silicic magma is viscous and flow is slow enough in a small, cold borehole that it is easily quenched forming a rock plug). (3) None of the intersected magmas had erupted in the last several thousand years. One interesting exception to this was a basaltic eruption that vented through a 1.1 km deep geothermal well to the surface at Krafla in 1977 (Larsen et al., 1979); the borehole remained open after the short-lived eruption occurred.

4.3.1 Exploration methods for imaging magma

For conventional hydrothermal plays, understanding the heat source is related to the imaging of magma bodies. For our training sites, this was accomplished via a combination of geologic mapping, seismic velocity, p-wave tomography, microearthquake analysis, electromagnetic (EM) – usually magnetotelluric (MT) – surveys, gravity surveys, and magnetic surveys. These methods are also appropriate in superhot plays. Because the velocity and attenuation of elastic waves depends on the mechanical properties of the medium, seismic methods can detect the presence of magma (Gailler et al., 2019). 3D seismic p-wave traveltime tomography has been used to image the magma sources beneath Mauna Loa and Kilauea volcanoes, Hawaii. Fault-controlled magma injection and associated deformation in the upper crust within the volcanic edifice and rift zones generate low-velocity signals beneath present-day shield volcanoes in Hawaii; whereas crystallized intrusive bodies (e.g., gabbro-ultramafic cumulates from which Hawaiian surface volcanism is derived) generate high-velocity signals that correlate with zones of high magnetic intensities (Okubo et al., 1997). The presence of melts has been inferred from seismic data in various environments from oceanic ridges to subduction zones, but wavelengths are sometimes too large (several tens of kilometers) to detect small magmatic bodies (a few tens of meters) especially at shallow depths (Gailler et al., 2019).

Magnetic and EM methods also have potential for detecting and imaging magma bodies at depth. Above the Curie temperature (580°C), magnetite is paramagnetic, so magnetic signals disappear in high temperature zones. This phenomenon has been used to map the Curie isotherm, which can proxy for heat sources (e.g., magma bodies if the composition of magma is well constrained). Electrical measurements are well suited for imaging the interior of active volcanoes, because the resistivity of volcanic rocks spans several orders of magnitude and magmas have the lowest resistivity values in volcanic environment ranging from about 20 to < 1 Ω.m (Gailler et al., 2019). However, hydrothermally altered rocks often show resistivity values only slightly larger than that of melts (Revil et al., 2002), creating the non-uniqueness problem with EM data discussed previously. That magma was encountered unexpectedly in IDDP-1 poses a challenge to standard MT data collection and interpretation. Lee et al. (2020) re-examined the MT data that were used to model the electrical resistivity structure at Krafla prior to drilling IDDP-1, determining that the MT data can only detect sills that are unrealistically large with very low resistivities; thus, the MT data and/or inversions were not sensitive to small rhyolite magma bodies near the bottom of IDDP-1. MT surveys have been used to identify a possible zone of partial melt underlying a portion of the Northwest Geysers geothermal field at a depth of ~7 km (Peacock et al., 2020).

4.3.2 Exploration methods for characterizing permeability

For hydrothermal plays, permeability is related to tectonic, structural, and porosity characteristics in a given reservoir zone in the upper crust. Permeable structures serving as fluid pathways (such as open faults and fractures or porous sedimentary formations that can store and transmit fluids) are key to the development of hydrothermal systems. For our training sites, these structures were located by mapping faults and dikes in boreholes and at the surface, and projecting or interpolating structures in the subsurface via geophysical imaging methods (seismic, EM/MT, regional stress, gravity) and stress analysis. The significant downside to these geophysical data is that they are challenging to interpret and non-unique. EM/MT and seismic surveys are the methods most often used to detect relative resistivity of subsurface features. Areas of high electrical conductivity can be interpreted as ‘clay caps;’ that is, argillic deposits forming above a hydrothermal reservoir resulting from intense and sustained alteration of the host rocks (Anderson et al., 2000). For seismic data, areas with low shear velocities / high Vp/Vs ratios indicate fluid filled fractures. Joint inversions are sometimes performed to help to resolve the non-unique nature of MT and seismic data. For superhot plays, the ‘reservoir zone’ is extended from the upper crust down to the BDTZ. Ongoing work by the DEEPEN team is evaluating key unknowns about permeability in and near the BDTZ. Resistivity and microseismic data from the Kakkonda geothermal system were used to interpret the presence of a ductile conductive intrusion under supercritical conditions, with some suggestions of permeability at the top and along the margins of this high temperature (≥ 500°C) intrusive body (Yamaya et al., 2022; Okamoto et al., 2022).

5. DEEPEN PFA Methodology Development

5.1 Play types

Moeck (2014) presented a comprehensive catalog of geothermal play types, which included an EGS play type that is conduction-dominated and characterized by crystalline basement rocks with low permeability and porosity, but with elevated heat production from radioactive decay. The stress field was noted as being a critical factor in being able to successfully stimulate and maintain open fractures. Exploration methods for this play type include gravity and MT surveys to detect the granitic intrusion, reflection seismic to identify fracture zones, and geosystem analysis to estimate the stress field and hydromechanical conditions. Moeck (2014) also identified two primary magmatic play types that would correspond to the conventional target depicted in Figure 1: one associated with volcanic activity, and another associated with young intrusions. Both of these play types are convection-dominated.

5.1.1 Key components of conventional geothermal plays in magmatic systems

Broad applications of PFA methods to geothermal systems have established three key components of a conventional hydrothermal resource. Those are:

(H) heat
(F) fluid
(P) permeability

Some PFA projects also included a "seal," "trap" or "cap" (S) component, wherein an impermeable mineral or rock layer is required to contain a convecting hydrothermal system physically and thermodynamically (e.g., Coolbaugh et al., 2015; Nielson et al., 2015; Shervais et al., 2016).

5.1.2 Key components of supercritical plays in magmatic systems

While there appears to be expert consensus around the 3-4 key components of conventional hydrothermal systems (H, F, P and sometimes S), no such consensus exists on the key components of supercritical geothermal resources. Exploitable supercritical resources may only require (H), (F), and very specific (P) conditions.

In all magmatic geothermal settings (volcanic, plutonic, hybrid), the ultimate heat source is magma, expected to accumulate just below a producing reservoir. However, magma has a wide range of behaviors in earth's crust depending on tectonic setting, magmatic composition, host rock composition and structure, and other factors. Most of the thermal energy in the system is contained within the magma, because magma's energy is released not just by cooling but by latent heat of crystallization (Eichelberger et al., 2021). Based on studies of IDDP-1, Heřmanská et al. (2019) propose that conductive heating of surrounding subcritical geothermal fluids near a shallow intrusion is a dominant mechanism in supercritical fluid formation. Tsuchiya (2017) notes that supercritical systems associated with magmatism are likely to be found in one of four tectonic settings: subduction arcs, mid-ocean ridges, continental rift zones, and hot spots; and that the key factors are the presence of a magmatic heat source, supercritical fluids, and fracture permeability.

To date, no uncontaminated samples are available to adequately characterize naturally occurring supercritical fluids. The chemical signatures of supercritical fluid are likely to be overprinted during ascent by mixing with cooler fluids, fluid-rock interaction, depressurization boiling and phase segregation (Heřmanská et al., 2019). There are limited modeling or experimental studies of the behavior of supercritical fluids, and even fewer studies exploring the behavior of aqueous supercritical fluids in subsurface reservoirs with adequate representation of fluid-rock interactions (Weingärtner and Franck; 2005; Watanabe et al., 2017). High-enthalpy fluids obtained from the IDDP-1 well at Krafla, Iceland had a discharge temperature of ∼440°C and specific enthalpy of ∼3200 kJ kg−1. Highly acidic geothermal fluids (pH ∼2) such as those encountered in wells in the Krafla system are thought to have formed by liquid condensed out of ascending supercritical fluid and the dissociation of volatile components. Predictions from hydrologic and chemical models of supercritical fluid formation and ascent compared to measured fluid compositions from the Krafla geothermal system suggest that they form by near-isobaric heating of liquid geothermal groundwater. Low concentrations of non-volatile elements in the supercritical fluid result from intensive, quartz-dominated mineral deposition near the magmatic intrusion during boiling of liquid to dryness (Heřmanská et al, 2019). Fluids were not sampled in the IDDP-2 but are thought to be modified seawater diluted with drilling fluid (Friðleifsson et al., 2021). Supercritical fluids may also originate from magmatic degassing, characterized by elevated CO2, SO2, HCl, and HF concentrations (Fischer and Chiodini, 2015) or form upon fluid entrapment during magma crystallization. DEEPEN partners are actively working on modeling and experimental approaches to predict superhot fluid compositions.

It remains an open question if permeability can be maintained at high enthalpy conditions near the transition to ductile behavior in rocks (Reinsch et al., 2017). Wells drilled to temperatures greater than 370°C have historically encountered little permeability, indicating that the BDTZ commonly occurs at 370°C to 400°C within active hydrothermal systems in magmatic settings (Fournier, 1999). Fluid entries were documented for some of the wells drilled into supercritical conditions (e.g., Venelle-2 in Italy), but fluids were not sampled or produced. The silica solubility minimum near the critical point for water has long been thought to have negative impact on reservoir permeability (e.g., Saishu et al., 2014). Recent experimental and theoretical studies, however, provide some evidence for permeable conditions at or near the BDTZ in certain settings (Watanabe et al., 2017; Parisio et al., 2019; Watanabe et al., 2021). One key factor might be dilatancy; the BDTZ predicted depth based on dilatancy agrees with observed attenuated seismicity in active volcano settings (Parisio et al., 2019).

The above observations imply that supercritical geothermal plays do not have the same key components as conventional hydrothermal plays. We propose the following key components govern the formation and behavior of supercritical plays in magmatic systems:

(H) Heat or heat flow
(SF) Supercritical fluid
(S) Seal
(P) Producibility

In supercritical plays, the heat (H) component draws from conventional hydrothermal plays: conductive heating rocks and fluids near a shallow intrusion as a dominant heat transfer mechanism. However, supercritical fluid formation may be directly linked to convective and advective heat transfer processes associated with transient episodes of magmatic intrusion. In supercritical plays, the fluid (F) component is quite distinct from conventional hydrothermal plays. The chemical signatures of thus-far sampled once-supercritical fluids have likely been overprinted by mixing with cooler subcritical fluids, fluid-rock interaction, depressurization boiling and phase segregation. Therefore, supercritical fluids have not yet been properly characterized, and THMC models predict a wide range of fluid characteristics. Supercritical plays require a seal (S) sufficient to entrap and maintain a voluminous “reservoir” of fluids at supercritical pressures. Pressure “Seals” sufficient to generate supercritical fluid reservoirs could include lithostatic overburden, mineral deposition, or both. Lastly, supercritical plays require a producibility (P) component. The producibility of fluids at supercritical pressures and temperatures over time is related to specific permeability and pressure conditions in the reservoir. These conditions are linked to the tectonic setting, strain/stress state, rock type and rock mechanics of the reservoir rocks.

5.1.3 Key components of superhot EGS plays in magmatic systems

Beardsmore and Cooper (2009) developed a geothermal systems assessment approach for the exploration of EGS resources. This approach identified the key geologic factors associated with EGS resources: elevated heat flow, thermal insulation of the resource, reservoir potential for creating and sustaining fractures, and a working fluid to extract heat from the system. Hoffmann et al. (2016) developed a hybrid discrete/finite element model to simulate hydraulic fracture development for an EGS reservoir in granitic basement. Based on their simulations, the most favorable conditions for a productive EGS reservoir were: (1) brittle rocks with inherently low permeability with at least two natural intersecting fracture sets, favorably oriented relative to the stress field for shear and dilation; (2) complex tectonic settings (e.g., strike-slip and thrust regimes) with small differences between the magnitudes of maximum and minimum horizontal stress. EGS technology creates reservoirs, but structural conditions, rock mechanics, and fluid-rock interactions must be favorable to allow the engineered reservoir to maintain open fractures over time. Rock mechanics and fluid-rock interactions between injected fluid and reservoir rocks can be predicted using THMC modeling to understand producibility. However, most EGS laboratory experiments and simulations to date have been conducted at sub-critical temperature and pressure conditions (e.g., Dobson et al., 2021), so this component deserves more research attention for superhot EGS plays. Experimental work conducted at relevant temperature and pressure conditions suggest that hydraulic fracturing may be able to create permeability in rocks seemingly within the ductile regime (Ishibashi et al., 2017).

Based on the above research, we propose that the following key components govern the formation and behavior of superhot EGS plays in magmatic systems:

- (H) Heat or heat flow
- (I) Insulation
- (P) Producibility

In superhot EGS plays, the (H) component is conductive heating rocks and fluids near a shallow intrusion, with thermal resistance, or (I) provided by overburden. Lastly, superhot EGS plays require a (P) component sufficient to sustain and produce fluids at high temperatures over time.

5.2 PFA Methodology Development

Following the compilation of exploration data at training sites, weights were developed for each of the evidence layers. Two different approaches were taken – a qualitative approach based on expert opinions, and a more quantitative statistical learning-based approach. In this section, both approaches are introduced and then discussed in the context of the PFA methodology.

5.2.1 Expert Opinion-Based Approach to Weighting Exploration Data

Most of the geothermal PFA work to date has used weights based on expert opinions (e.g., DeAngelo et al., 2016). This is in part due to convenience and resource limitations, but there are advantages to expert opinion-based approaches. One advantage is that experts bring complex and nuanced understanding regarding the interactions of different types of exploration data and how those data relate to the presence and grade of a geothermal resource. Without a comprehensive dataset consisting of examples of all possible scenarios for magmatic geothermal systems, it is nearly impossible to understand the data's relationship to the presence of magmatic geothermal systems without expert opinions. Another advantage is that the logic behind expert opinion-based decisions is relatively transparent and can be documented clearly. Disadvantages to expert opinion-based approaches include (1) opportunity for bias; (2) reliance on others to provide well-thought-out opinions, which takes time and can be unreliable. In addition, gathering expert opinions does not provide new information to the industry as a whole.

We first generated expert opinion-based weights using a review of literature related to magmatic plays included in the following projects funded by the US. Department of Energy's Geothermal Technologies Office: Geothermal PFA projects, EGS demonstration projects, characterization projects for candidate sites for the Frontier Observatory for Research in Geothermal Energy (FORGE), and additional international projects characterizing superhot plays. Within the Geothermal PFA project-related literature, the expert opinion-based numerical weights generated by the projects were compiled. For all other sites, weights were generated based on the interpreted utility of each exploration dataset as described within the literature. It is important to note that an additional layer of bias is introduced by our interpretations of the utility of each exploration dataset from the literature. In addition, most of these PFA approaches used different combinations of evidence layers, so that their weighting schemes could not be compared directly.

After the literature review was completed, gaps existed in our weightings since not all types of exploration data were collected and discussed in published literature. To resolve these gaps, additional expert opinions are being collected using the Analytical Hierarchy Process (AHP). AHP is a well-established method for decision making and was used by the Washington PFA project for compiling differing expert opinions for ranking and weighting of evidence layers (Forson et al., 2017). An online tool allows AHP to be performed using decision matrices to quantitatively combine expert opinions (Goepel, 2018).

5.2.2 Statistical Approach to Weighting Exploration Data

Employing expert opinion-based judgements introduces bias that is amplified through interpretations of expert opinions. To circumvent this and other disadvantages, a more quantitative approach to weighting exploration methods was applied that is based on statistical analyses rather than expert opinions.

Within this analysis, multiple classification models are trained to identify superhot EGS or supercritical resources (response variable) using exploration data (features). The classification models utilize feature selection in combination with statistical approaches to quantify feature importance in terms of predicting the response. Feature selection filters out the evidence layers that do not provide additional information. Feature importance quantification measures quantify the impact each individual feature has on the response variable, typically within a machine learning model. The models are trained and tested on a held-out portion of the exploration data before multiple feature importance quantification methods are used to analyze the learnings. The models' performances are assessed and the results of each set of feature importance values are then compared to one another to identify consistent, and therefore more likely accurate, results. Agreement between statistically produced feature importance values suggests that the statistical models are "learning" the same relationships.

The outputs of this type of statistical analysis are a subset of the original features, or evidence layers, each with an associated feature importance or weight. The weights from each feature importance quantification method are compared to expert-opinion based weights and will be validated through a comparison of final favorability models produced from each set of weights. The expert opinion-based weights will not be used for rigid validation because we are hoping to learn relationships that expert opinions do not tell us.

5.2.3 PFA Methodology

Once analyzed and validated, both sets of weights will be input into the 3D PFA workflow discussed in Poux and O'Brien (2020). This workflow combines multiple exploration datasets to produce 3D geothermal favorability models and expands beyond previous work which has only done so in 2D, using Leapfrog Geothermal to integrate geologic, structural, geophysical, and other data to suggest the best drilling target within a play. This computerized approach to exploration data integration reduces human-induced bias and mistakes, lowering the overall risk associated with geothermal exploration. Leapfrog provides advantages over other 3D modelling software in that it is relatively fast and dynamic. The Leapfrog Edge module is used in combination with Leapfrog Geothermal to provide advanced geostatistical and resource estimation tools, along with the capability to apply complex calculations on the data, which is crucial to this workflow.

This approach considers heat, fluid, permeability, clay cap/seal, and drilling constraints. The workflow is outlined in Figure 3 below. The first step after all the data has been input into Leapfrog is to prepare and interpret each individual modeled dataset. This may include multiplying the average magnitude by the density of seismic events, doing distance and intersection analyses on faults, or other analyses. Next, the models will be converted to block models to allow calculations on each piece of the total volume. The third step includes assigning index values by category or by value intervals (e.g., 0 for the lowest favorability and 5 for the maximum favorability), which results in an index model with a unique value assigned to each block within each index model. Lastly, weights will be applied to each index model based on their importance to the PFA. These weights along with their associated index models will then be used to produce an overall favorability index model (Poux, 2021).

Both sets of weights will be used in Step 4 of the workflow to produce two separate 3D favorability models. These models will also be compared to each other to investigate the impacts of differing sets of weights, and to determine the overall most favorable area for drilling.

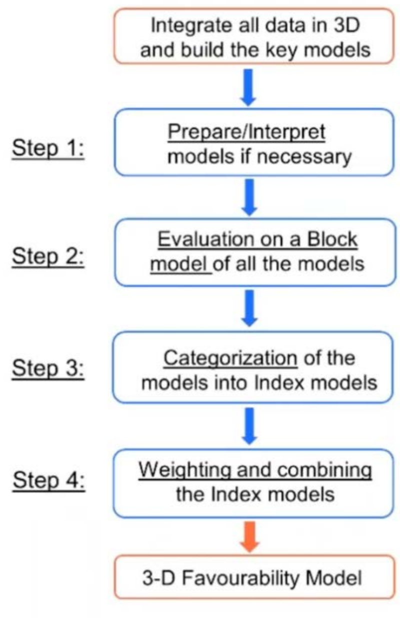

Figure 3: Flow chart displaying PFA workflow described by Poux (2021). This workflow will be utilized along with the expert opinion-based and statistical weights for each exploration method to produce two 3D favorability models for Newberry.

6. Indicators for multiple plays in magmatic systems

Exploration for supercritical geothermal resources will require understanding of signals from transient and complex hydrothermal systems in dynamic volcano-magmatic environments. A "goldilocks" environment will likely be required for the conditions to be just right for power production. The signals that can be captured to locate supercritical geothermal resources can be adapted from hydrothermal ore deposits and geothermal exploration. Examining the characteristics of extinct high-enthalpy hydrothermal systems has partially informed expected geophysical signatures of active ones. Garwin (2019) and Tosdal and Dilles (2020) review the geological characteristics, geochemical signature and geophysical expression of porphyry deposits. For example, contrasts in magnetics, resistivity, chargeability, and gravity can be interpreted as structural boundaries and/or transitions between zoned alteration and mineralization. Patterns of demagnetization, especially dikes/structure and pyrite mineralization are useful for constraining the mineralizing system as are MT-defined resistivity lows associated with clay alteration and sulfide mineral occurrence. Silicification can be identified with resistivity and gravity highs. Gravity contrast between intrusions and country rock help to define the boundaries at depth, and gravity highs can potentially identify basement structure that may be an important control on mineralization. Steep chemical and physical gradients observed in hydrothermal ore deposits, driven by dynamic pressure, temperature, and chemical composition (PTX) conditions, are signals potentially able to guide exploration for supercritical resources.

A database of supercritical indicators was compiled for European countries as part of the EU-funded IMAGE project. Supercritical indicators developed for the IMAGE project include the 400°C isotherm, crustal thickness, earthquake density and estimated depth to the BDTZ (Manzella et al., 2019). Table 5 presents a preliminary set of qualitative indicators for key components of supercritical plays, with applicable exploration methods and data for each of the key components.

Table 5. Preliminary indicators of key components of supercritical plays, based on Manzella et al., 2019; Dobson et al., 2017; Stimac et al., 2017; Bertani et al., 2018; Garwin, 2019; and Tosdal and Dilles, 2020.

Key Component	Indicator	Applicable exploration data and methods
(H) Heat	Depth to the 400 ^{0}C isotherm	Similar to conventional hydrothermal plays (Heat flow data/ mapping and conceptual modeling)
(SF) Supercritical Fluid	*Indicators being developed by DEEPEN team*	Geochemical sampling and THMC modeling to define characteristics of supercritical fluids, geophysical signals of steep changes in alteration mineralogy
(S) Seal	Presence of a mineralogic/lithologic seal	Well logs/cores or geophysical evidence for presence and quality of lithologic/mineralogical seals
(P) Producibility	Permeability Depth to the BDTZ Stress state	Earthquake density, fracture/fault density Well logs, cores and/or geophysical data for deep 3D geologic structure Geophysical data for structure and depth to BDTZ

Exploration for superhot EGS resources should theoretically require fewer “goldilocks” conditions since the reservoir will be created. Still, surface exploration to target optimally producing EGS wells must be capture key components of these play types (Table 6).

Table 6. Preliminary indicators of key components of superhot EGS plays, based on Beardsmore & Cooper, 2009 and input from DEEPEN team members.

Key Component	Indicator	Applicable exploration data and methods
(H) Heat	Depth to the 400°C isotherm	Heat flow data (well PT logs, HF mapping)
(I) Insulation	Crustal thickness and thermal conductivity of overburden	Well logs, cores and/or geophysical data for information about properties of overburden strata
(P) Producibility	Depth to the BDTZ Stress state	Well logs, cores and/or geophysical data for deep 3D geologic structure Fracture/fault density Detection of seismicity that might signal fluid movement and permeability Stress and geomechanical data THMC modeling to predict water-rock interactions between injected fluids and host rock(s) at superhot conditions

7. Next steps

Many datasets have been compiled to develop 3D models for the training sites, and additional data collection is underway to increase the number of evidence layers and to fill in data gaps. The weights produced for use in the 3D PFA methodology will be refined, analyzed, and validated. Uncertainty will be quantified with respect to each of the exploration methods and incorporated into the PFA approach and weights will be input into the 3D PFA workflow discussed in Poux (2021). This methodology could be validated using systems not included as training sites. The PFA methodology will then be applied to Newberry Volcano in Oregon, USA as a case study for superhot EGS exploration, where a team is actively proposing a superhot EGS proof of concept (Bonneville et al., 2021); and to Hengill Volcano in Iceland, the planned future site of IDDP-3 (e.g., Sánchez-Pastor et al., 2021). Additional data acquisition is underway at both sites which will increase the number of evidence layers able to be used in each site's PFA and to fill in gaps in existing data.

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