Supercritical Geothermal Systems - A Review of Past Studies and Ongoing Research Activities

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PROCEEDINGS, 41st Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 13-15, 2017
SGP-TR-212

Supercritical Geothermal Systems - A Review of Past Studies and Ongoing Research Activities

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Keywords: supercritical geothermal systems, brittle-ductile transition, international collaboration

ABSTRACT

Supercritical geothermal systems are very high temperature geothermal systems that are located at depths near or below the brittle-ductile transition zone in the crust where the reservoir fluid is assumed to be in the supercritical state, e.g., for pure water temperature and pressure are respectively in excess of 374°C and 221 bar. These systems have garnered attention in recent years as a possible type of unconventional geothermal resource that could yield much higher well productivities due to their very high enthalpy fluids. Supercritical conditions are often found at the roots of volcanic-hosted hydrothermal systems. Deep wells drilled in geothermal fields such as The Geysers and Salton Sea, USA, Kakkonda, Japan, Larderello, Italy, Krafla, Iceland and Los Humeros, Mexico, have encountered temperatures in excess of 374°C, and in some cases have encountered fluid entries. The IDDP-1 well at Krafla encountered magma, and ended up producing very high enthalpy fluids; however these fluids were very corrosive and abrasive. Innovative drilling and well completion techniques may be needed to deal with the extreme temperatures and aggressive fluid chemistry compositions of these systems. New efforts are underway in Japan (northern Honshu), Italy (Larderello), Iceland (Reykjanes peninsula), Mexico (Los Humeros), and New Zealand (Taupo Volcanic Zone) to investigate supercritical systems. The Japan Beyond Brittle Project (JBBP), the New Zealand Hotter and Deeper Project (HADES), the FP7 project IMAGE as well as the Horizon 2020 projects DEEPEGS, DESCRAMBLE, GeoWell and GEMex, funded by the European Commission, provide an unprecedented opportunity for international collaboration to help solve the technical challenges associated with characterizing, drilling, and developing these high temperature systems. To facilitate interaction, METI Japan organized a meeting with invited representatives from selected G7 countries to discuss international collaboration for supercritical geothermal development as a part of the Innovation for Cool Earth Forum (ICEF) 2016. This paper, which grew out of the ICEF workshop, reviews past studies, describes current research efforts, and outlines the challenges and potential opportunities that these systems provide as geothermal resources.

1. INTRODUCTION

High temperature geothermal systems have been harnessed for electrical power generation for over a hundred years. Most developed geothermal systems have temperatures on the order of 150-300°C. Higher temperature geothermal systems (T > 250°C) are almost always associated with active volcanic centers, with elevated temperature gradients resulting from high heat flow caused by shallow intrusions of magma. Igneous-related geothermal systems represent a significant potential energy resource; identified magmatic systems in the United States are thought to contain much more thermal energy than all known hydrothermal systems in the same region (Smith and Shaw, 1975; 1979; Tester et al., 2006). Because of the technical challenges associated with drilling deeper into the higher temperature roots of hydrothermal systems, there are very few wells that have encountered supercritical (T > 374°C, P > 221 bar for pure water) conditions.

The transition to supercritical conditions occurs near the brittle-ductile transition zone, where magmatically dominated fluids are found in the lower, hotter plastic rock, and hydrothermal fluids circulate through the overlying cooler brittle rock (Fournier, 1999). One key aspect of this environment is that quartz develops retrograde solubility – this might result in sealing of any fractures that would be generated (Fournier, 1991; Tsuchiya and Hirano, 2007; Saishu et al., 2014). However, laboratory experiments on fractured granite (Watanabe et al., 2017) suggest that there is not a step-function decrease in permeability associated with the brittle-ductile transition, and that potentially exploitable resources may occur in nominally ductile granitic crust at temperatures of 375-460°C and depths of 2-6 km. Recent studies have demonstrated that wells that tap supercritical fluids could have much higher well productivities due to the high enthalpies of such fluids, which could make such wells economically attractive (e.g., Fridleifsson et al., 2007). These fluids also have high rates of mass transport because of their much higher ratios of buoyancy forces relative to viscous forces in the supercritical state (Elders et al., 2014a). Exploiting these higher temperature roots of existing geothermal systems could result in increased productivity and sustainability for these fields. In addition to a number of deep hot wells that have been drilled in existing geothermal fields, more recently there have been several initiatives that have focused on identifying the potential opportunities and challenges associated with these extreme conditions. The overall objective of these studies is to demonstrate the viability of these supercritical resources for power generation. The following sections review some of the physiochemical features associated with supercritical geothermal systems, a description of the previous drilling results for wells that encountered supercritical conditions in existing geothermal field, review the current research initiatives associated with these resources, and discuss some potential opportunities for international collaboration in this field.

2. INITIAL EXPERIENCE WITH SUPERCRITICAL SYSTEMS

The earliest encounters with supercritical geothermal systems were associated with deep drilling in the roots of existing volcanically hosted conventional geothermal systems and in Enhanced Geothermal Systems (EGS) projects. Exploratory as well as production wells have been drilled into, in some cases unexpectedly, conditions either exceeding the critical temperature alone or critical temperature and pressure conditions for water. Some of the wells were dry, encountering very low permeability conditions. All wells experienced serious issues with regards to the rock-physical properties as well as physical and chemical fluid conditions, leading to problems related to drilling, completion and fluid handling. Below are brief summaries of some of these drilling efforts; there may be additional high temperature wells associated with other geothermal systems that are not described here.

2.1 Drilling of Supercritical Systems in Italy

Bertini et al. (1980) report about the drilling venture of well Sasso 22 within the Larderello geothermal field down to 4092 m. It was planned as an exploration well to investigate potential reservoir formations underlying the productive horizons at that time. Almost the entire well was drilled with total circulation loss in very hard and inhomogeneous formations. Due to elevated temperatures, severe drilling problems like tool deviation, drill pipe corrosion, breakage, fishing and side tracking arose below 3000 m. The authors attributed the breakage to elevated temperatures and the corrosive environmental conditions. Core samples and logs could be retrieved from that well. It was found that the formations down to the bottom of the well are highly fractured. Measured temperatures reached up to 380°C in 3970 m depth. Due to an unsuccessful primary cement job of the 9 5/8" production casing and successive squeeze jobs that were not successful in stabilizing the casing, the casing was heavily damaged after many string maneuvers and shocks in an empty space down to 2200 m. The well, therefore, had to be abandoned soon after drilling finished (Baron and Ungemach, 1981). A second well, San Pompeo 2, targeted the same reservoir interval as Sasso 22 (Batini et al., 1983). Again, drilling problems led to side tracking the well. In 2930 m a fractured horizon was found and the well violently blew out. This led to formation cave-in, blockage of the drill string and accumulation of debris in the well. During subsequent cleaning operations, the well blew out again and could not be controlled, leading to it being abandoned. Downhole, a temperature and pressure up to 394°C and 212 bar was measured at 2560 m depth. Extrapolated to the depth of 2930 m, the reservoir conditions were estimated to be >400°C and >240 bar (Batini et al., 1983).

At San Vito (Mofete geothermal field), a well was completed after two side tracks had to be drilled. The well was drilled down to 3045 m at 6". Temperature measurements with a zinc melting tablet indicated a temperature in excess of 419°C at the well bottom following a one week shut-in period at the end of drilling (Baron and Ungemach, 1981). Close to San Vito, high temperature wells exhibited modest permeability (Buonasorte et al., 1995).

2.2 Drilling of Supercritical Systems in Iceland

A 2265 m deep well (NJ-11) drilled at the Nesjavellir geothermal field on the NE flank of the Hengill volcano in 1988 unexpectedly encountered temperatures > 380°C with very high fluid pressures and inflow rates (Steingrimsson et al., 1990; Fournier, 1991). Because of the threat of a blowout due to these conditions due to experiencing greater than hydrostatic pressures, the lower portion of the well was plugged with a gravel plug. However, this well led to the concept of deliberately seeking out supercritical temperatures as part of the Deep Vision initiative in Iceland in 2000, which transformed into the Icelandic Deep Drilling Project (Fridleifsson and Elders, 2005; Fridleifsson et al., 2007).

The primary objective of the Icelandic Deep Drilling Project was to conduct deep drilling at selected sites with very high thermal gradients in Iceland to validate the concept that supercritical fluids with temperatures ranging from 450-600°C could be encountered and produced from depths of 3.5-5 km and be used for commercial power generation (Fridleifsson and Elders, 2005; Fridleifsson et al., 2007; Elders and Friðleifsson, 2010; Friðleifsson et al., 2014). Observed seismic activity at these depths indicated that brittle failure occurs in this region, suggesting that there are permeable zones even at these elevated temperatures. The initial attempt was made to deepen an exploratory well on the Reykjanes peninsula (RN-17) – however, the 3.1 km deep well suffered a wellbore collapse during flow testing, so this well could not be deepened. The next effort shifted to the Krafla geothermal field, where the IDDP-1 well was spudded in 2008. The drilling plan was to drill this well to a depth of 4.5 km – however, rhyolitic magma was encountered at a depth of 2104 m, and the well was completed just above this point at 2072 m (Elders and Friðleifsson, 2010; Elders et al., 2014a, c). Subsequent flow testing resulted in production of superheated steam with flow rates of 10-12 kg/s, wellhead temperatures reaching up to 450°C, fluid enthalpies of 3200 kJ/kg, and wellhead pressures of up to 140 bar (Friðleifsson et al., 2014). The well and its associated surface equipment experienced corrosion resulting from acid gases (HCl, HF, and H_2S) along with silica scaling and erosion; well head valve failure ultimately led to this well being shut in (Einarsson et al., 2015). Hauksson et al. (2014) conducted field and laboratory tests that demonstrate that a variety of scrubbing techniques could be employed to mitigate the effects of the produced fluids. Continuing efforts for this project are described Section 3.1.1.

2.3 Drilling of Supercritical Systems in Japan

A deep scientific exploration well was drilled in 1994-1995 at the Kakkonda geothermal field in Japan as part of the Deep Geothermal Resources Survey, led by NEDO (Muraoka et al., 1998). This well, WD-1a, was drilled to a depth of 3729 m, and penetrated through the upper hydrothermal system into a high temperature granitic pluton with a conductive temperature gradient and a bottom-hole temperature of 500°C. An inflection in the temperature profile of the well at ~ 380°C appears to indicate the brittle-ductile boundary for this system – no permeable fluid entries were observed below this transition, and a lower fracture density was observed in the conductive portion of the well (Kato et al., 1998). While this well did not produce supercritical fluids, it demonstrated the feasibility of drilling at these elevated temperatures using borehole cooling techniques, and confirmed that the pluton underlying the Kakkonda geothermal field was the heat source for the hydrothermal system and had even higher temperatures. This study led to research on the possible utilization of such resources for geothermal power generation (e.g., Hashida et al., 2000).

2.4 Drilling of Supercritical Systems in the US

Elevated temperatures have also been encountered in a number of geothermal systems in the United States (e.g., Elders et al., 2015). Several high temperature wells have been drilled at The Geysers geothermal field and its environs. The Wilson No. 1 well was drilled in 1981 outside of the main field on the flanks of Mount Hanna to a depth of 3672 m (Fournier, 1991; DOGGR online well records). While the maximum measured (unequilibrated) temperature for this well is 325°C, fluid inclusions recovered in cuttings suggest bottom hole temperatures of up to 400°C. The well encountered a high-pressure zone near the bottom of the well, and a steam entry was observed at total depth. Casing collapse led to the abandonment of the well. The highest temperatures that have been encountered to date at The Geysers were measured in a well that was deepened in 2010 as part of a US DOE-funded EGS field demonstration project in the NW Geysers in the high temperature reservoir. A steam entry was encountered in the deepened Prati-32 well at 3352 m with a measured temperature of 400°C. Drilling difficulties caused by elevated temperatures (the well was drilled with air) led to very low penetration rates (3 m/h) and extreme bit wear (the last bit only lasted 30 m), thus the well was completed at a depth of 3396 m. This well was used as the injection well for the EGS production-injection well pair for this project (Garcia et al., 2016).

A temperature of 390°C was reported for the IID-14 well in the Salton Sea geothermal field (Kaspereit et al., 2016; DOGGR online well records). This well is located on Red Hill, one of the very young rhyolite domes associated with this geothermal system. This exploration well was drilled in 1990 to a depth of 2073 m, and was plugged and abandoned due to the elevated pressures that were encountered at depth. Although high, this temperature does not represent supercritical conditions; given that the Salton Sea fluids have extremely elevated salinities of 20-30%, supercritical temperatures would need to exceed 550°C (Driesner and Heinrich, 2007). Several investigators have suggested that the Salton Sea geothermal field constitutes an ideal target for accessing supercritical geothermal fluids at reasonable (< 4 km) depths because of the very high thermal gradient resulting from this area representing a continental rift zone that transitions into a strike-slip plate boundary (Shnell et al., 2015; 2016).

Very high temperatures were also encountered in a well drilled in the Puna geothermal field in Hawaii. The well KS-13, drilled as an injector in 2005, intersected dacitic magma at a depth of 2488 m shortly after encountering a diorite intrusion (Teplow et al., 2009). While the temperature of the melt was not measured directly downhole because drilling problems resulted in a section of drill string being stuck and the well being completed at a depth of 2124 m, petrological study of the dacitic glass that was recovered suggests that it had a temperature of ~ 1050°C.

2.5 Drilling of Supercritical Systems in Mexico

Within the Los Humeros geothermal field in Mexico, at least seven deep (> 2100 m) wells have estimated stabilized temperatures greater than >380°C (García-Gutiérrez et al., 2002; Espinosa-Paredes and Garcia-Gutierrez, 2003; Elders et al., 2014b). Two of the wells (H-26 and H-12) appear to have encountered young intrusions at depth. Most of the wells with elevated estimated stabilized temperatures appear to lie above the boiling point-depth curve (Garcia-Gutierrez, 2009). Most of the deep reservoir rocks at Los Humeros have relatively low permeability, making them potential targets for EGS. The supercritical portion of this field will be studied as part of the recently initiated GEMex project (see below).

3. RECENT AND CURRENT RESEARCH EFFORTS

Prior, during and after drilling into supercritical conditions, a number of serious issues were encountered while trying to successfully handle and utilize fluids from geothermal reservoirs at temperature and pressure conditions exceeding supercritical conditions of water. It was concluded that different aspects of the geothermal development chain have to be addressed and a need for in-depth investigations was formulated:

1. Exploration methods for better resource assessment
2. Laboratory experiments for investigate in-situ fluid as well as in-situ rock physical properties
3. Adapted drilling and completion technologies
4. Logging and monitoring instruments and strategies
5. Numerical simulation tools capable of handling supercritical conditions
6. Field laboratories to gain more knowledge about downhole conditions and test technological approaches along the entire development chain

Complementary investigations are currently being carried out in the framework of recent or upcoming drilling campaigns in field laboratories with supercritical conditions in Japan, New Zealand, Mexico and Europe. Work being done in collaborative projects in Europe is being framed with initiatives in individual member states. European research activities are listed in Reinsch et al. (2016) as well as on www.geothermalresearch.eu. Below are short summaries of recent and current activities relating to field experiments, numerical simulation methods, and high temperature instrumentation related to supercritical geothermal systems.

3.1 Field Laboratories

There are a number of recent and ongoing field studies related to supercritical geothermal systems. These include the Iceland Deep Drilling Project (IDDP), the Japan Beyond Brittle Project, the DESCRAMBLE project at Larderello, Italy, the Hotter and Deeper (HADES) project in the Taupo Volcanic Zone of New Zealand and the GEMex joint EU-Mexico project, in Mexico. Below are brief descriptions and results to date of each of these projects.

3.1.1 Iceland Deep Drilling Project

The current phase of the Iceland Deep Drilling Project (IDDP-2) involves deepening of the RN-15 well in the Reykjanes geothermal field from its original depth of 2507 m to a depth of ~5 km (Figure 1). The well was completed on Jan. 25, 2017 at a depth of 4659 m, where an unequilibrated bottomhole temperature of 427°C was recorded together with a fluid pressure of 340 bars (www.iddp.is); several permeable zones below 3000 m were also encountered. Future plans for this well include petrographic analysis of retrieved core and cuttings samples to characterize the lithology and alteration of the well, running (as conditions permit) a comprehensive suite of downhole well logs, injecting cold water into the completed well to stimulate fracture permeability, and flow testing the well. The IDDP consortium is organized and funded by an Icelandic energy consortium (HS Orka, Landsvirkjun, Orkuveita Reykjavíkur, and Orkustofnun (the National Energy Authority)) with additional support from Alcoa (2007-2013) and Statoil (2007-2011). In 2015, Statoil renewed its commitment until 2020. In December 2015, the IDDP-2 became part of the European Union supported project **DEEPEGS** (Deployment of Deep Enhanced Geothermal Systems for Sustainable Energy Business). The ultimate objective of the DEEPEGS project in Iceland is to deliver steam for electrical power generation (Fridleifsson et al., 2016). The International Continental Scientific Drilling Program (ICDP) US National Science Foundation (NSF) have also provided additional funding for this project.

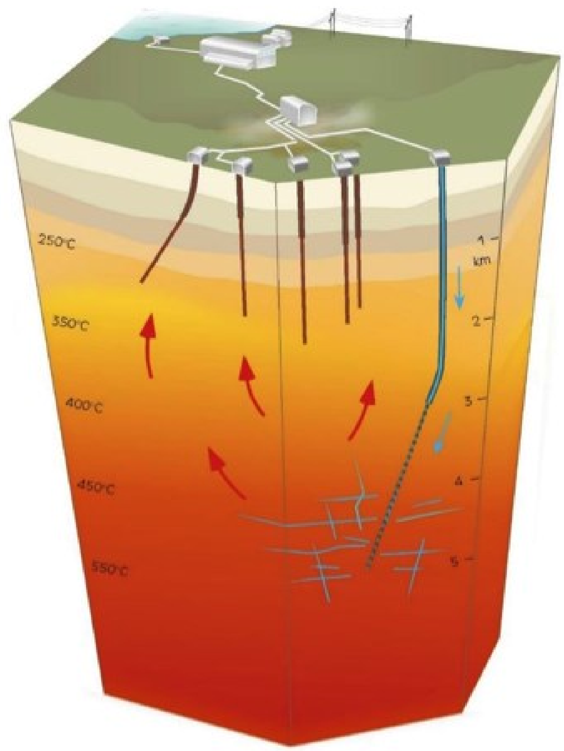

Figure 1: A conceptual model showing the EGS system in the Reykjanes field (Friedleifsson et al., 2016)

3.1.2 Japan Beyond Brittle Project

The Japan Beyond Brittle Project was initiated to investigate the feasibility of creating enhanced geothermal systems in the brittle-ductile transition zone (Muraoka et al., 2014; Asanuma et al., 2012; 2015, Figure 2). This study grew out of the initial deep drilling work that was conducted at Kakkonda. Several expected advantages of such a system include a very large potential geothermal energy resource that could result in economic energy extraction, simpler reservoir design and control of the reservoir, reduced parasitic fluid losses, and reduced induced seismicity effects. The Tohoku area of northern Honshu in Japan has been identified as a promising target for this effort, as data from geophysical surveys in this region have identified velocity and conductivity anomalies underlying Miocene and younger calderas in this region, suggesting the presence of shallow magma chambers that would provide a widespread source of heat (Figure 2). Evaluation of an uplifted young granite-porphyry system in this region (Tsuchiya et al., 2016) revealed several episodes of natural hydrothermal fracturing to form different groups of veinlets (quartz veins, hydrothermal breccia veins and glassy veins) in the rock mass under supercritical and subcritical conditions. Studies of other young uplifted and exhumed plutons in Japan (e.g., Bando et al., 2003) support the idea that supercritical conditions of 400-500°C can be found at depths of 3-5 km in association with cooling and fractured young magmatic intrusions. Current work is focused on identifying a field site where a deep well will be drilled into such a supercritical system.

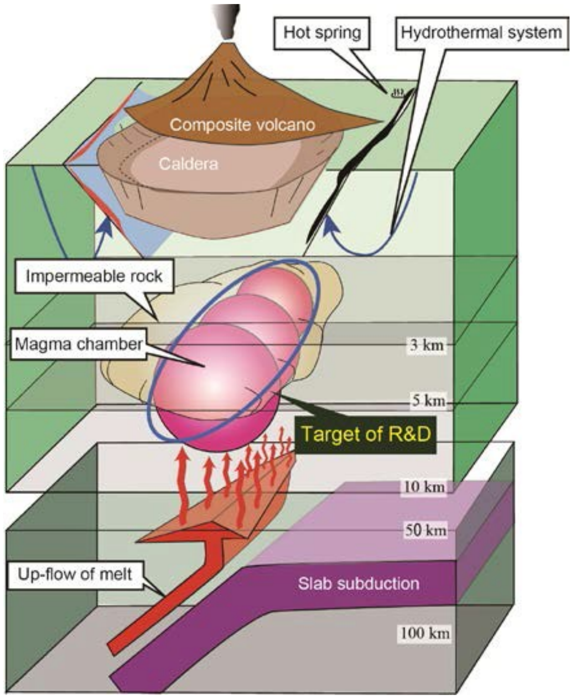

Figure 2: Conceptual model for supercritical geothermal systems in northern Honshu, Japan (Asanuma et al., 2015). These systems lie above shallow magma chambers that are associated with Miocene and younger caldera complexes in the Tohoku region.

3.1.3 Italy DESCRAMBLE Project

One of the objectives of the DESCRAMBLE project is to deepen the existing Venelle-2 well in the Larderello geothermal field in Italy from its current depth of 2.2 km to a depth of 3 to 3.5 km in 2017. The goal of this project is characterize and test the deep high temperature resource (which is expected to have a temperature of ~ 450°C and a pressure of ~ 250 bar) – if the initial phase is successful, a pilot plant would be developed. The expectation is that productivities of up to ten times those found in standard geothermal wells can be obtained from supercritical resources due to the presence of much higher enthalpy fluids. The main research objectives of DESCRAMBLE are to improve drilling methods and to develop better ways to physically and chemically characterize deep crustal fluids and rocks (Fridleifsson et al., 2016).

3.1.4 New Zealand Hotter and Deeper Project

Research efforts in New Zealand have included study of the deep (5-7 km) geothermal resource potential for the Taupo Volcanic Zone (Figure 3), which is estimated to have temperatures > 400°C and a potential of 10 GWe (Bignall, 2010; Bignall and Carey, 2011). A team of investigators is conducting a comprehensive regional geophysical characterization of the Taupo Volcanic Zone to examine the links between the shallow hydrothermal systems and the deeper magmatic heat source. Newman et al. (2015) and Bertrand et al. (2015) used 3D MT modeling to provide evidence of deep-seated electrically conductive plumes down to 10 km depth that were interpreted to represent magmatic intrusions underlying hydrothermal systems. Bannister et al. (2015) conducted a passive-seismic broadband survey of the region to elucidate changes in crustal velocity structure between 3 and 8 km depth. One of the goals of these surveys is to develop an integrated image of the brittle-ductile transition zone and identify potential deep drilling targets.

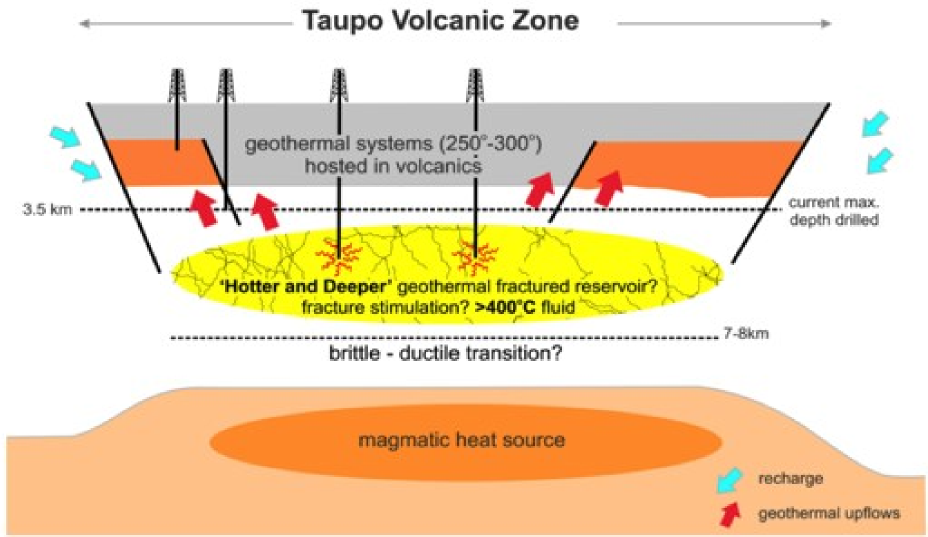

Figure 3: Conceptual model for the HADES project (from Bignall and Carey, 2011, after Heise et al., 2007)

3.1.5 Mexico GEMex Project

GEMex, the first joint geothermal research project launched by Europe under the framework of Horizon 2020 and Mexico in 2016, aims to assess the resources of two unconventional geothermal sites in Mexico: EGS development at Acoculco, and a super-hot resource in Los Humeros. This project will use innovative techniques and approaches of reservoir characterization, numerical modeling, and laboratory experiments, in order to make this renewable energy source cost-effective and affordable both for electricity and heat production. The project will adhere to the strictest environmental standards and address issues around social acceptance of the technology. In a second stage, drilling into the explored reservoir is anticipated.

3.2 Numerical Simulation Studies

There has been extensive work conducted by a number of researchers on the topic of numerical simulations of supercritical geothermal systems. Fournier (1999) developed a comprehensive conceptual model of the link between magmatic and hydrothermal systems, noting that there are sharp thermal and fluid pressure gradients across the brittle-ductile transition at around the supercritical temperature. According to this model, there are episodic breaches of this higher temperature plastic zone that result in discharge of fluid into the overlying brittle domain, leading to faulting, brecciation, and hydrothermal alteration and vein mineralization. Early work focused on developing simulators that could handle temperatures ranging from those found in hydrothermal systems up to the elevated temperatures of magmatic systems (e.g., Hayba and Ingebritsen, 1994). Ingebritsen et al. (2010) provide an overview of numerical modeling of magmatic hydrothermal systems, looking at the transfer of heat and metals from magma bodies into the overlying crust through fluid-rock interaction. Yano and Ishido (1998) utilized the STAR general-purpose geothermal reservoir simulator incorporating the HOTH2O equation-of-state package to model flow from a well from a supercritical reservoir, and noted that complex behavior might be expected due to the nonlinear changes in compressibility and fluid viscosity. Norton and Dutrow (2001) concurred with this observation, suggesting that magma–hydrothermal processes should be thought of as complex dynamical systems whose behavior near the supercritical region is likely chaotic; this is also consistent with the observations of Fournier (1991), who suggested that zones of increased permeability might be episodic features associated with elevated strain rates. Watanabe et al. (2000) identified that the high heat capacity of supercritical fluids allows for more effective heat mining from high temperature rocks.

More recent work has focused on regions with supercritical conditions, which pose challenges for many conventional reservoir model simulators due to the rapid changes in the physical properties of water. Croucher and O'Sullivan (2008) updated the thermodynamic formulation used in TOUGH2 from IFC-67 to the more recent IAPWS-97 formulation to allow this code to handle supercritical conditions. O'Sullivan et al. (2015; 2016) have made further refinements to the AUTOUGH2 code. Magnusdottir and Finsterle (2015) developed a new equation-of-state module (EOS1sc) following the approach of Croucher and O'Sullivan to extend the applicability of iTOUGH2 to temperatures and pressures above 800°C and 100 MPa, while obtaining better accuracy and higher computational speeds. Gunnarsson and Aradottir (2015) have developed a simple conceptual model that uses shallow dike intrusions as the heat source for volcanic-hosted geothermal systems. Weis and Driesner (2013) postulate the presence of a hydraulic divide between the non-static permeability within a supercritical reservoir in contrast to more steady-state fluid flow within the overlying hydrothermal system from their numerical simulations of magmatic hydrothermal systems, and noted many similarities between supercritical geothermal systems and porphyry copper systems. Driesner et al. (2015) developed a new modular numerical simulator platform, known as Complex Systems Modeling Platform (CSMP++), to simulate geological processes such as fluid flow and heat transfer while also capturing geo-mechanical and geochemical processes. Scott et al. (2015a, b) have applied this modeling approach to evaluate processes in the supercritical zone in the IDDP-1 well near a magmatic intrusion. Scott et al. (2016) have modeled the temporal evolution of high-enthalpy geothermal systems associated with shallow level intrusions, and observed that host rock permeability and composition, intrusion depth, intrusion geometry, and strain rate all play important roles in the thermal structure of the resulting high-temperature geothermal system. Scott et al. (2017) noted that for saline hydrothermal systems, the depth of magmatic intrusions powering geothermal systems impacts the efficiency of heat transfer. In their models for intrusions > 4 km deep, heat transfer is maximized by phase separation occurring via condensation, whereas less efficient heat transfer occurs via boiling in shallower (< 2.5 km) systems.

In addition to coupled process modeling, additional work has focused on developing improved geophysical models that capture the changing physical properties associated with the brittle-ductile transition zone. Carcione and Poletto (2013) proposed an elastic-plastic rheology to model the brittle-ductile transition (BDT) based on the Burgers mechanical model including the effects of anisotropy and seismic attenuation and temperature by the Arrhenius equation. Carcione et al. (2014) presented an algorithm to simulate full seismic wave propagation in heterogeneous media in the presence of the BDT, based on the Burgers mechanical model and the Arrhenius equation to take into account the viscoelastic behavior and the temperature dependence and rock melting conditions. Carcione et al. (2016) extended the theory to include poro-viscoelastic media by explicitly modeling the effects of fluids under supercritical conditions. Farina et al. (2016) applied this algorithm to simulate full-waveforms, demonstrating that discontinuities associated with the transition to supercritical conditions and the presence of magmas can be seismically observable. These studies and tools can be used for seismic characterization purposes in conjunction with passive seismic, exploration seismic and seismic while drilling (Poletto et al., 2011a; 2011b) in extreme geothermal and BDT areas.

3.3 High Temperature Instrumentation and Method Development

One critical challenge confronting the commercial utilization of supercritical geothermal systems is the need for drilling systems, well completions, power plants, and logging tools and characterization methods that can withstand the high temperatures and aggressive fluids associated with such systems. The **HiTI** project focused on developing high temperature tools and methods for characterizing and exploiting supercritical geothermal systems (Sanjuan et al., 2010; Ásmundsson et al., 2014). This work focused on the development and testing of a high temperature DTS cable and a wireline temperature tool, the MultiSensor memory tool that records temperature, pressure, fluid flow and casing collar locations, high temperature borehole televiewer and resistivity logging tools, and new Na/Li geothermometeric relationships (Sanjuan et al., 2010; 2014), and high temperature tracers (Gadalia et al., 2010; Juliusson et al., 2015). The **DESCRAMBLE** project has resulted in the development of a slick-line temperature and pressure logging tool by SINTEF that can withstand downhole conditions of 450°C and 450 bars for up to 8 hours. The **IMAGE** (**I**ntegrated **M**ethods for **A**dvanced **G**eothermal **E**xploration) initiative has led to the development of new seismic and electromagnetic investigation methods for characterizing supercritical systems – these methods have been employed at the IDDP sites in Iceland. One of these approaches involves adapting the seismic-while-drilling method to geothermal systems (Poletto et al., 2011a, b). The objective of the **GeoWell** project is to develop reliable, cost effective and environmentally safe well completion and monitoring technologies to accelerate the development of geothermal resources for power generation in Europe and worldwide. These technologies were deployed on traditional production wells as well as deeper wells where the pressure may be as high as 150 bars and temperature can exceed 400°C. They include all aspects of the well completion process, such as optimization of cementing and sealing procedures, selection of materials and coupling of casings, temperature and strain measurements in wells using fiber optic technologies to monitor well integrity, and development of risk assessment methods.

4. FUTURE OPPORTUNITIES

To promote the successful development of supercritical geothermal systems, our discussions at the ICEF workshop identified three main areas of future international collaboration. These consist of the following topics: 1) data sharing; 2) coupled process modeling; and 3) underground field laboratories. We also noted a great deal of overlapping interests in other areas of research relating to supercritical systems that could lead to fruitful collaboration between different research teams.

4.1 Data Sharing

The US DOE Geothermal Technologies Office (GTO) now requires that data created by all funded projects be uploaded to the Geothermal Data Repository (GDR), a node of the National Geothermal Data System (NGDS) (Allison et al., 2013; Weers and Anderson, 2015; 2016). As part of the NGDS initiative, large amounts of existing data and reports were also catalogued and uploaded into this system. This system also includes a number of data visualization and query tools, such as Geothermal Prospector (Getman et al., 2015). These data and tools are freely accessible to any interested party. These databases and tools on geothermal systems can all be accessed via the geothermal energy page of the OpenEI website (http://en.openei.org/wiki/Gateway:Geothermal), a wiki page that allows interested parties to contribute information to this collection of geothermal data. This database includes all data generated by the DOE GTO EGS field projects.

One of the activities of the Integrated Methods for Advanced Geothermal Exploration (IMAGE) project has been the development of an international petrophysical property database (P^3) that could provide inputs for geothermal numerical models. This open access repository contains peer-reviewed hydraulic, thermo-physical and mechanical property data along with electrical resistivity and magnetic susceptibility data for rocks of geothermal interest (Bär et al., 2017).

Data sharing for supercritical systems could be expanded to drilling experiences in accessing these elevated temperatures, as well as subsurface characterization and sampling of these regions. Sharing of lessons learned from past projects could help improve the success of future activities.

4.2 Coupled Process Modeling

There are numerous research groups in the geothermal community that have developed numerical simulators for use in coupled process modeling of geothermal systems. As mentioned in an earlier section, there are specific challenges associated with modeling supercritical systems. One mechanism for facilitating the testing and validation of these codes is to develop a collaborative network to assist with developing benchmarking tests and code comparison efforts. The US DOE GTO has been conducting a geothermal code comparison study to develop test problems that would evaluate the ability of numerical simulators to accurately model coupled thermal, hydrologic, mechanical, and chemical (THMC) processes associated with enhanced geothermal systems (e.g., White and Phillips, 2015; Fu et al., 2016). These efforts are focused on developing a reliable set of modeling tools for use at the proposed US DOE Frontier Observatory for Research in Geothermal Energy (FORGE).

Similar efforts could be conducted on an international scale. Coupled THMC process modeling has been done for a number of benchmarking problems defined by the DEvelopment of COupled models and their VALidation against Experiments (DECOVALEX) project. This international collaboration (www.decovalex.org), initiated in 1992, is focused on advancing the understanding and mathematical modeling of coupled thermo-hydro-mechanical (THM) and thermo-hydro-chemical (THC) processes in geological systems related to radioactive waste disposal, as exemplified by a study of the effects of thermal, chemical, and mechanical processes on the permeability of fractured rocks (e.g., Rutqvist, 2015). The geothermal community could emulate this type of international collaboration to advance the use of numerical simulations in supercritical systems.

More recently, the development of robust simulators for enhanced geothermal systems focused on quantifying processes within the reservoir including fault systems, induced fractures and well paths. This relied on coupling existing geomodeling tools to various simulators via open-source meshing software, e.g., MeshIt (Cacace and Blöcher, 2015). The goal was to extend the predictive capabilities of existing TH-coupled simulation (Watanabe et al., 2016; Jacquey and Cacace, 2016) on the lifetime performance of a reservoir (Blöcher et al., 2010) by including additional mechanical and chemical feedback effects.

4.3 Underground Field Laboratories

Most valuable for the successful development of high temperature geothermal systems is learning from past field activities; these lessons learned provide invaluable insights that can be applied to new experiments at supercritical field sites. As a key instrument, the authors propose joint workshops on the ongoing as well as planned high temperature underground field laboratories as listed in Section 3. In addition, a number of underground field laboratories at low enthalpy sites are being utilized by the geothermal research community to improve reservoir characterization, stimulation, and monitoring techniques for Enhanced Geothermal Systems. While these facilities do not replicate the temperature and pressure conditions associated with supercritical systems, they do permit initial testing of new technologies and approaches that could be utilized for supercritical geothermal systems, and provide the opportunity for international collaboration.

The **Grimsel Test Site** in Switzerland is being used by the Swiss Competence Centre for Energy Research - Supply of Electricity (SCCER-SoE) for a suite of in-situ hydraulic stimulation, thermal circulation, and tracer experiments (Jalali et al., 2016; Jung et al., 2016; Vogler et al., 2017). The **Sanford Underground Research Facility** (SURF) in Lead, South Dakota, USA, has been used for hydraulic fracturing experiments in crystalline rock to characterize the stress field, understand the effects of rock fabric on fracturing, and gain experience in monitoring using a variety of geophysical methods (Oldenburg et al., 2016), and is the selected site for a new suite of EGS field experiments (the DOE Collab initiative). A geothermal research well doublet is located in **Groß Schönebeck** (north of Berlin, Germany). This site is equipped with a thermal fluid loop including an electrical submersible pump as well as a research power plant, and is being used to investigate EGS technologies for deep sedimentary basins (e.g. Blöcher et al., 2016). The **Äspö Hard Rock Laboratory** in Sweden has hosted a series of multi-stage hydraulic fracturing experiments in boreholes drilled in granodiorite to evaluate how differences in fluid injection (continuous, progressive, and pulse pressurization) affect the amount and intensity of induced seismicity and changes in fracture permeability (Zang et al., 2017). The US Department of Energy's Geothermal Technology Office has created the **Frontier Observatory for Research in Geothermal Energy** (FORGE) to develop and test the next generation technologies needed to characterize, access, create, and sustain EGS reservoirs. Two sites are currently under study – the Fallon site in Nevada (Siler et al., 2016; Blankenship et al., 2017) and the Milford site in Utah (Gwynn et al., 2016), with final site selection expected in 2018.

4.4 Other Areas of Collaboration

In addition to the topics listed in 4.1-4.3 it is important to note that research activities along the entire geothermal value chain, as identified in Section 3, are underway in all regions worldwide where people try to utilize supercritical geothermal systems. As part of our team's discussions at the ICEF workshop, we identified a number of research areas related to supercritical geothermal systems where our groups had overlapping interests. Although not all topics are being investigated in participating member countries, the general focus of research targets the same scientific questions. It is important to note that while the participants at the ICEF workshop were restricted to G7 countries, we envision that current and future research efforts related to supercritical geothermal systems will involve researchers from many other countries, most notably (based on the experimental field sites) Iceland, New Zealand, and Mexico. Here are some of the areas of ongoing research that could benefit from international collaboration:

1. Exploration methods for better resource assessment
    - Geophysical exploration methods
    - Field stress measurements
    - High temperature geothermometers
    - High temperature tracer tests
2. EGS reservoir characterization and stimulation
    - High temperature logging and downhole monitoring tools, including optical methods
    - Microseismic monitoring methods
    - Soft stimulation methods

3. High temperature drilling and completion methods
    - Improved drilling methods for high temperature systems
    - Improved well completion methods for high temperature systems
4. Surface systems
    - Scrubbing and fluid handling strategies for dealing with supercritical fluids and corrosive gases
    - Optimized designs for surface fluid handling, power conversion, and cooling systems for supercritical fluids
5. Modeling and laboratory characterization of supercritical systems
    - THMC modeling of supercritical systems
    - Geologic and geophysical modeling of brittle-ductile transition zone
    - Calibration of models using laboratory measurements of rock and fluid properties
6. Enabling international collaboration
    - Data sharing
    - Lessons learned from field experiments
    - Workshops
    - Exchange opportunities for students, postdocs, and researchers

Collaboration in the mentioned fields of research might be facilitated by hosting joint workshops or benchmarking individual methods or technologies that could be tested in joint field campaigns. The principal objective of this paper is to encourage additional international collaboration that will help advance our knowledge of supercritical geothermal systems.

ACKNOWLEDGMENTS

We thank METI, AIST and NEDO for organizing the workshop on international joint R&D on high temperature geothermal development at the Innovation for Cool Earth Forum 2016 that led to this manuscript. P. Dobson was supported by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (EERE), Geothermal Technologies Office (GTO) under Contract No. DEAC02-05CH11231 with Lawrence Berkeley National Laboratory. Many thanks to Jeff Hulen and Dennis Kaspereit for sharing their knowledge of the IID-14 well at the Salton Sea geothermal field. Thanks also to Jeff Winick, Wilfred Elders, Jim Shnell, and Will Osborn for their constructive reviews of this paper. Many thanks to Ruggero Bertani for his contribution to the Italian presentation at ICEF with an introduction to DESCRAMBLE. The collaboration with Japan is supported by the European Energy Research Alliance (EERA) joint program geothermal energy (JPGE) and also by the Helmholtz program Geothermal Energy System. The IMAGE project (GA No. 608553) has received funding from the European Union's Seventh Programme for research, technological development and demonstration. The projects GeoWell (GA No. 654497) and GEMex (GA No. 727550) have received funding from the European Union's HORIZON 2020 research and innovation programme. The authors E. Huenges, F. Poletto, T. Reinsch, and B. Sanjuan are deeply involved in at least one of the ongoing EU-projects (GeoWell, IMAGE, and GEMex) and in the EERA JPGE.

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