

# Heat Extraction from SuperHot Rock: A Survey of Methods, Challenges, and Pathways Forward

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## Keywords

*Superhot rock, SHR, hot dry rock, supercritical geothermal, EGS, engineered geothermal systems, hydraulic stimulation, zonal isolation, gap analysis, technology*

## ABSTRACT

High enthalpy SuperHot Rock (SHR) Engineered (or Enhanced) Geothermal Systems (EGS) (>375 °C) are gaining recognition as one of the most promising paths to scale clean, firm, cost-competitive geothermal electricity production worldwide, but significant scientific and development uncertainty surrounds these potential high-value resources. In this paper, we discuss the technologies needed to create SHR reservoirs and describe critical gaps where targeted public and private investment can break down roadblocks.

We begin with a brief review of existing SHR wells and describe insights from these experiences as they pertain to SHR EGS reservoir creation. Then we describe the utility and challenges of working from reservoir analogs in economic mineral deposits formed at similar pressure, temperature, and permeability conditions. Finally, we describe two distinct heat extraction techniques for engineered geothermal systems, stimulated rock volumes and closed-loop, before exploring the current state-of-the-art and gaps.

Creation and operation of superhot engineered geothermal systems involve risks and opportunities that need to be further evaluated by lab testing and field demonstrations, such as a) well and tool integrity, b) fluid-rock-casing interactions, c) reservoir management and longevity, and d) the possibility of felt or damaging injection-induced seismicity. The technology development and testing needed to plan for, drill to, characterize, and mine heat from SHR include: a) numerical models, b) laboratory studies of rock geomechanics, fluid dynamics, and fluid-rock interaction at SHR conditions, c) SHR materials and equipment – drill bits, drill string, proppants, diverters, sealants, instruments, and zonal isolation tools, and d) for SHR EGS reservoir creation, stimulation tools, and methods, tested at wellbore and reservoir scales.

The scope of the challenge invites collaboration between geothermal and oil and gas operators, and those with broader expertise in deep, higher-temperature geologic systems, such as economic geologists and metamorphic petrologists, or engineers and laboratories that routinely work in superhot and supercritical conditions.

## 1. Introduction

Recovery of just 2% of the thermal energy stored in hot rock 3 to 10 km below the continental US is equivalent to 2000 times the primary US energy consumption (Tester et al., 2006). By

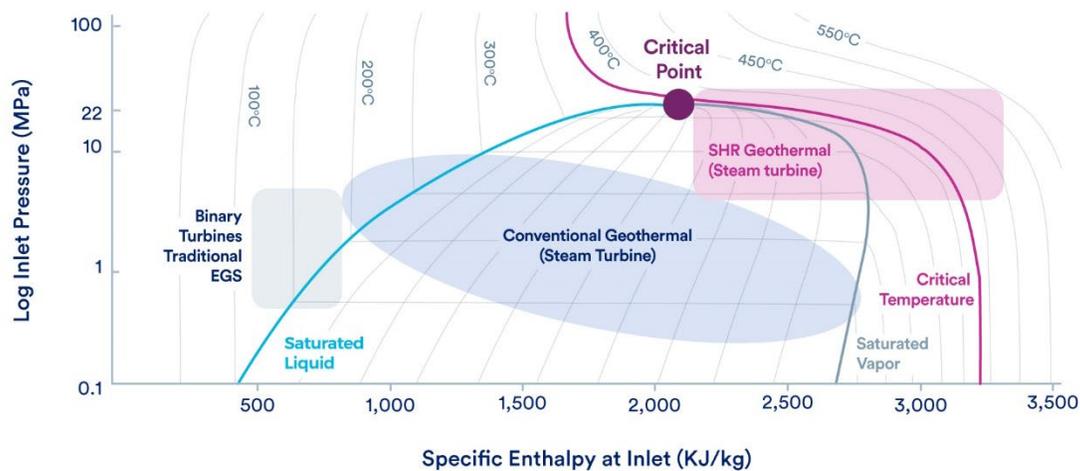
developing these resources, clean, firm renewable geothermal power becomes possible virtually anywhere. Over the past few decades, most engineered geothermal system (EGS) R&D and deployment has focused on resources less than 200 °C. However, the goal of economic *EGS anywhere* may not be achievable unless power production per well can be significantly improved. There are three ways to increase power production per well: increase flow rate, increase flow temperature, or both. Cladouhos et al. (2018) proposed that drilling into superhot rock (SHR) resources and producing high-enthalpy fluids (>2100 kJ/kg) is one of the most promising potential paths to scale clean, firm, cost-competitive geothermal electricity production worldwide. In this paper, we update that argument and focus on the current status of technologies and geoscience needed to create SHR EGS reservoirs to mine heat and produce power.

We use the term superhot rock (SHR) to refer to systems with formation temperatures above 375 °C. The “super” adjective has two sources. First, “super” is a progression of existing terminology used in the O&G industry – High Pressure High Temperature (HPHT) (150-205 °C), ultra HPHT (205-260 °C), and extreme HPHT (260-300 °C) (Shadravan and Amani, 2012). “Super” at 375 °C avoids any overlap with these classes. Second, pure water is in a “supercritical” state at temperatures above 374 °C and pressures above 22 MPa (Figure 1). Under these conditions, the density and viscosity of pure water decrease, and the enthalpy of the fluid increases. Due to the compelling properties of supercritical fluids, much emphasis has been placed on “supercritical” resources. However, as discussed in Driesner (2021), the terminology around these systems varies and fluid encountered or produced from superhot wells may not be accurately characterized as “supercritical.” Several dozen or more wells have encountered temperatures in excess of 375 °C (Figure 2), but the reported pressures are often not >22 MPa (Kruszewski and Wittig, 2018), suggesting the native fluid is superheated, but not supercritical. Even in truly supercritical resources, as fluid flows up a well, the pressure may drop below the critical pressure and the produced fluid flowing through a turbine will likely not be supercritical (McClure, 2021). However, getting fluid to the surface while maintaining pressure above 22 MPa is possible; the Habanero well pair in the Cooper Basin, Australia produced 19 kg/s of 215 °C (not superhot) water with a production wellhead pressure of 32 MPa and an injection well pressure of 43 MPa (Hogarth and Bour, 2015). In any case, we prefer a temperature-only and more generic definition “superhot.”

Naturally occurring supercritical resources found near young magmatic intrusions are outliers even in producing hydrothermal fields (Figure 2) and are not scalable for global geothermal energy production. However, SHR resources, rock hotter than 375 °C, occur everywhere on the planet, at depths dependent on the local temperature gradient. *Therefore, to achieve the goal of scalable, clean, firm, cost-competitive geothermal electricity production worldwide, developing the technologies to create engineered superhot rock geothermal systems in low permeability rock could prove transformative and worth the additional effort and investment.*

Superhot rock engineered geothermal systems can be globally scalable because they can theoretically compete with most other forms of electricity production due to dramatically increased enthalpy and the possibility of higher flow rates from reduced density and viscosity (Uddenberg, 2021; Uddenberg et al., 2022) (Figure 1). The most complete description of the energy of a geothermal fluid is enthalpy. As steam fraction, pressure, and temperature change in the journey from formation into and up the well, enthalpy will only be reduced by minimal heat loss to the formation along the wellbore (which can be mitigated by using insulated casing or, if conventional casing is used, will drop with time as the well-adjacent rock heats up). Superhot geothermal

systems may produce fluids with usable enthalpy greater than 2100 kJ/kg at the surface compared to an enthalpy of  $\sim 700$  kJ/kg for a 190 °C EGS resource (Figure 1). The higher enthalpy of the produced fluid results in much higher thermal-to-electricity conversion efficiency and less parasitic load (Moon and Zarrouk, 2012) as a steam power plant would be connected to the SHR wellfield rather than a binary power plant (Figure 1).



**Figure 1: Pressure vs Enthalpy graph for pure water showing conditions at the wellhead or inlet to the power plant typically encountered in lower temperature EGS, conventional hydrothermal fields, and the promise of SHR geothermal.**

Augustine et al. (2023) suggests that achieving the 2021 US DOE Energy Earthshot of \$45/MWhr can be achieved for EGS at 175 °C but at much higher flow rates (125 kg/s) than has been demonstrated in even the most successful EGS projects to date (Norbeck and Latimer, 2023). Levelized cost of electricity (LCOE) targets of \$20-35/MWhr (Hill et al., 2021) and \$46/MWhr (Cladouhos et al., 2018) have been calculated for SHR EGS at flow rates of 80 kg/s. In all three scenarios, the projected costs assume an "nth of a kind" (NOAK) plant after technology de-risking and reduced costs due to mass manufacturing. The cost of electricity from the first of a kind (FOAK) plant and its immediate successors will likely be much higher as EGS developers learn-by-doing. Identifying uncertainty and improvements needed to start at FOAK and continue to NOAK is a key purpose of this paper.

Superhot geothermal resources have caught the attention of the general public and interested investors. Much of the focus in the public press (i.e., Morenne, 2022; Newcomb, 2022; Raz, 2022; Thompson, 2022; Rassenfoss, 2023) has been on drilling to the SHR resource. Left unaddressed in these stories are the methods or technologies to extract the heat from SHR resources once it is reached by a drill bit. In the professional literature, others have reviewed the general challenges and technological needs for supercritical and SHR geothermal systems (Dobson et al., 2017; Reinsch et al., 2017; Lu, 2018; Petty et al., 2020; Driesner, 2021; Ingason and Kristjansson, 2021; Petty, 2022; Petty et al., 2023). In this paper we focus on the challenges and opportunities of reservoir creation: from rock-mass characterization using reservoir analogs and geomechanical results needed for project design to relevant subsurface engineering such as drilling, well logging, well completion, zonal isolation methods, and seismic monitoring. The goal of the paper is to

identify knowledge gaps requiring future research and development. In the example of an SHR engineered geothermal system created using hydraulic fracturing techniques, some of the most important gaps include:

- Integrated, physics-based, validated fracture propagation models which fully account for rock mass heterogeneity, supercritical fluid properties, and rock properties near the brittle-ductile transition.
- Field and laboratory data to validate and constrain modeling assumptions.
- The role of natural fractures or other mechanical heterogeneities on fracture propagation and connectivity in SHR resources.
- Supportable projections for fracture propagation size and operating flow rates, the parameters most critical for SHR EGS power generation, longevity, and thus LCOE.

To shed light on these and other questions, we reviewed the conditions encountered in wells already drilled into SHR geothermal resources. In addition, because relatively few wells have been drilled in SHR conditions, we searched for reservoir analogs that may provide the best reservoir-scale insight into geomechanics, fracture mechanics, and fluid-rock interaction until an SHR EGS pilot can be completed. The observations made in reservoir analogs can be compared to laboratory results and used to calibrate geomechanical, geochemical, and reservoir models.

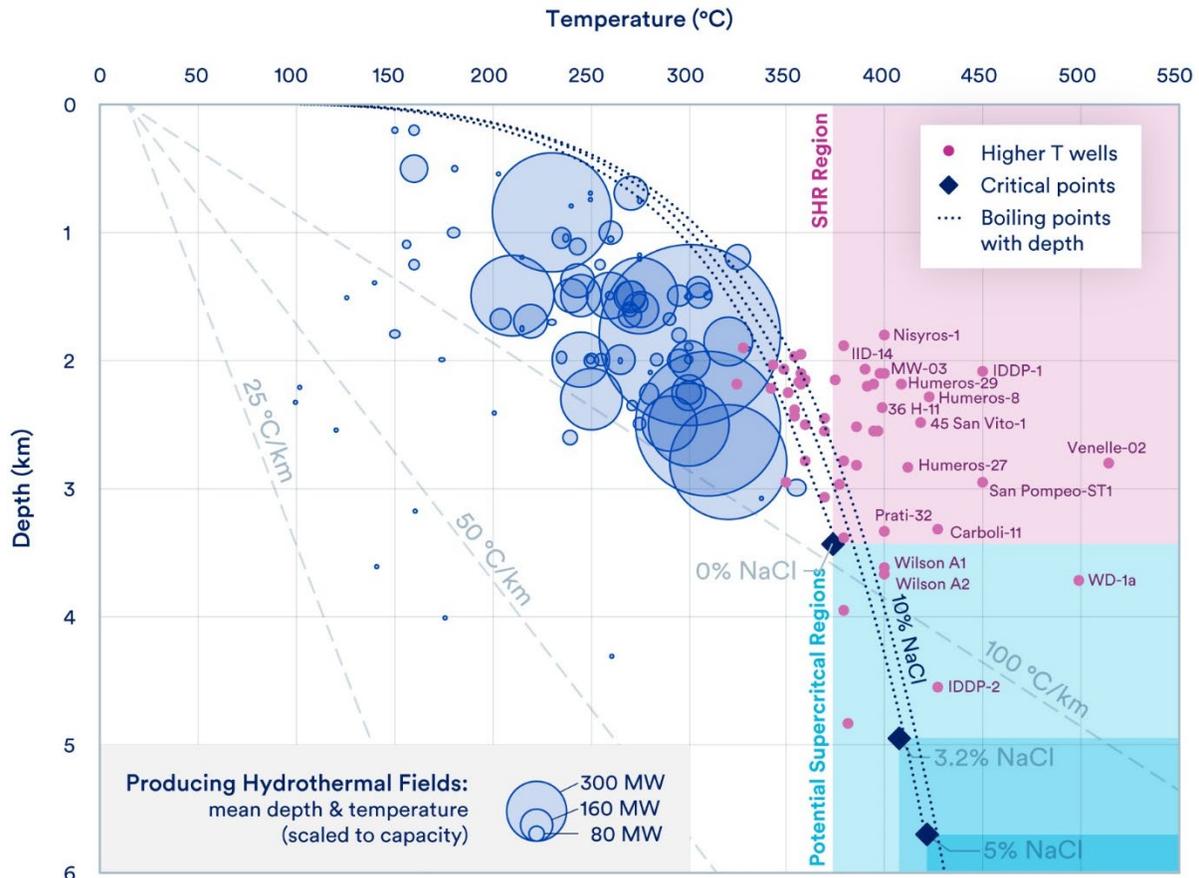
## 2. Background

### *2.1 Geologic Highlights and Drilling Challenges from Existing SHR wells*

Superhot rock resources have been described in association with traditional hydrothermal fields since at least the 1980s (Gianelli and Scandiffio, 1989; Steingrimsdottir et al., 1990; Zan et al., 1990; Fournier, 1991; Muraoka et al., 1998), with the intentional search for supercritical temperatures accelerating in recent years as part of joint industry, government, and academic efforts in Iceland, Japan, Mexico, New Zealand, and recently in the US. The details of these efforts are synthesized in Reinsch et al. (2017), Kruszewski and Wittig (2018), Bromley et al. (2021), and Hill et al. (2022). Here we highlight observations from these high-temperature experiences that are especially pertinent to issues of reservoir creation and management.

First, although existing SHR wells have been drilled in volcanic terrains, reservoir lithologies encountered in these wells include igneous, sedimentary, and metamorphic rock units. Well-known, high-temperature resources at The Geysers, Salton Sea, Taupo, and Campi Flegrei all include sections of clastic sedimentary reservoir rocks, such as sandstone, greywacke, and shale. In Acoculo, Mexico, and Latera, Italy, reservoir rocks include carbonates (limestone, marble, skarn). Fractured intervals in heterogeneous metamorphic rock (phyllite to gneiss) host supercritical fluids in the Larderello geothermal field in Italy. And volcanic, volcanoclastic, and plutonic host lithologies have produced superhot temperatures in Iceland, Hawaii, and Japan. Even in plutonic-hosted systems, mineralogy ranges from mafic to felsic, which has implications for the thermal conductivity and mechanical behavior of fractured reservoirs at elevated temperatures. Despite the significant emphasis placed on improved drilling rates and outcomes in high-temperature crystalline rock, reservoir stimulation strategies and reservoir modeling should anticipate a full suite of host rocks; granitic rocks should not be considered the only reservoir targets during exploration or modeling. On one hand, this increases the complexity of designed systems, as rock properties, mineralogy, fracture networks and mechanical discontinuities may be

quite varied between potential SHR EGS sites (e.g., Watanabe et al., 2017a). However, on the other hand, the native state of potential SHR EGS sites may be simpler than typical hydrothermal sites, which tend to form in structurally complex, tectonically active areas; that is what creates and maintains the permeability that allows convection. EGS targets will have heat but not permeability, so are likely to be less complex and active than hydrothermal sites, which should reduce drilling and stimulation risks.



**Figure 2. Temperature versus depth for SHR wells and producing geothermal fields described in Zan et al. (1990), Wamalwa et al. (2016), Kruszewski and Wittig (2018), and Ball (2022). The boiling-point-with-depth curves after Haas (1971) assume a pressure gradient imposed by a near-boiling hydrostat to the surface. Critical points of different fluid compositions after Bischoff and Pitzer (1989). The nominal mean reservoir depth and temperature of producing hydrothermal fields around the globe scaled to generating capacity after Callahan (2018). Wells >550 °C which intersected magma in Iceland (Elders et al., 2014), Kenya (Ball, 2022), and Hawaii (Helz and Wright, 1983; Teplow et al., 2009) are not shown.**

Second, the composition of high-temperature fluids encountered in superhot wells has been diverse, which has an elevated impact on reservoir behavior near the critical point of fluids. An example of this difference occurred in Iceland between drilling IDDP-1 and IDDP-2. Both wells are broadly located in the same tectonic setting, but IDDP-2 in the Reykjanes area encountered hydrothermal fluids with a higher salinity due to communication with sea water at depth (Friðleifsson, 2017). In addition to compositional variability related to fluid source and

compositional changes related to magmatic-hydrothermal processes, host rock lithology will also impact the properties and behavior of fluids in engineered fracture volumes at SHR conditions. We see this impact in unusual fluid chemistry in hydrothermal systems hosted in carbonate and sedimentary reservoirs (e.g., elevated Li, B,  $\text{NH}_3$ , F in Latero (Gianelli and Scandiffio, 1989)) or exceptionally high brine contents in the Salton Sea (Stimac et al., 2017). The composition of fluid has demonstrated impact on wellfield infrastructure (corrosion, erosion), but also the *properties* of the fluids in an engineered reservoir: the critical point of water depends on the character and quantity of dissolved solids (Figure 2). For instance, the critical temperature of seawater (3.5 wt% NaCl) is  $\sim 407^\circ\text{C}$ , and in magmatic/hydrothermal brines ( $\sim 14$  wt% NaCl) the critical temperature and pressure are  $>500^\circ\text{C}$  and 58 MPa (Bischoff and Pitzer, 1989). The complexity of native fluid chemistry and the impact this has on fluid properties near the critical point is well described in Driesner (2021) and may represent a significant challenge for future SHR reservoir modelers and engineers during operation of natural SHR hydrothermal systems and creation and operation of SHR engineered geothermal systems.

Fortunately, fluids circulated through an engineered geothermal system are likely to be much less corrosive and laden with total dissolved solids than native supercritical fluids. Native fluids are sourced from magma that may include volatile, corrosive gases and/or meteoric fluids which have achieved equilibrium with the formation over thousands of years. In contrast, EGS fluids will be in contact with reservoir rock for a short time period (months), and have little time to equilibrate with the formation, although equilibration times could be quite short at SHR conditions. The tendency for undersaturated EGS fluids to dissolve and then precipitate minerals will need to be further studied and is identified below as a knowledge gap.

Third, several wells exhibit interesting behavior that may highlight the importance of the brittle-ductile transition in SHR reservoirs. The brittle-ductile transition (BDT) is a transition that occurs at high temperatures in rock that will impact the mechanics of drilling, well completions, hydraulic stimulation and EGS operations. In this transition, deformation gradually changes from brittle/localized to ductile/distributed. But many variables control this transition, including strain rate, rock type, and fluid content (Violay et al., 2010; Violay et al., 2012; Violay et al., 2015; Parisio et al., 2019b; Acosta et al., 2021). For example, at lab strain rates ( $10^{-5} \text{ s}^{-1}$ ) the BDT occurs around  $800^\circ\text{C}$  in quartz and feldspar-rich rocks (i.e., granites), while at tectonic strain rates ( $10^{-14} \text{ s}^{-1}$ ) the BDT is at  $400 \pm 100^\circ\text{C}$  (Violay et al., 2017). For basalts, the BDT is at  $850^\circ\text{C}$  for lab strain rates and  $550 \pm 100^\circ\text{C}$  at tectonic strain rates (Violay et al., 2015) (Table 1).

An apparent transition to more ductile behavior was described in WD-1a at Kokkanda, Japan (Figure 2). Hydrothermal circulation was documented to  $\sim 3100$  m and  $380^\circ\text{C}$ . However, below 3100 m, fractures diminished and temperatures increased linearly to  $500^\circ\text{C}$  at the bottom of the well (3729 m), consistent with conductive heat transfer and reduced permeability within the brittle-ductile transition zone (Muraoka et al., 1998). Similarly, an increased rate of penetration and temperature gradient in Vennelle-2, Larderello, Italy, at 2.9 km and  $507^\circ\text{C}$  may have indicated the onset of ductility and/or supercritical conditions (Baccarin et al., 2019). The pressure and temperature conditions in the transition zone in this well are not well constrained, but in other wells that did encounter SHR temperatures in Larderello, Nesjavellir, The Geysers, and Salton Sea greater-than-hydrostatic fluid pressures have been reported (Fournier, 1991; Dobson et al., 2017; Kruszewski and Wittig, 2018). The reduction in permeability and increase in fluid pressure in the BDT may be ascribed to changing rock rheology (Manning and Ingebritsen, 1999; Watanabe et

al., 2017b; Acosta et al., 2021) or enhanced mineral precipitation and sealing (Fournier, 1991; Dobson et al., 2021). The rheology of rocks near the brittle-ductile transition may present challenges to fracture stimulation and sustainability in SHR reservoirs, especially in felsic or quartz-rich rocks that become ductile at lower temperatures than in mafic rocks (Fournier, 1999). Alternatively, some have suggested that aspects of this behavior may be desirable by reducing seismic hazards and leak-off in engineered reservoirs below the BDT (Muraoka et al., 2014).

**Table 1. Strain Rate, Temperature, Lithology, and BDT**

<b>Limit of Dilatant Brittle Deformation (Onset of Ductile Deformation)</b>			
<b>lithology</b>	<b>laboratory strain rate (<math>10^{-5}</math>/s)</b>	<b>tectonic strain rate (<math>\sim 10^{-14}</math>/s)</b>	<b>reference</b>
mafic (basalt)	up to 850 °C	450-650 °C	Violay et al. (2015)
felsic (granite)	up to 800 °C	300-500 °C	Violay et al. (2017)

### ***2.3 Evaluating Reservoir Analogs in Magmatic and Metamorphic Systems***

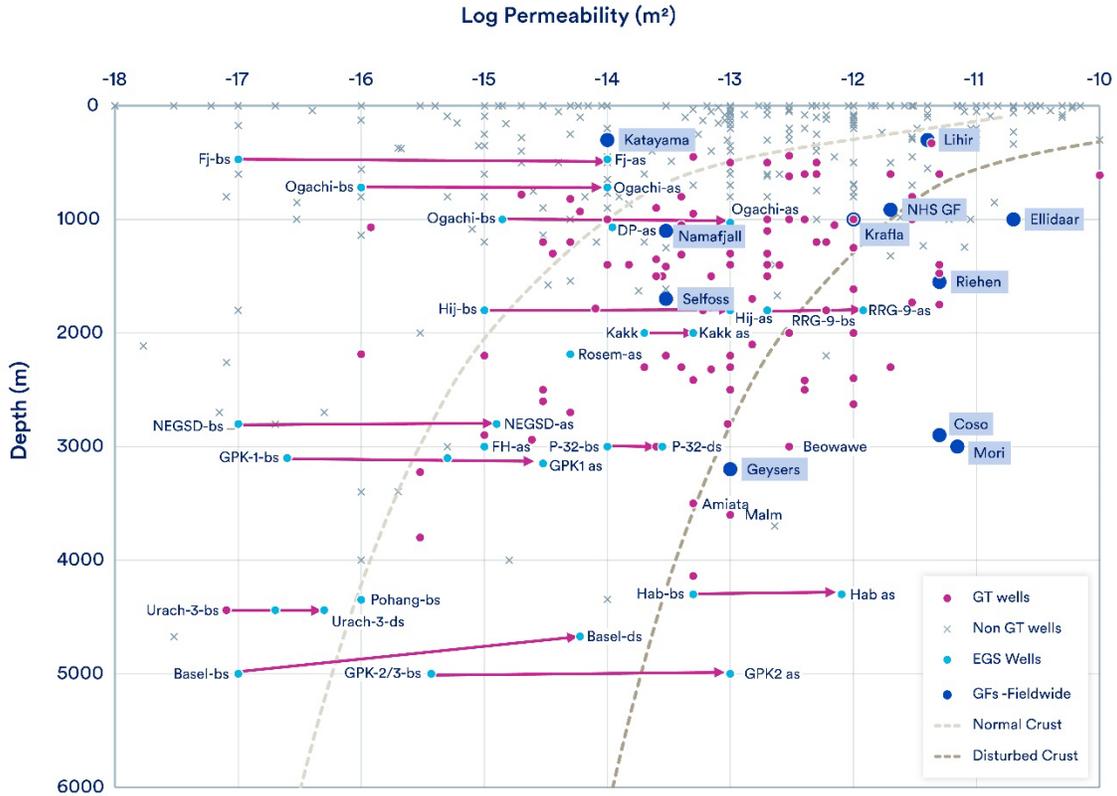
The physical properties and chemical processes likely encountered in SHR hydrothermal and EGS projects are expected to be distinctly different from those encountered in lower-temperature hydrothermal systems. For this reason, it may be useful to look to analogs observed in magmatic and metamorphic assemblages to better understand 1) the physical and chemical processes governing the behavior of supercritical fluids and the behavior of reservoir rocks near the brittle-ductile transition, and 2) describe the lithologic and structural framework of specific SHR projects from outcrop as targets for development emerge. Siliciclastic, carbonate, and fractured basement outcrop analogs are used in this way in oil & gas endeavors to improve conceptual models, identify laboratory test conditions, validate analytical models, and obtain suitable laboratory test specimens (Zeeb et al., 2013; Kolawole et al., 2019; Callahan et al., 2023). However, the selection of appropriate outcrop analogs is not trivial.

Several SHR wells have encountered hydrothermal systems and very high temperatures associated with young granitic intrusion, inviting comparisons with granitic porphyry-style mineral deposits and outcrops (Bando et al., 2003; Tsuchiya, Yamada and Uno, 2016; Amanda et al., 2022). Porphyry-style mineral deposits are critically important contributors to Cu, Au, Mo and are arguably some of the most well-studied mineral systems in the world (Sillitoe, 2010; Reed et al., 2013). They form in plutonic systems emplaced in rapidly exhuming contractional magmatic arcs from 2 to greater than 5 km depth, with environments ranging from magmatic to epithermal, include hypersaline magmatic to dilute meteoric fluids, and pressures transitioning from lithostatic to hydrostatic through the BDT. Boiling or phase separation results in the generation of hypersaline brines and vapor phases, each with evolving physical properties, including transitions back and forth between fluid-like or vapor-like behavior as the compositions evolve toward or away from their respective critical points. Mineral deposition and self-sealing along with ductile deformation around these systems contribute to increases in fluid pressure from hydrostatic toward lithostatic (Fournier, 1991; Dutrow and Norton, 1995; Fournier, 1999; Redmond et al., 2004), which may drive repeated cycles of hydrofracturing, brecciation, pressure decline, and resealing. Pressure fluctuations may change the solubility of minerals like quartz, driving cycles of dissolution and precipitation even in isothermal conditions (Rusk and Reed, 2002).

There are intriguing observations from the porphyry deposit literature that may have parallels in SHR reservoirs. First, the transition between hydrostatic and lithostatic pressure, possibly related to sealing/rupturing cycles and/or fracture closure due to more ductile behavior, is reported from multiple porphyry ore deposits, and encountered in SHR wells in The Geysers, Salton Sea, Iceland, and Japan (Fournier, 1999). Based on these observations, lower permeability and higher ambient fluid pressure, *and potentially very dynamic changes in pressure*, may need to be considered in SHR EGS development. Second, changing fracture styles, from more diffuse and irregular to longer and more planar, have been described from porphyry systems and SHR outcrops that transitioned from ductile to more brittle behavior (Henley and Berger, 2000; Sillitoe, 2010; Amanda et al., 2022). This is potentially mirrored in high-temperature deformation experiments described below (Goto et al., 2021b) and suggests that the resulting fracture cloud networks may significantly weaken rocks at the microscale and need different modeling approaches.

As SHR EGS development expands beyond magmatic regions with elevated geothermal gradients, the suite of appropriate reservoir analogs may broaden to include non-magmatic ore deposits, regional metamorphic belts, and even deep sedimentary basins. Greenschist facies temperatures (300-500 °C) and minerals have been reported in several high-temperature and SHR environments, including wells in The Geysers (Fournier, 1991), the Salton Sea (Swanberg, 1983; Cho et al., 1988; Shearer et al., 1988), and on the flanks of Newberry Volcano, Oregon (Waibel, Frone and Jaffe, 2012). Although these specific sites are peripheral to magmatic systems, they invite analogy with orogenic mineral deposits hosted in greenstone to amphibolite facies metamorphic conditions, where lower salinity fluids and both brittle and ductile features are often encountered (Sibson et al., 1988; Cox, 2005; Mancktelow and Pennacchioni, 2005; Lawley et al., 2023; White et al., 2023). This is a knowledge gap that may benefit from engaging with economic geologists, who may be able to evaluate whether this analogy could provide the geomechanics data currently missing from SHR EGS conceptual models and designs.

Of particular interest to SHR EGS reservoir creation in these analogs will be the properties of fault and fracture networks in low permeability rocks. Decreasing permeability and porosity of the crust with depth has been described by many (i.e., Manning and Ingebritsen, 1999; Ingebritsen and Manning, 1999, 2010; Manga et al., 2012). Scibek (2020) presents a particularly relevant, recent, systematic, and multidisciplinary compilation of permeability measurements of fault zones measured in wells. For the EGS wells captured in this database (Fjallback in Iceland, Urach in Germany, Kakkonda and Ogachi in Japan, Habanero in Australia, Basel in Switzerland, GPK-1/2/3 in Soultz-sous-Forêts, France, Fenton Hill, and Raft River in USA) the permeability measurements before, during, and/or after stimulation are given, providing a comparison between native permeability and what can be engineered (Figure 3). Also shown are field-wide permeability estimates for commercial geothermal fields, which are generally greater than  $3 \times 10^{-13} \text{ m}^2$  (300 mD). The curves from Manga et al. (2012) show permeability with depth curves for undisturbed crust and disturbed crust – the latter being distinguished by the occurrence of earthquake swarms and fluid movement. The consistently low permeability measured in deep (>3000 m) wells outside of hydrothermal fields illustrates that heat mining cannot rely on preexisting permeability and that to make “geothermal *anywhere*” a reality an engineered system is needed. There are currently two end-member approaches to this engineering challenge: closed-loop geothermal systems (CLGS), which do not attempt to change the permeability of the formation, and engineered geothermal systems (EGS), which do.



**Figure 3: Graph of permeability data from Scibek (2020) and Manga et al. (2012). Large blue dots are for field-wide estimates of permeability or cannot be attributed to individual faults; thus, are in the “excluded” portion of Scibek’s fault permeability database. EGS wells after stimulation are also in the “excluded” portion of database due to not being a natural state permeability measure. Both data sets are useful for this purpose. Arrows link permeability in zones before and after stimulation. Newberry (NEGSD) data from Cladouhos et al. (2015). Abbreviations: NHS GF = Neal Hot Springs geothermal field, USA, EGS projects: Fj = Fjällbacka, Sweden, FH =Fenton Hill, USA, DP = Desert Peak, USA, RRG-# = Raft River, USA, P-32 = NW Geysers, USA, GPK-# = Soultz-sous-Forêts, France, Hab = Habanero, Australia, Kakk= Kakkonda, Japan. Urach-# = Urach, Germany, bs=before stimulation, ds=during stimulation, as= after stimulation.**

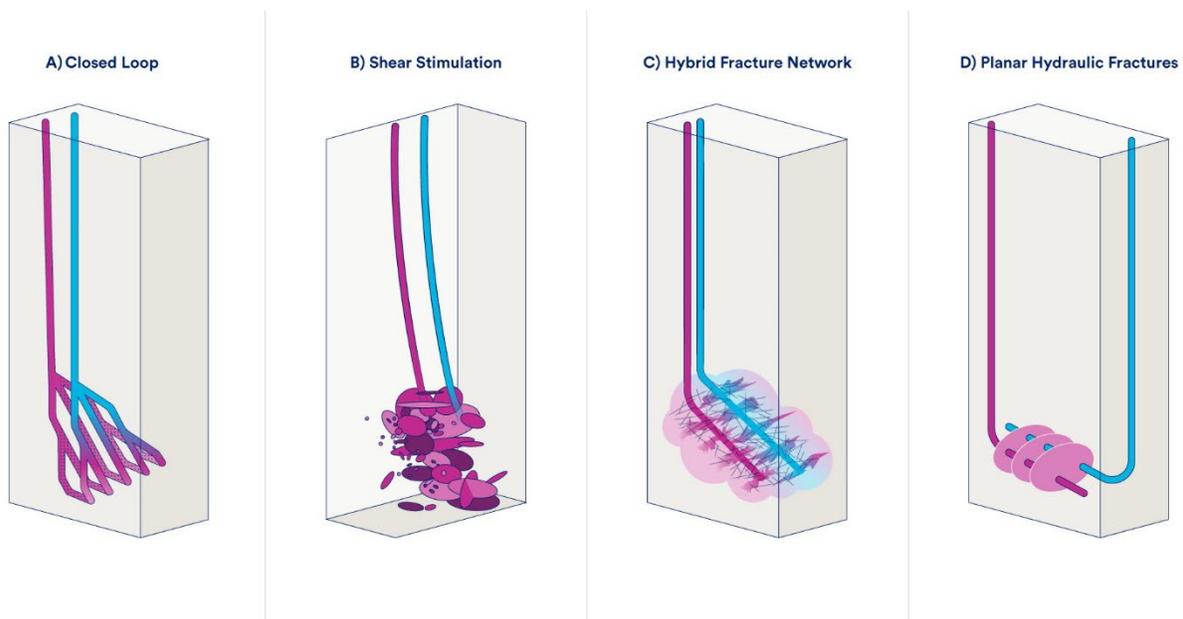


Figure 4: Heat mining approaches to EGS described in text.

## 2.5 Stimulated Rock Volumes - EGS

### 2.5.1 Conceptual models and results of representative EGS projects

In the simplest case, an engineered geothermal system comprises two wells connected via an engineered fracture network which allows heat mining in large volumes of rock between the wells (Figure 4 b,c,d). Since the first project at Fenton Hill (Brown et al., 2012; Kelkar, et al., 2016; Norbeck et al., 2018), several EGS pilot projects have been executed around the world but only a few are operational and producing power, for example, Soultz-sous-Forêts in Alsace France produces about 1.7 MW from 150 °C fluid (Ravier et al., 2019). One of the highest temperature EGS hydraulic well stimulations attempted so far was in 2014 in a well with a BHT of 320 °C at Newberry Volcano, Oregon, U.S.A. (Cladouhos et al., 2016).

Comprehensive reviews of the broad challenges and performance indicators of past EGS projects are given by Breede et al. (2013), Grant (2016), and Pollack et al. (2021). McClure and Horne (2014) reviewed ten historical EGS projects with a focus on EGS reservoir creation and the considerable debate about the mode of brittle deformation in past EGS projects. Simple conceptual models from their review are shown in Figure 5. Pure opening mode (POM) is the classic concept of hydraulic fracturing in which high-pressure fluids are pumped into a rock formation, exceeding the strength of the rock, and creating fractures that open against the minimum stress. Pure simple shearing (PSS) is the concept of hydroshearing, in which large-volume, lower-pressure injection induces slip and self-propping on pre-existing, optimally oriented fractures. Mixed-mechanism stimulation (MMS) is what the authors proposed occurred in many of the past EGS projects they evaluated. And finally, primary fracturing with shear stimulation leak-off (PFSSL) is a hybrid of all three modes listed above. Of particular relevance for SHR EGS projects: developers will need to choose a conceptual model, well and stimulation design based on the geologic setting,

temperature limits of tools and materials, and whether a new well will be drilled or an existing well repurposed.

Shear stimulation or hydroshearing (Figure 4b) as an EGS technique has been successfully performed in open hole completions where sufficient, well-oriented, preexisting fractures could be stimulated and connected to existing permeability and wells. Several projects in the Rhine Graben of France and Germany, such as Landau and Soultz-sous-Forêts, have seen success both technically and economically at relatively low temperatures (150-170 °C) using this technique (Genter et al., 2016).

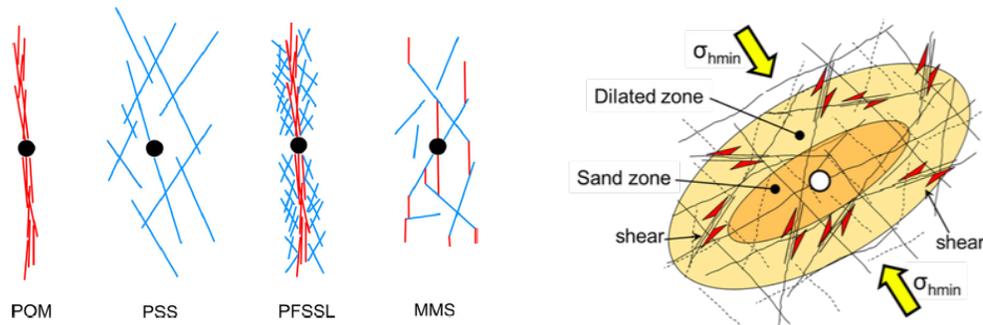
AltaRock's Newberry EGS demonstration project was performed in an existing hot, dry well drilled in 2008 for geothermal exploration. An open hole stimulation at a wellhead pressure near the minimum principal stress (hydroshearing) was performed with a pumped diverter to stage multiple zones at temperatures up to 320 °C. This method achieved an improvement in injectivity and permeability of 5-10x; however, given the ultralow baseline permeability ( $10^{-17}$  m<sup>2</sup>, 10 μD) of the treatment well, an improvement of over 100x was needed (Cladouhos et al., 2015). Further study has indicated that the existing fracture population and stress tensor may not have been as suitable for hydroshearing as expected (Aguar and Myers, 2018).

Just this year, Fervo's Project Red adjacent to an operating conventional geothermal field at Blue Mountain, NV, became the first EGS project to fully implement an O&G drilling, completion, and hydraulic fracturing approach (Figure 4d) with two parallel, 1 km long horizontal, fully cemented laterals, and plug-and-perforate stimulations with sand proppant. During a 37-day production flow test, a peak flow rate of 63 l/s of 169 °C fluid was achieved and a net power production of 1.5-2.0 MWe estimated (Norbeck and Latimer, 2023).

The Fervo project is arguably the most successful EGS project yet when considering increased permeability and the resulting flow. Project Red has enlightened many to the possibility of making geothermal power possible *anywhere*. However, the lower enthalpy of the production fluids (700 KJ/kg) in comparison to that anticipated from an SHR well (>2100 KJ/kg, Figure 1) will cap the power production potential of any lower-temperature EGS well and may ultimately limit its ability to compete with other low-cost, firm power sources on a global scale. There are three ways to increase power production per well: increase flow rate, increase flow temperature, or both. The laterals of the Project Red wells land at 191 °C because the currently available tools for plug-and-perforate stimulations max out near 200 °C, which is the upper limit of the gas generation window. Thus, to continue with the same tools, the only option to increase generation will be to increase the flow rate by drilling 50-100% longer laterals and stimulating more stages (Norbeck and Latimer, 2023), further increasing the system cost. The goal of SHR Engineered Geothermal Systems is to develop the technologies and methods to drastically increase the enthalpy of produced fluids through accessing increased temperature and flow. Oil-and-gas-inspired hydraulic fracturing completions may ultimately be extended to superhot rock, but not by using currently available off-the-shelf equipment.

Another relevant technical debate is the importance of natural fractures in hydraulic stimulations that will impact surface area, thermal performance, and well connectivity in an enhanced geothermal system. At one end-member is the concept that the surface area connected to the well after hydraulic fracturing is dominated by planar, proppant-filled tensile fractures that have grown with little impact from existing natural fractures (Figure 4d). An alternative concept is that existing

natural fractures impact fracture growth, particularly in the region between wells, and that natural fractures connected to and enhanced by hydraulic fracturing also provide significant surface area connected to the well (Figure 4c). The evidence for brittle deformation of the planar fractures is often called “complexity” in microseismic and flow test interpretations. A hybrid approach to heat mining is one in which planar hydraulic fractures are generated at the wellbore, which connect to and enhance natural fracture networks. The final connection between wells could thus be along both propped and natural fractures. The importance of natural fractures and complexity at SHR conditions is clearly unknown and is discussed below as a knowledge gap.



**Figure 5: Left panel: Schematic of four conceptual models for the mechanism of stimulation in EGS from (McClure and Horne, 2014). The black dot represents the wellbore of the first well in a doublet or triplet. New fractures are represented with red lines, and preexisting fractures are represented with blue lines. The mechanisms are: pure opening mode (POM), pure shear stimulation (PSS), primary fracturing with shear stimulation leak-off (PFSSL), and mixed-mechanism stimulation (MMS). Right panel: Fracture-plane view of interaction between hydraulic tensile fracture and shear fractures from Dusseault (2023) - another view on the mode shown as PFSSL at left.**

### 2.5.2 Numerical modeling of EGS

A simple numerical modeling approach for heat mining was first formulated by Gringarten, Witherspoon and Ohnishi (1975). Recent modeling papers based on this approach include Li, Shiozawa and McClure (2016), Doe, McLaren and Dershowitz (2014), Augustine (2016), and Kennedy et al. (2021). The performance target for EGS models of this type is often stated as <10% temperature decline in 20-30 years (Kennedy et al., 2021), but this may be overly conservative for optimal ROI (McClure, 2021). A key finding of Kennedy et al. (2021) is that to meet performance targets (5 MW over a 20-year lifetime with a 150 °C initial  $\Delta T$ ) about 4 million m<sup>2</sup> of surface area are needed for reasonable rock and fluid thermal properties. As an example, to achieve that amount of surface area would require 200 fractures along a 2 km long lateral (assuming a 10 m fracture spacing), 200 m well spacing, and 100 m high fractures. Of course, there are many other geometries and fracture models to achieve the 4 million m<sup>2</sup> of surface area required for a sustainable system including the other three conceptual models shown in Figure 4.

The most widely used fracture propagation models were developed for hydraulic stimulation in O&G fields (Baker Hughes’s MFrac, Halliburton’s Gohfer, Carbo’s FracPro). But early SHR EGS targets are not expected to be layered sedimentary rocks. Most likely, SHR EGS projects will be in metamorphic or igneous rocks with geomechanical characteristics (from lab sample to reservoir-scale) much different than the layered shales or sandstones that are hydrocarbon source rocks or reservoirs. Furthermore, natural fractures, faults, foliation, dikes, sills, volcanic flow boundaries, intrusive contacts, and other structural complexities will play a greater role in brittle deformation

in SHR than in shales. Therefore, the geomechanics knowledge base and modeling tools utilized in oil and gas stimulations will have limited applicability until shown otherwise.

In contrast to the O&G fracture propagation codes, ResFrac has built-in geothermal specific capabilities, including supercritical water, preexisting fractures, and thermal modeling of long-term circulation. ResFrac has been used at EGS projects such as FORGE (McClure, 2023a) and Fervo's Project Red (Norbeck et al., 2023; Norbeck and Latimer, 2023). Recent modeling by McClure (2023b) shows the strength of an integrated hydraulic fracture and reservoir simulation model at a modeled temperature of 246 °C. The results of this physics-based model suggest that thermoelastic fracture opening and downward propagation during long-term circulation can improve the thermal longevity of an engineered geothermal system by providing access to new hotter rock. This is also a capability that full THMC models such as TReactMech can perform (Sonnenthal et al., 2018), thus a code comparison and extension to SHR fracturing could be used to check these intriguing results. Field evidence for downward propagation of fracture below cold injectors such as microseismic catalogs would also help test the model of McClure (2023b).

There are many examples of geomechanical models that address some aspects of brittle deformation at lower (<200 °C) temperatures. For example, discrete fracture network (DFN) applied to generic EGS designs (Doe et al., 2014), Itasca software applied to Fallon FORGE (Pettitt et al., 2018) and TreactMech applied to Fallon FORGE candidate site (Sonnenthal et al., 2018). Utah FORGE well stimulations were history-matched to the results, but pre-stimulation projections were not provided and it is clear that geomechanical parameters needed large adjustments to match the results (Lee and Ghassemi, 2023; McClure, 2023a). Thus, without field results, a predictive model will still likely miss the mark. One key gap is a lack of knowledge of the geomechanical parameters for different rock types at elevated temperatures and pressures, which are needed for this modeling work. Furthermore, natural and engineered geothermal systems appear to be dynamic in nature, and thus geomechanical parameters (i.e., bulk modulus) can change over time, as has been shown for the NW Geysers EGS field demonstration project (Vasco et al., 2013; Rutqvist et al., 2016). Further discussion of modeling needs and gaps is provided below in § 3.1.

## ***2.6 The closed-loop approach***

A relatively new approach suggested for heat mining is a closed-loop geothermal system created by drilling into hot rock and relying on conduction to heat fluid in the well (Figure 4a). Models of heat mining for closed-loop systems rely on the *Wellbore Heat Transmission* solution first formulated by Ramey (1962) for injection of hot fluids down tubing and the resulting *heat loss* to the formation (but which is also applicable to heat gained from the formation). Recent designs employing this approach use two main wells and directional drilling and ranging to connect multilaterals (Eavor, 2023a) or single-well pipe-in-pipe designs (Nalla et al., 2005; XGS Energy, 2023). In the multilateral well concept, the directional drilling part of the shale revolution is leveraged, but not hydraulic stimulation. Recent modeling papers based on conductive heat flow to a solid, cased wellbore include Toews and Holmes (2021), Liu et al. (2023), White et al. (2023), and Beckers and McCabe (2019). The performance targets for closed-loop geothermal systems are improved predictability by reducing geologic uncertainty, reduced real and perceived risks of induced seismicity, and reduced water loss to the formation. These targets can be achieved by complex drilling and completion plans. Built into the design and economic projections of closed-loop geothermal systems is decline in power output (or temperature) of more than 50% in the first

year, and then a pseudo steady-state output at less than 50% of the initial production for up to 30 years. For example, Toews and Holmes (2021) model that a closed-loop geothermal system with 72 km of multi-laterals drilled into rock with an average temperature of 350 °C and flow rate of 96 kg/s will initially (for less than a month) generate over 18 MWe and then an average of 8 MWe for 30 years.

The closed-loop approach is not a focus of this report for two reasons. First, reaching SHR conditions is not a primary goal of closed-loop developers at this time. The Eavor-Deep project recently reached 250 °C at 5.5 km vertical depth, a significant achievement but significantly cooler than SHR temperatures (Eavor, 2023b). Similarly, the closed-loop geothermal approach proposed by XGS Energy, in which conductive materials are emplaced near the wellbore, cold working fluid flows down an insulated pipe, and heated fluid flows up the annulus (aka pipe-in-pipe or monowell) seems to be targeting formation temperatures less than 300 °C (XGS Energy, 2023; Liu et al., 2023). Second, because flow rates will be relatively high in a closed-loop geothermal system compared to the rate of conductive heat flow, the rocks adjacent to the well will cool rapidly and the fluids produced will have an enthalpy of <800 KJ/kg rather than >2100 kJ/kg (Figure 1). Still, we expect that CLG progress in drilling, well completion, monitoring while drilling (MWD), ranging and navigation will be valuable contributions to SHR EGS developments as described below.

### **3. Developing a SHR resource – State of the Art and Gaps**

Next, we review the state of the art in multiple disciplines and identify gaps in knowledge or technology that require investment and should be addressed by research and development to increase TRL level in order to succeed with SHR resource development. These needs and gaps are first summarized in Table 2, and then expanded upon in the following subsections. Although the list below is broad, the focus is on aspects related to what is needed for reservoir development, as shown in Figure 4.

Table 2. Summary of State-of-the-Art, Gaps, and Solutions. See text in §3.1 for more details and supporting references.

§	Category	BASIC SCIENCE		
		Current Status	Gap	Solution
2.3	Reservoir Analogs	Porphyry-style systems investigated as analogs in Japan.  Disconnect between Geothermal, O&G, mining industries.	Deeper, non-magmatic analogs needed to text conceptual models for SHR anywhere.	Engagement with economic geologists, metamorphic petrologists.
3.1	Fracture modeling	Fracture propagation models designed and validated to O&G stimulations.	No coupled model incorporating rock/fractures mechanics, flow, reactions at SHR conditions.	Push fracture modeling into SHR space. Code comparison.  Laboratory and field validation.
3.1	Reservoir models	THMC and reservoir models for < SHR conditions.	Coupled reservoir models with supercritical fluids, BDT mechanics, dynamic long-term changes.  Thermodynamic and kinetic data needed for modeling fluid-rock interaction within the P-T conditions of the supercritical regime.	Coupled THMC modeling and validation from demonstration sites.  Conducting laboratory experiments.
3.2	Rock/Fracture mechanics into brittle-ductile transition realm.	Rock mechanics testing to ~800 °C.  High-temperature fracture testing in industrial materials and limited geologic materials.  Identification of cloud-fracture networks at higher T.	Impact of BDT and supercritical fluids on fracture propagation, arrangement, and longevity.  Induced seismicity potential near the BDT. Fracture mechanical testing of diverse lithologies at high T.	Lab Testing: involve facilities beyond geoscience.  Expand capabilities at existing facilities.  Reservoir analogs for fracture properties.  Field demos and validated models.
3.2	Material Testing & Development	Facilities exist for high temperature testing beyond the geoscience community.  Many existing materials and tools fail between 200-350 °C.	Testing and identifying materials for SHR conditions (casing, cement, diverters, proppant, tracers).	Leverage material science tools beyond geoscience community.
3.3	Site Selection, Exploration, and Characterization	Modern techniques have identified SHR conditions below existing fields.	Reliable identification of drilling hazards (magma, high pressures), and geophysical techniques for SHR greenfields remain elusive.	Testing and validation of geophysical techniques and signatures (“K-horizon”) in more diverse settings.

<b>TOOLS &amp; INFRASTRUCTURE</b>				
<b>§</b>	<b>Category</b>	<b>Current Status</b>	<b>Gap</b>	<b>Solution</b>
3.4	Well Completions and Directional Drilling	SHR conditions exceed typical geothermal and O&G experiences. SHR wells have been drilled to >500 °C but have been accompanied by several notable failures.	Directional drilling/MWD above 350 °C Technologies for rapid, deep drilling for SHR anywhere. Reliably identifying pressure kicks in low permeability crystalline rock.	Insulated Drill pipe for cooling during drilling, all metal motors. Testing and developing new drilling tools and well completions (rock pipe, vitrification).
3.5	Well Logging Tools	Temperatures measured to >500 °C. National Lab Image logs to 280 °C. Other geophysical logs to 260 °C.	Tools for reliable characterization to SHR temperatures. Reliable stress measurements in SHR conditions.	Well bore cooling during logging. LWD. Higher temperature or better heat shielded instruments.
<b>STIMULATION &amp; RESERVOIR TECHNOLOGY</b>				
<b>§</b>	<b>Category</b>	<b>Current Status</b>	<b>Gap</b>	<b>Solution</b>
3.6	Stimulation Design	Open-hole hydroshearing in inclined wells to 320 °C.  fracturing in sedimentary and metamorphic units <200 °C.	Tools for directional drilling, well construction, and zonal isolation impact stimulation design.  Models for fracture initiation and propagation in BDT zone.	Basic science on rock and fracture properties. Materials testing and development. Test sites.
3.6.1 3.6.2	Zonal Isolation	Open-hole hydroshearing with diverters or packers in prior EGS to ~320 °C.  Hydraulic fracturing (plug & perf) in sedimentary and metasediments <200 °C.  Portland cement up to 300-350 °C. Sanding back.	Cement above 350 °C.  Packers >330 °C	All metal ECPs, other sealants. Materials testing and development. Test sites.
3.6.5	Proppant	Injected proppant limited to ~200 °C. Stimulation designs that assume hydro- or self-propping.	Chemical and mechanical stability in SHR. Longevity of fractures in SHR and BDT	Lab and field testing.

3.7	Induced Seismicity	Established mitigation protocols by USDOE and EU for < SHR conditions.	Competing ideas about the risk of induced seismicity within or near BDT zone.	Robust mechanical testing, analog investigations, coupled THMC modeling and validation, demonstration sites.
3.8	Roadmap to commercialization	Power Purchase Agreements for conventional geothermal for 20-30 years.  Limited opportunity for field expansion.	Industry demonstrations.  Commercial Scale-up roadmaps.	Creative financing (10-15 year wells).  “Expanding Field” models to leverage learning-by-doing and reduce mobilization costs.
3.9	Diagnostics & Characterization	Surface or remote methods: InSAR, gravity, magnetotellurics.  Near-reservoir: microseismic monitoring.  In-reservoir: DAS-FO to 200 °C.; pressure monitoring, circulation testing, tracer testing, etc.	Demonstration of remote sensing and monitoring techniques in SHR EGS settings.  Tools and models designed for SHR temperatures and brittle/ductile conditions.	Lab and field testing.

### ***3.1 Modelling of fracture propagation and reservoirs in superhot rock***

There is a broad array of models needed to design, create, and manage an engineered SHR reservoir: geodata models, geophysical models, numerical reservoir models, coupled THMC (thermo-hydraulic-mechanical-chemical) models, fracture propagation models, power plant models, and techno-economic models.

As discussed above in the background section, geochemical geothermal models have begun pushing into supercritical pressure-temperature space (e.g., Magnúsdóttir and Finsterle, 2015; Battistelli et al., 2020; O’Sullivan et al., 2020; Lamy-Chappuis et al., 2021; Sonnenthal et al. 2021; Feng et al., 2021; DePaolo et al., 2022; Altar et al., 2023; Xu et al., 2023) but an integrated model (i.e., Figure 4 of Driesner (2021)) for brittle deformation in superhot reservoirs with the influence of natural fractures does not yet exist. The challenges of modeling fracture propagation and fluid flow in a SHR reservoir including the physical properties of water, such as density and viscosity, change rapidly in the vicinity ( $\pm 75$  °C and  $\pm 5$  MPa) of the critical point of pure water. For example, during both the stimulation and operational phases of an SHR EGS, the same water could undergo multiple phase changes, 10x changes in viscosity, and 5x changes in density. The geomechanical behavior of rocks in the BDT and influence of thermal cracking due to the large temperature contrast between rock and injected fluid are also not included in most models.

Numerical reservoir models and coupled THMC models that can simulate the equations of state for supercritical water, phase changes, mixed steam-water flow, and geochemistry will be necessary to predict the longevity of SHR EGS due to permeability changes and thermal decline. However, there is a lack of thermodynamic and kinetic data needed for modeling fluid-rock interaction within the P-T conditions of the supercritical regime that will require further laboratory experiments to derive this information.

The results of simple parallel plate models (Gringarten) and more complex fracture networks were introduced in the background (e.g., Kennedy et al., 2021). Reservoir models which allow more complex hydraulic and natural fracture models will also be useful for SGR EGS scenario modeling.

One critical issue for THMC models of SHR EGS operations is the role of mineral dissolution and precipitation on fracture transmissibility. In particular, quartz, which has retrograde solubility, may precipitate and seal fluid pathways unless countermeasures can be developed (Saishu et al., 2014; Watanabe et al., 2021a). This is an uncertainty that can be further investigated in the lab, as discussed in the next section.

Finally, code comparisons like those performed at lower temperatures (Molloy et al., 1980; White and Phillips, 2015; Kennedy et al., 2021) have not been performed on code developed for SHR EGS. Even more critical is the need for data from field experiments for history matching to validate SHR EGS codes.

#### Gaps

- A comprehensive survey is needed of the capabilities of existing modeling packages at SHR and BDT conditions and the upgrade pathways.

- Fracture propagation in diverse lithologies with unpredictable structural relationships. Hydraulic fracturing software was designed to predict hydraulic fracture apertures, dimensions, and propagation direction in a layer-cake stratigraphy of sedimentary rocks.
- There is a lack of thermodynamic and kinetic data needed for modeling fluid-rock interaction within the P-T conditions of the supercritical regime.
- Models that can test ideas for creation of sufficient surface area and flow paths to maximize heat extraction from the rock volume in a sustainable manner.
- Physics-based models for fracture propagation that account for geomechanics in rock approaching the BDT, with abundant and unpredictable natural features, using near-critical point water that will experience rapid changes in pressure, viscosity, and density.
- Reservoir modeling – heat conduction from rock to fluids and supercritical thermodynamics of fluid in reservoir.
- Coupled DFN and Reservoir Model – upscaled discrete element modeling of entire systems for analysis and planning.
- Until reliable data is available for model validation, comparison of results between different codes can be used to evaluate results.
- Inclusion of impacts of phase transition (esp. through critical point) on geomechanics and flow properties within models.
- Development of appropriate stress conditions and rock property parameters for these systems
- Models are also needed for projection of long-term operations of sustainability (thermal and pressure changes) and geochemical effects such as dissolution and precipitation along fractures and proppants.

### ***3.2 Laboratory Testing at Reservoir Conditions***

Currently available laboratory test equipment generally is limited to temperatures of 300 °C or below, most often at temperatures below 200 °C. The geomechanics lab at EPFL (Violay et al., 2010; Violay et al., 2015; Acosta et al., 2021) has been running experiments (strain, elastic properties, and compressive strength) through the BDT on a variety of rock types up to 800 °C. A higher upper-temperature limit is needed in laboratory experiments to account for faster strain rates in experiments than EGS operations and especially tectonics.

State-of-the-art geomechanical testing has also been performed at labs in Japan (Watanabe et al., 2017a, b; Goto et al., 2021a; Goto et al., 2021b), New Zealand (Rendel et al., 2021), and Iceland (Nono et al., 2020). Hydraulic fracturing experiments have been performed in granite samples at temperatures of 200-450 °C using water (Goto et al., 2021b) and CO<sub>2</sub> (Pramudyo et al., 2021). These experiments showed cloud or distributed brittle deformation at the grain-scale near the BDT.

There have also been number of relevant geochemical experiments conducted to develop a suite of mineral-fluid thermodynamic properties for supercritical systems, fluid properties (Schultze, et al., 2022), and geochemical constraints (Hermanska, Kleine, and Stefansson, A., 2020). Quartz solubility in supercritical fluids is of great concern and has been investigated in the lab by Rendel, and Mountain (2023), Saishu, Okamoto, and Tsuchiya, (2014), and Watanabe et al. (2021a).

The durability of well construction materials at SHR conditions has been a concern since on-site testing at IDDP-1 was found to contain highly corrosive HCl and HF (Karlsdottir et al., 2014). Thorhallsson et al. (2020) performed a corrosion study of steels and alloys by testing in a simulated superheated geothermal environment (SSGE) in flow-through reactors.

A key component of state-of-the-art laboratory testing is monitoring of acoustic emissions (AE). For example, Ko et al. (2023) used AE to determine packing strength and crush resistance of proppants at temperatures of 320 °C. Goto et al. (2021b) used AE to measure the onset of rock failure difficult to observe by other means.

Vendors and service providers often test or certify their own equipment but are unlikely to test at SHR conditions until there is an identifiable market opportunity.

Most other lab tests have not been performed at SHR conditions, thus there are many gaps.

### Gaps

Several types of test apparatus will be needed for measurement of properties of rock, cement, and other downhole materials at SHR conditions (375-600 °C) as outlined by Petty et al. (2023):

- A comprehensive, worldwide survey is needed of the capabilities of existing laboratories and upgrade pathways to reach SHR conditions.
- Lab measurements of fracture toughness and the effects of thermal shock on rock weakening.
- Robust measurement of the geomechanical properties of various rock types at high temperatures and pressures.
- Porosity, density, and permeability of various rock types as a function of temperature and pressure.
- Thermal properties – thermal conductivity, thermal diffusivity, thermal expansion and heat capacity – of various rock types at high temperatures and pressures.
- Fluid/rock interactions – dissolution and precipitation in rocks and cements.
- Material properties - solubility, stability, strength, and thermal properties for materials such as cements, proppants, diverters, drilling fluids, tracers and additives such as corrosion and scale inhibitors, treatment chemicals, friction reducers, foaming agents, and others.
- Mechanical properties of casing materials and casing components at very high temperatures and under stresses produced with thermal cycling.
- Downhole instrumentation and tools such as logging instruments and cables as well as methods for conveying and deploying downhole tools and instruments.
- Further laboratory study of the behavior of rock near the BDT. For instance, will the cloud fracturing reported by Goto et al. (2021b) have an impact on rock strength and fracture propagation in the field? What laboratory scale (if any) tests can be done to investigate?
- Quantification of the impact of phase transition (esp. through critical point) on flow properties of EGS fluids.

### ***3.3 Site Selection and Characterization***

Geologic mapping, exploratory and offset wells, historical seismic data and tools like magnetotellurics, electromagnetic induction tomography, and active & passive seismic surveys

will be used to find and characterize targets for SHR EGS projects. These geoscience surveys will provide the data for technical synthesis, seismic risk analysis, induced seismicity mitigation plans (Majer et al., 2016), geo-models, play fairway analysis (Kolker et al. 2022), and fracture and reservoir models. Also important for SHR EGS project siting will be market analysis, off-taker identification, transmission, and community benefits.

Identifying supercritical fluids, magma, and other hazards before drilling remains challenging. For example, at Larderello, 2D and 3D active seismic survey data highlighted a deep seismic marker named the “K-horizon” that was hypothesized to be supercritical fluids based on the offset well San Pompeo 2 (Baccarin et al., 2019). However, this seismic marker was not found to be supercritical fluids when intersected by the deepened Vendelle-2 well.

Passive microseismic arrays can be used for exploration, well siting, and stimulation monitoring of superhot and supercritical resources (also see §3.9). Ambient seismic noise tomography is being used to site the next IDDP (Iceland Deep Drilling Project) target in the Hengill geothermal field, SW Iceland (Sanchez-Pastor et al., 2021). In New Zealand, there have been a number of studies of the roots of the existing geothermal system in the Taupo Volcanic Field using 3D seismic tomography (Bannister et al., 2015) and MT (Bertrand et al., 2015). And in Mexico, studies conducted as part of the GEMex project have characterized the architecture of the Los Humeros geothermal system (e.g., Norini et al., 2019).

Characterizing SHR EGS reservoirs after hydraulic stimulations will use the same geophysical methods (e.g., passive seismic monitoring, seismic tomography, etc.) used pre-drilling, therefore collecting baseline data is critical for later data collection and interpretation.

### Gaps

- Geophysical surveys and seismic monitoring continue to need validation through drilling.
- Reliable, drilling-validated geophysical signatures of SHR targets will reduce risk of SHR development and well targeting.

### ***3.4 Directional drilling in SHR — Summary of Current Technologies***

Drilling into SHR resources has already been accomplished by pushing the limits of existing geothermal drilling and well completion technologies, and is not covered in great detail here. Drilling a vertical or near vertical well into rock above 500 °C has been accomplished with PDC or roller cone bits (Kruszewski and Wittig, 2018) without monitoring while drilling (MWD) or rotary steerable systems (RSS). The Prati 32 well at The Geysers was drilled to a bottom hole temperature of 400 °C using air drilling, but the final tricone bit only lasted 30.5 m, with reduced penetration rates (< 3 m/h), due to the extreme temperature conditions of the well, as air drilling does not cool the wellbore (Garcia et al., 2016). The DESCRAMBLE project on the Vennelle-2 well reached a BHT of 507-517 °C at 2.9 km using fluids and rotary drilling (Baccarin et al., 2019). The last two drill bits were Stingblades, PDCs with conical diamond elements, that drilled at 4.0 and 9.2 m/hr and lasted 101 and 179 m (Baccarin et al., 2019).

Past failures of well casing in SHR wells that have resulted in unusable wells have often been related to thermal cycling and cold-water quenching. For example, in Iceland, IDDP-1 and Hellisheidi-45 damage to the shallow portion of the wells were caused by emergency injection of cold water to prevent blow-outs (Ingason and Árnason, 2022). IDDP-2 failed due to an incomplete

cement job at 2300 m (Ingason and Árnason, 2022). Well completions that can withstand thermal cycling, either planned or unplanned, will be critical for constructing SHR wells that will last.

Compared to the SHR hydrothermal wells, such as IDDP-2, in which corrosive and abrasive fluids were encountered (Kruszewski and Wittig, 2018), SHR EGS wells are not expected to encounter significant volumes of harsh native fluids, so drilling may be somewhat easier. However, pressures in the BDT may be greater than traditional hydrothermal wells, a knowledge gap that needs to be explored.

For SHR EGS reservoir creation, a key challenge for current technology is directional drilling at SHR conditions to maximize well length and fracture intersections in the resource. The well in the IDDP-2 project in Iceland was directionally deepened from 2500 to 4659 m in 168 days to a maximum measured temperature of 426 °C (Stefánsson et al., 2021). The project deployed a 300 °C directional drilling system developed by Baker Hughes using DOE funds (Dick et al., 2012) that employed helium down-hole refrigeration, MWD, and all-metal mud motor (M2M) (Baker Hughes, 2020). The well was deepened vertically to 2750 m, then inclination was built to and held at about 30° (Baker Hughes, 2020), although the plan had been to hold at 20° (Stefánsson et al., 2021). Unfortunately, this particular M2M technology has not been further developed or used.

In SHR EGS, there will be no specific drilling target or source lithology to follow. Instead, the reason for directional drilling of the first well will be to maximize lateral reach of a well in order to intersect or create more vertical fractures. Fully horizontal wells may not be the most cost-effective and there is no requirement that wells be drilled along an isotherm, rather a well that gets hotter with depth may be preferable. But inclinations greater than 30° from vertical will likely be necessary. Directional drilling, MWD, and navigation will be critical in the second and third wells of a triplet in order to maximize intersection of permeability created in the first well.

For EGS development, various trajectories and inclinations have been proposed and drilled for EGS wells to maximize the number of fracture stages, increase connectivity, and minimize thermal breakthrough. These well geometries include subvertical (Cladouhos et al., 2016; Cladouhos et al., 2018), horizontal toe to heel (Shiozawa and McClure, 2014), and horizontal heel to heel (Norbeck et al., 2023).

In closed-loop systems, directional drilling, MWD and navigation, and magnetic ranging (Eavor, 2023a) will be even more critical since completing the loops will require laterals to connect at great depth and temperature.

Another recent demonstration is the use of Insulated Drill Pipe (IDP) at the Eavor-Deep well in New Mexico (Brown et al., 2023). IDP and mud coolers can be used to cool the well bore of a 350 °C well to 150 °C, allowing for the use of ordinary (elastomer dependent) MWD and mud motors. The Eavor-Deep well only reached 250 °C formation, so IDPs full advantage has not yet been tested in SHR (Eavor, 2023b). IDP will be even more effective when paired with continuous circulation and cooling systems at the surface as downhole temperatures spike quickly when circulation is broken for any reason.

## Gaps

- Directional drilling in SHR has been demonstrated just a few times and is likely to be expensive and time-consuming. Serious investment and learn-by-doing will be needed to further reduce risks, costs, and drilling time.
- Due to the great risk to drillers and project success, measures to contain extreme pressures must be developed and implemented.
- Well completions that can withstand extreme thermal cycling from SHR production to cold-water quenching will need to be designed and tested.

### ***3.5 Well Logging***

The most important downhole borehole logs in EGS are temperature, image logs, and sonic velocities. Active and passive seismic data collection in boreholes is discussed in section 3.9.

Measuring temperatures in the 375-500 °C range will be possible provided appropriate tools are selected. The HiTI project (Asmundsson et al., 2014) developed several new high temperature downhole instruments, including a DTS system, a downhole analog wireline temperature tool, and a multisensory (T, P, spinner) downhole memory tool. In the DESCRAMBLE project, temperature logs were collected up to 517 °C (Baccarin et al., 2019).

Image logs, ultrasonic (UBI, BHTV) and/or microresistivity (FMS), are used to characterize natural and induced fractures (depth, orientation, aperture, filling, etc.), and borehole stress indicators (breakouts and drilling-induced tensile fractures). These logs are critical to wellbore stability, wellbore trajectories, and stimulation design. The commercial versions of these logging tools can reach 180 °C. The Sandia BHTV can reach 280 °C (Davatzes and Hickman, 2011). For wireline deployments injection during logging or circulation through drill pipe in advance of logging can be used to cool a well hotter than these limits, although this may cause local thermal stresses and influence the interpretation of regional stress orientation or magnitude (Permata and Tutuncu, 2019). Another option is to use LWD (logging while drilling or tripping) to cool the well, which resulted in a successful run of a full suite of logs down to a formation temperature of 500 °C in IDDP-2 (Stefánsson et al. (2021), see also Nabors (2023)).

Measuring stress magnitudes, specifically the minimum principal stress magnitude and orientation is also important for stimulation design. This is done through an XLOT (extended leak-off test), which should be possible at SHR conditions but has not been performed as far as we know so must be evaluated. Another challenge of measuring stress is that any one stress measurement may be nonrepresentative of the rock volume due to mechanical heterogeneities or structures. It is common in geothermal fields with critically stressed faults to observe large stress rotations across faults (Hickman et al., 2000). In low permeability EGS fields (i.e., undisturbed crust of Figure 3), this may not be an issue; however, so few stress measurements have been taken at depth that this risk is unknown.

Other traditional geophysical surveys such as dipole sonic logs, spectral gamma ray, compensated density, and neutron are typically limited to 260 °C.

#### Gaps

- Tools and methods to gather fracture and stress data (XLOT, image logs, etc.) must be extended to superhot conditions (i.e., 450 °C).

- The potential for variability of stress orientations at depth has not been evaluated due to limited stress measurement data at depth.

### ***3.6 Hydraulic stimulation overview - Application***

To maximize the chance of EGS success in all geologic and tectonic settings, the default plan for hydraulic stimulation should include zonal isolation and high-pressure stimulations. Whether the stimulation mechanisms expected are tensile fracturing or hydroshearing, zonal isolation provides the best chance for maximizing surface area and connectivity between two wells. The technologies needed for creation or enhancement of permeability in all rock formations can be divided into:

- 1) Wellbore completion, which can be subdivided into
  - a. Zonal isolation on the outside of casing, and
  - b. Zonal isolation on the inside of the casing.
- 2) Hydraulic stimulation, which can be subdivided into
  - a. Fracture initiation,
  - b. Fracture growth, and optionally
  - c. Proppant emplacement

The technologies and tools used in O&G stimulations from these operations are generally designed for maximum temperatures of less than 200 °C so SHR stimulations will require different approaches. A potential exception to the 200 °C limit in O&G would be steam floods for EOR (i.e., as practiced in the Central Valley of CA and Alberta) (Zerkalov, 2015; Settari et al., 2018).

#### Gaps

- Testing of a complete system as described above requires either field testing in SHR wells or an extremely large sample (i.e., >1 m blocks), superheated rock mechanics laboratory. Individual, specific components and solutions discussed below, can also be tested separately.

#### 3.6.1 Zonal isolation outside casing allows for multistage stimulation.

The current practice in O&G wells and recently demonstrated in geothermal operations at 230 °C at FORGE (Cariaga, 2023; Norbeck et al., 2023) and 190 °C at Project Red (Norbeck, et al., 2023) is to cement casing in the production interval to provide zonal isolation outside of the casing. At  $T < 200$  °C, ordinary Portland cement is sufficient; however above 300 °C, advanced cements will be needed (Sugama and Pyatina, 2022). Calcium aluminum or phosphate-based cements have been lab-tested up to 400 °C (Sugama and Pyatina, 2022, Sakuma et al., 2021) but not yet field-tested above 350 °C (Petty, 2022).

Even if cements can be developed to withstand superhot temperatures there will be challenges and disadvantages of cemented completions. A disadvantage of cementing may be the flow constriction at the well bore since fluid will only be able to flow into or out of wells past perforations. Another risk is that the cement slurry will invade fractures away from the well, effectively destroying the fracture permeability needed for EGS. A good cement job in conventional geothermal wells is notoriously difficult (Finger and Blankenship, 2012). A bad cement job will not provide zonal isolation, making the risk of a useless well high.

Conventional packers and bridge plugs that use polymer sealing elements will not be suitable in SHR wells. At FORGE, these tools failed at 200 °C (EGI, 2020). Liners and serial all metal external casing packers have been designed for 330 °C and 6000 psi with plans for 10,000 psi and >400 °C (Esquitin and Vasques, 2021). The most cost-effective approach to well isolation may be to develop methods that do not require steel and cement. Open hole stimulations have been performed up to 320 °C (Cladouhos et al., 2015; Cladouhos et al., 2016), although a perforated liner (uncemented) was eventually needed. Other approaches to eliminating liner installation include mineral coating, such as RockPipe (Eavor, 2023a) or vitrification (Houde et al., 2021), installed after or during drilling.

### Gaps

- Development and testing of cements and steel designed to withstand SHR conditions.
- Advanced cements need to be used and evaluated in SHR wells.
- Tested alternative methods to provide zonal isolation behind casing such as mineral coating, or advanced materials to fill annular space.
- Further development and testing of external casing packers for  $T > 400$  °C

### 3.6.2 Zonal Isolation inside casing

In addition to zonal isolation outside of the casing or liner as described above, there must be methods to isolate zones on the inside of the casing to focus flow rate and pressure to a selected treatment zone. In O&G well stimulation, this is provided by plugs and balls or sliding sleeves. In principle, there is no reason that these tools cannot also be used at SHR conditions if all metal tools can be designed.

Other methods to isolate inside the casing include sequential filling of the casing with sand (sanding back) to temporarily block already stimulated zones, or diverters such as TZIM (Cladouhos et al., 2018).

Vendors and service providers often test or certify their own equipment but are unlikely to test at SHR conditions until there is an identifiable market opportunity.

### Gaps

- Testing of all methods and tools at SHR conditions, first in labs (see §3.2) and then in the field.

### 3.6.3 Fracture Initiation

Plug-and-perf hydraulic stimulation has been demonstrated up to 190 °C (374 °F) (Norbeck and Latimer, 2023), however, this is expected to be near the maximum operational temperature for this approach using current off-the-shelf technology. Therefore, a different approach may be needed for SHR, at least until service companies develop tools for SHR and cements are developed for these temperatures (see above).

Using a high-pressure stream of water and abrasive, hydro-jetting can be used to perforate holes into hard formations which will create a weak point in the well for fracture initiation (Bour and

Petty, 2016). This tool is SHR-ready because there are no temperature-vulnerable components and the jetting keeps the tool and well cool.

Other approaches to fracture initiation and growth include thermal shocking, acids (Lucas et al., 2020), chelating agents (Watanabe et al., 2021b), and targeting natural fractures.

#### Gaps

- Due to the importance of scale, it will be difficult to test any fracture initiation methods anywhere but in SHR wells and SHR EGS demonstration projects.

#### 3.6.4 New Fracture Growth

Hydraulic stimulation and tensile fracture growth in rock below 200 °C is a complex but relatively well-understood process. Modern shale wells typically have flowing fracture surface areas at the scale needed for sustainable heat mining (i.e.,  $9 \times 10^6 \text{ m}^2$ ) (McClure, 2021). With successful zonal isolation and fracture initiation as described above, the new fracture growth stage of a hydraulic stimulation relies on the hydraulic pumping power provided by pumps, and proppant to keep the main fractures open after the pressure is removed. Additional permeability enhancement and connectivity may be achievable using lower-pressure hydraulic stimulation (aka, hydroshearing (Cladouhos et al., 2011; Cladouhos et al., 2016)). The goal of all of the above is to maximize fracture length, well spacing, and total surface area of fractures, all of which have a direct impact on power generation and sustainability.

For EGS projects a reservoir length or well spacing goal of 500 m has been commonly adopted. To date, much smaller well spacing has been achieved, such as 120 m (Fercho et al., 2023). Yet this is the most important input to calculate thermal breakthrough times and well-pair sustainability.

#### Gaps

- No one has performed hydraulic stimulations at high or moderate pressures in SHR, thus the geomechanics of rocks near the BDT, thermal cracking, and the effect of the unusual properties of supercritical fluids have not been field tested.
- Maximum fracture length induced by stimulations in SHR EGS represents a critical knowledge gap due to the impact of supercritical fluid, BDT, thermal fracturing, and intragranular fracturing. Results from models and lab testing (see above) may provide useful predictions; however, until field tests in actual SHR wells are performed and documented potential fracture size in SHR EGS reservoirs will remain one of the most important unknowns.

#### 3.6.5 Fluids, Proppants, and fracture transmissivity

Like hydraulic fracturing in O&G, the fluid most likely to be used to create hydraulic fractures in SHR EGS stimulation will be water. The water need not be potable and can be re-used for circulation once the EGS reservoir is created. Additives commonly used in conventional geothermal fields and hydraulic stimulations such as acids, friction reducers, and scale inhibitors will likely be needed. Given the extreme temperatures and depths, the additives will likely not be the same as those in current use. In the first author's experience, the use and composition of any

additives pumped into the subsurface during drilling, stimulation, or long-term injection are disclosed and reviewed by both federal and state regulators.

In some cases, heavy salts such as NaBr and NaCl might be useful to increase the density of the water column and thus the downhole fluid pressure (Hogarth and Holl, 2017) during fracturing.

Alternative fracturing fluids such as compressed, supercritical CO<sub>2</sub> may be effective in the stimulation of very hot rock. Hot wet CO<sub>2</sub> would be very corrosive and could help to dissolve and etch the rock to preserve open fractures without proppants (Petty et al., 2020). However, care would need to be taken as hot wet CO<sub>2</sub> would also be detrimental to any steel casing.

Proppants must be strong, resistant to crushing, and chemically stable at SHR conditions. Quartz sand, sintered bauxite, resin-coatings, and ceramics have been tested up to 320 °C (Jones et al., 2014; Lisabeth and Norbeck, 2020; Ko et al., 2023), but not into SHR conditions. Based on basic mineralogy, it is expected that these proppants will alter at SHR conditions resulting in significantly reduced fracture permeability. However, the right material selection (Ko et al., 2023), and/or adjustment of working fluid composition (Jones et al., 2014) may provide a solution for proppant longevity in fractures. Diverter materials in the slurry, including thermally degradable zonal isolation materials (TZIM), may be useful to prevent leak-off, extend fractures, and facilitate proppant transport and placement (Petty et al., 2022). An alternative to the use of proppants would be to operate at fluid pressures high enough that fractures are hydro-propped, that is the operating injection pressure would be significantly greater than the magnitude of the minimum horizontal stress. The economics of hydro-propping at resource temperatures from 175-350 °C were modeled by Frash et al. (2023a; 2023b). Technically, operating at high pressures is feasible, for example, the Habanero well pair in the Cooper Basin, Australia produced 19 kg/s of 215 °C water with a production wellhead pressure of 32 MPa and an injection well pressure of 43 MPa (Hogarth and Bour, 2015).

Related to proppant and alteration is the initial fracture transmissivity (often called fracture permeability, which is not technically accurate) and its evolutions with time and flow. Very little is known about this topic at SHR conditions so it represents a large gap for both laboratory and field studies.

Lastly, tracers are key tools to characterize pathways between wells. Napthalene sulfonates, a standard conservative tracer used at lower temperatures are thermally unstable above 350 °C (Sajkowski et al., 2021); therefore SHR-durable tracers will need to be developed.

### Gaps

- Research and development of non-toxic additives to prevent scale, reduce friction, and enhance flow rates at SHR conditions.
- Proppant placement and chemical, thermal, and mechanical durability at SHR conditions. A wide range of proppants and fluids should be tested in flow-through reactors developed for SHR testing (also see section 3.2).
- If proppants cannot be developed to withstand the heat, are there other methods (high-density fluid, hydropropping, chemical treatments, or others) to maintain create and maintain permeability?

- Will fracture permeability increase or decrease with time? Factors causing a decrease will include fracture closure, proppant dissolution, and precipitation. Factors causing an increase will include thermal cooling, host rock dissolution, and fluid channeling.
- What tracers can be used at SHR conditions?

### ***3.7 Induced seismicity***

Induced seismicity has been a major concern for EGS for decades (Majer et al., 2007; Cladouhos et al., 2010). The DOE has developed a robust Induced Seismicity Mitigation Protocol (ISMP) for US projects (Majer et al., 2012; Majer et al., 2016), and operators have experience implementing them in EGS projects since the ISMP was developed and tested (Cladouhos et al., 2016; Norbeck and Latimer, 2023). Expertise in minimizing induced seismicity has also been developed in the Rhine Graben projects (Shapiro, 2015; Richard, et al., 2016) where some projects initially caused felt events at Basel (Baisch et al., 2009) and Soultz-sous-Forêts (Dorbath et al., 2009). A notable exception to the progress in preventing induced seismicity occurred in 2017 in Pohang, South Korea, when a Mw 5.4 earthquake was likely caused by injection in a critically stressed fault (Kim et al., 2018). Possibly the most important lesson is that EGS projects in urban areas like Pohang and Basel should be avoided until a method to identify blind, critically stressed faults in advance of well stimulations is developed.

It has been suggested that reservoir creation near the brittle-ductile transition will reduce seismic risk (i.e., Japan Beyond Brittle, Muraoka et al., 2014). However, seismologic observations and numerical models suggest many earthquakes nucleate at depths of 7-10 km in rocks near the BDT (i.e., Chen and Molnar, 1983; Lapusta and Rice, 2003) and others argue that SHR EGS may be prone to enhanced seismicity (Parisio et al., 2019a), so this idea needs further testing.

Fortunately, areas with high temperature gradients (>100 °C/km) where the first SHR projects will be tested, correlate with areas of low seismic risk due to thinner brittle crust and high heat flow. It is documented that the Ridgecrest earthquake swarms of 2020 were suppressed in the Coso geothermal area (Kaven, 2020).

#### Gaps

- Better understanding of the geomechanics in the brittle-ductile transition/ K Horizon. Given that the zone does not transmit S waves as readily will it have an impact on reducing seismic risk?
- Investigating whether induced seismicity due to cold fluid injection migrates downward as modeled by (McClure, 2023b). Can seismic data from geothermal injection programs (i.e., Hartline, Walters and Wright (2019)) be used to test the hypothesis?

### ***3.8 Roadmap to Commercialization. Thermal longevity of wells and variable pricing***

Optimizing EGS reservoir design and operations will require financial considerations. As examples, below we identify two potential changes in the expectations for geothermal projects.

The standard lifespan assumed for geothermal wells is often 20-30 years, consistent with the lifespan of the power purchase agreement (PPA) and power plant (Kennedy et al., 2021; Toews and Holmes, 2021). This follows a work plan for conventional plants in which a well field is drilled out, a power plant built, and the resource team and drillers move on to another development only

to be called back if wells are performing poorly (usually cooling) compared to initial reservoir models. While make-up wells can be built into resource plans, geothermal power plants often operate under capacity due to lack of pro-active planning and ready-capital or lack of extra resource.

An alternative strategy for the lifespan of geothermal wells is 10-15 years (i.e., McClure, 2021). By drilling fewer wells up-front, and operating at thermally “non-sustainable” flow rates, capital costs for drilling can be spread out over the lifetime of the project. One could even imagine a strategy more akin to O&G field development where a well is always being drilled on the site. This would also provide more opportunities for learning-by-doing both for drilling and stimulation (Latimer and Meier, 2017), and reduce mobilization and far-from-drilling support center costs which can currently represent 10-30% of the costs at remote locations.

In the past, geothermal power production has been considered baseload generation. With few exceptions, PPAs have provided flat pricing, thus there has been no incentive for producers to produce more or less than the PPA when asked by the offtaker or utility. If properly designed and paid for, geothermal power plants can provide flexible electricity generation. This is especially true of SHR geothermal power plants because the steam produced can be flexibly throttled or boosted to meet demand. For example, stored heat from solar energy can be used to superheat steam to generate more power at times of high demand and high price (Rosenfeld and Petty, 2023), or surplus electricity can be used to build up subsurface pressure for later use (Ricks, Norbeck and Jenkins, 2021, 2022). In either case, the off-taker and geothermal developer need to work together during project development to maximize project flexibility and provide the right incentives.

These are specific examples of that could be part of the roadmap to SHR geothermal commercialization. More broadly, a roadmap is needed to evaluate the investment in time and money to progress from pilot to commercial power generation.

### Gaps

- Industry demonstration and commercial scale-up roadmaps.
- In addition to low LCOE, investigations of other advantages can SHR EGS provide. For example, baseload/firm power, energy security via local energy resources; power for growth and new industries in developing countries; hydrogen transportation fuels.
- What creative financing and PPA ideas can make all geothermal even more economically attractive?

### ***3.9 Diagnostics and Characterization***

To model, target, and manage an SHR enhanced geothermal system, the native state and final state of the rock volume must be well-characterized. Not only will this result in a higher likelihood of success, but it will also reduce hazard and investment risk and increase public confidence. There are many geothermal, geophysical and well engineering methods for measuring properties and changes in the earth’s crust and geothermal reservoirs. This is a very large subject worthy of another full report, we present some highlights of the state of the art and no gaps.

Microseismic monitoring has been used since Fenton Hill to image EGS reservoirs and fracture systems (Majer and Doe, 1986; Fehler et al., 1991). Since then, a wide variety of microseismic monitoring techniques have been used in geothermal field characterization and EGS projects.

Seismic data is used for well targeting, induced seismicity mitigation plans, determining stress from focal mechanisms, and tomography to measure changes in elastic moduli.

At the Newberry Volcano EGS Demonstration, the microseismic array (MSA) deployed 8 shallow (~250 m deep) BH sensors to reduce surface noise and increase coupling to saturated bedrock and 7 surface sensors to provide focal sphere coverage for moment tensor analysis (Cladouhos et al., 2016). Another approach to surface and near-surface MSAs is a large-N nodal array to stack time data and create coherent signals (Edwards et al., 2021; Zhang et al., 2022).

Downhole geophone arrays often used in O&G hydraulic fracturing jobs, have had limited success in geothermal fields due to the relatively low temperature tolerance of geophones and high shallow temperatures in geothermal fields. At FORGE Utah, a distributed acoustic sensing (DAS) fiber optic (FO) array installed in a 985 m deep monitoring well outperformed borehole geophones for locating microseismic events (Lellouch et al., 2020). An even more effective approach is to install DAS-FO sensing arrays in multiple wells (injectors, producers, and monitoring wells) at reservoir depth (Norbeck and Latimer, 2023). An extra benefit of installation of fiber optics in reservoir or near-reservoir depths is the ability to also perform distributed strain sensing (DSS) (Norbeck and Latimer, 2023; Ward-Baranyay et al., 2023). While distributed acoustic sensing fiber optic arrays have only been used up to 200 °C, AFL has recently developed a 500 °C gold-coated FO cable (AFL, 2023) which could be used in SHR wells in the near future.

Other geophysical methods that may be useful for EGS characterization are INSAR (Mellors et al., 2018), gravity modeling (Bonneville et al., 2017), and magnetotellurics (Pauling et al., 2023). Finally, well testing will be crucial to the characterization of any EGS, including pressure monitoring, pressure transient analysis, circulation testing, tracer testing, etc. (Horne, 1995).

#### **4. Proposed Paths Forward**

The gaps in technology and knowledge for SHR EGS reservoir creation listed in Table 2 and Section 3 are broad and multidisciplinary. Part of the solution to solving the challenges of producing SHR is one of system integration. Many of the pieces may be out there, but scientists, engineers, and service providers around the world may not yet know that they hold knowledge and technology that can transform geothermal energy. Two obvious examples where outreach and education could provide new insights for SHR geothermal are earth scientists and engineers in the O&G industry and academic institutions.

The tools of the shale revolution, horizontal drilling and multistage fracturing, proppants, and microseismic monitoring, are now being applied to geothermal projects at temperatures below 230 °C. Extending those tools and methods to SHR conditions will be one pathway to filling some of the gaps needed for SHR geothermal. However, many innovations needed for SHR geothermal may come from groups not working on hydraulic fracturing; for example, service companies working on steam floods, in situ pyrolysis, and deep-water fields may have the needed.

In academic institutions, examples of experts that have not yet engaged in and have little knowledge of SHR resources include economic geologists, volcanologists, seismologists, and structural geologists. As the section on reservoir analogs shows, geologists and geophysicists have been studying rocks on both sides of the BDT for many years and can bring many insights to the challenges likely to be encountered in SHR development. In the US, more collaboration between

researchers normally funded by NSF (National Science Foundation) and those normally by DOE would yield benefits.

One of the most effective approaches to system integration is public investment in demonstration projects. In countries with strong geothermal industries and government support (Iceland, Italy, New Zealand, and Japan), there is ongoing support for superhot geothermal both at the system integration and targeted funding levels. The latest funding opportunity for EGS pilot projects (which includes funding for a SHR EGS demonstration) from the US DOE (DOE, 2023), summarizes the learnings and objectives of pilot demonstrations as follows:

- “as exemplars, proving reliability and performance ultimately de-risking the technologies,”
- “as experiments from which to learn, because upscaling typically identifies new problems that are not apparent at smaller scales and allows the community to settle on a ‘dominant’ design,” and
- “as opportunities for collaboration, such that best practices can be established, and processes can be standardized and improved.”

In planning and executing demonstration projects, gaps not anticipated during the proposal writing phase will be revealed. It is important that funding agencies recognize that to maximize successes and learnings from demonstration projects, additional secondary funding for data analysis, tools development, and new collaboration will be necessary. For example, a gap discovered during a demonstration project on one continent might be best solved by a collaborator on a different continent.

Public investment will be essential to bring SHR geothermal projects to fruition in a timeframe that could be useful to address issues such as greenhouse gas mitigation and energy security. Bridging the gaps identified in this paper will require significant financial commitments globally to support investigations at academic institutions, national laboratories, and public-private partnerships. Such investment will result in reducing risk for further investment of venture capital. Moreover, early projects will need to occur where the heat is relatively shallow. This will inherently be a global endeavor. Projects in Iceland, Italy and elsewhere funded under the European Union’s Horizon 2020 program provided foundational groundwork in the drilling of supercritical geothermal systems and spurred several drilling projects that resulted in significant learnings and technologies in turn. The Iceland Deep Drilling Project (IDDP) has drilled two superhot wells, IDDP-1 and IDDP-2, and is planning a third. The learnings from this two-decade long project on drilling, well completion, corrosion, etc. have been immense and the extensive published literature will be invaluable for future SHR projects worldwide. The DEEPEN project is an EU-funded project with a global team with the goal to develop a methodology to explore and characterize superhot and supercritical geothermal plays (Kolker et al., 2022). International collaborations like these should be encouraged and continued. For example, an annual international workshop with a narrow focus on SHR geothermal with a broad invite list to include scientists and engineers with expertise across the gaps would serve to facilitate the interdisciplinary and international collaboration needed to develop solutions and fill gaps. Ideally, these workshops would be hosted at potential SHR sites (i.e., in Japan, Iceland, Italy, New Zealand, Oregon, California).

Public funding for geothermal field projects commonly requires public and technical outreach to share results and build support for geothermal. Recent US examples being the FORGE project (<https://utahforge.com/outreach/>), and the latest funding opportunity for EGS pilot projects from the DOE (DOE, 2023). Even privately funded companies are sharing their results publicly and transparently (Eavor, 2023b; Norbeck and Latimer, 2023), a notable change compared to traditional geothermal operators who often treat internal data as proprietary. Many online tools are now available for paper, internal report, and data sharing such as the USDOE's Geothermal Data Repository (<https://gdr.openei.org/>); however, the US focus leaves out the many advances in the EU and Japan (which have their own data sharing sites).

## 5. Conclusion

High enthalpy superhot rock EGS presents a promising path to scale clean, firm, cost-competitive geothermal electricity production worldwide, but significant scientific and development uncertainty surrounds these resources. In this paper, we discussed the technologies needed to create SHR reservoirs and describe critical gaps ripe for public and private funding necessary to break down potential roadblocks.

A key conclusion is that solving the challenges of creating and producing SHR geothermal reservoirs will require international and multidisciplinary collaboration, system integration, and demonstration projects. The scope of the challenge invites partnership, not just between geothermal and oil and gas operators, but also with those that offer broader expertise in deep, higher temperature systems, such as economic geologists and metamorphic petrologists, and engineers and labs that routinely work beyond the critical point of water.

Although superhot rock geothermal will push the limits of many subsurface tools and is beyond the bounds of current hydrothermal and EGS projects, it should be noted that humans safely and routinely operate equipment that contains materials above 375 °C. Coal power plants burn at 550 °C, nuclear power plants at 700 °C, and pizza ovens at 400 °C. That is, we can engineer equipment to access, contain, and extract energy from the global SHR resource - engineers and scientists need the incentive to do so.

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