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Supercritical Fluids - Learning about the Deep Roots of Geothermal Systems from IEA Geothermal Collaboration

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ABSTRACT

In recent years, projects in several member countries of the International Energy Agency (IEA) Geothermal Technology Collaboration Programme (TCP), Working Group 12, have undertaken research into the deep, high-temperature roots of conventional geothermal systems. The objective is to source and evaluate higher value energy resources for future use. These countries include: Iceland (IDDP-2), Italy (DESCRAMBLE), Japan (Super-Critical), USA (NW Geysers EGS), Mexico (GEMex), Switzerland (COTHERM) and New Zealand (HADES). This paper compares the learnings from these projects to help guide future research programs. These learnings will enable researchers to focus on the technical problems that remain and to share the benefits of knowledge already acquired.

The huge potential energy resource of 'deep roots' is undisputed; it can be estimated in terms of gigawatts of electricity generation per resource area, over minimum lifespans of 30 years. The most important remaining issues are related to: drilling problems at high temperature and pressure (casing, drill-string, cement and mud fluids); material selection to cope with corrosion from gassy super-critical fluid; well-bore stability under super-critical operating conditions; and finding, creating, and sustaining permeability in ductile conditions.

1. INTRODUCTION

Supercritical geothermal systems are located at depths near the brittle-ductile transition zone where the reservoir fluid is in a supercritical state (i.e. for pure water, >374 ºC and >221 bar; for seawater > 406 ºC and >298 bars). A recently published review of research studies into supercritical geothermal systems (Reinsch et al., 2017) has succinctly summarized the key challenges and achievements to date with respect to exploring the deep roots of known geothermal systems, particularly where underlying, ultra-hot, magmatic heat sources are inferred. The co-authors of this study represent research organisations and projects in USA, Japan, Germany, Italy and France, all members of the collaboration efforts undertaken through Working Group 12 (WG12) of the IEA-Geothermal Technical Cooperation Programme (TCP). Researchers from institutes in Switzerland (e.g. Scott et al., 2018), Iceland (e.g. Fridleifsson et al., 2017), Mexico (e.g. Jolie et al., 2018) and New Zealand (e.g. Ratouis, 2017) have also contributed significantly to international collaboration on this topic since the establishment of WG12 in 2015. Details of workshops and meetings organised or supported by WG12 can be found in the annual reports of IEA-Geothermal (2019).

The transfer of heat and fluids from the deep roots of volcanic geothermal systems to shallow depths is complicated (e.g., Fournier, 1999). It involves the emplacement of magma, heat transfer by conduction, convection or advection, flow of single-phase, two-phase or supercritical fluids, chemical (water-rock) reactions with gases and brines, and so on. Such processes cannot be simulated with conventional geothermal modelling tools. Developing a strategy for deep roots energy utilisation therefore requires improved modelling methods, innovation of measurement tools and better understanding of high temperature water-rock-gas interaction. Advances are accelerated by collaborative research, close cooperation and coordination of international research groups. Many of those groups are represented by IEA-Geothermal participants. Working Group 12 participants have developed strategies to address these challenges, as follows:

Task A: Compilation of conceptual models of the roots of volcanic geothermal systems and associated research methods, using open-source information from participating countries to provide background material for deep-roots research, including information on exploration and modelling methods and tools.

Task B: Advancement of methods for deep geothermal exploration to disseminate information on advances in exploration methods, facilitate cooperation amongst research-groups, and enhance the depth resolution of available methods by using the power of joint interpretation of data-sets.

Task C: Methods for modelling conditions and processes in deep geothermal resources, by advancement of methods applied in the modelling of physical processes, revealing the overall process of upwards heat transfer, improving geothermal reservoir modelling, and enhancing synergy by avoiding duplication of effort and improved sharing of open-source software.

Wells drilled into supercritical conditions are expected to yield much higher energy flow, in theory, due to very high enthalpy fluids (>2086 kJ/kg) (Scott, 2018). An order of magnitude increase in productivity is envisioned (e.g. Fridleifsson & Elders, 2017) for wells that encounter good permeability in such conditions. This theoretical productivity increase is due to higher enthalpies and higher buoyancy forces (lower density fluid) relative to viscous forces (resisting flow). Supercritical systems are likely to be hosted in the deep roots of volcanic-hosted geothermal systems or close to active magmatic intrusions in extensional tectonic regimes. Fluids that meet the minimum criteria for high temperature and enthalpy, but not for pressure, may be termed 'super-heated' (or 'ultra-hot'). They also retain the potential for very high productivity, given sufficient permeability. Therein lies one of the challenges: ductile conditions vary with rock-type (lower temperature for more silicic rock) but ductility is often coincident with supercritical temperatures and host rocks are often assumed to be of lower permeability because of the ductile rather than brittle mode of failure under stress change. This could lead to a deficit of fractures, and conduction rather than convection-dominated heat transfer. Countering this hypothesis, however, is the evidence from the depth extent of micro-seismicity (active fracturing) which occurs within supercritical conditions, presumably within the brittle-ductile transition (BDT) zone. We consider these apparent contradictions in more detail in the following sections.

Challenges in supercritical conditions include drilling and well completion (particularly cementing of casings). Another serious challenge that faces development of supercritical resources is the chemical and physical nature of the fluids, and how to handle them in the well-bore and above-ground pipe-work. Despite best efforts, fluids originating from a supercritical reservoir have not yet been discharged for testing purposes. Attempts to model the flow dynamics within the wellbore have been undertaken and these suggest some instabilities may occur as fluids transition through the critical point on their way up to the surface. Also, some theoretical geochemical studies and laboratory experiments have simulated the possible fluid-rock and casing interactions. These hint at corrosion/erosion that might occur during the passage of supercritical or ultra-hot fluids, especially those fluids containing entrained salts and/or magmatic gases.

However, the benefits of successfully solving these challenges is not only a potential increase in the number of volcanic-hosted systems available to develop, but also improved economic resource estimates for known, conventionally developed, geothermal systems. Rising productivity and long-term sustainability of such resources may lead to increased investment in maintaining and improving existing geothermal power-plants and associated infrastructure, particularly for those systems that are approaching their turbine and infrastructure 'retirement' age.

This paper, as a collaboration effort of IEA-Geothermal WG12 participants, reviews and summarizes previous work aimed at demonstrating the viability of supercritical resources for power generation. We discuss the chemical and physical issues that have arisen thus far, and enlarge on potential opportunities for further international collaboration on this topic.

2. REVIEW OF SUPERCRITICAL PROJECTS

2.1 Overview

The results of 'deep roots' and 'supercritical' drilling projects that seek to investigate unconventional but potentially highly productive resources was summarised in Reinsch et al. (2017). Temperatures exceeding the critical temperature (374 °C for pure water) have been encountered at: The Geysers, Puna and Salton Sea (USA), Kakkonda (Japan), Larderello (Italy), Krafla, Reykjanes and Nesjavellir (Iceland), Menengai (Kenya) and Los Humeros (Mexico).

Figure 1: Geothermal areas where super-hot temperature (> 374 °C) have been recorded

Very high temperature geothermal wells (>350 °C) in these and similar geological settings have often been associated with the onset of steep conductive temperature gradients or elevated pore pressures at the base of a productive high-temperature geothermal reservoir. This would suggest a transition from high to low permeability, near an elastic-plastic transition (Watanabe et al., 2017). Such observations have, in the past, discouraged even deeper exploration drilling. However, the assumption of low permeability roots has been challenged, and in the case of Reykjanes (Iceland) disproved. Other technical challenges have emerged instead. For example, the challenges of reliable long-term measurements of temperatures in supercritical resources was discussed by Jacobsen (2017).

Superheated fluid produced from a basaltic magma encountered in the IDDP-1 well at Krafla proved to be very corrosive and abrasive (Einarsson et al., 2015). Although wet scrubbing of the steam using injected brine was found to be a successful surface treatment method, some other novel technologies may be needed in the future to deal with such corrosive fluids in a safe and economic manner, particularly downhole. In Japan, the former "Beyond Brittle" (JBBP) project and the more recent "Ultra-Hot Geothermal" project address similar issues. In New Zealand the former "Hotter and Deeper" (HADES) project has been replaced by laboratory research into water-rock interaction and modelling at supercritical conditions. In Europe, several projects have investigated different aspects of the topic, including the following: the FP7 project IMAGE and the Horizon 2020 projects DESCRAMBLE, DEEPEGS, GeoWell (at Larderello, Italy and in Iceland) and the Horizon 2020 joint European-Mexican project GEMex (conducted at Los Humeros, Mexico).

Okamoto et al. (2019) undertook a global assessment of selected ultra-high-temperature resources by collating available data from Kakkonda, Nesjavellir, Krafla, Reykjanes, Rotokawa, Larderello and The Geysers, to assist in developing conceptual models of the deeper parts of these selected geothermal systems. These authors' expectation is that crustal fluids at supercritical conditions could provide a previously under-utilised energy source for future power generation. The concept was then applied to an estimate of the energy potential within current drillable depth (i.e. <5 km) that potentially exists beneath volcanoes and calderas in north-east Japan (Tohoku), where new renewable energy resources to provide baseload power are highly desirable to help replace existing nuclear power stations. Various geophysical datasets, including seismicity and MT resistivity data, were used to help inform the volumetric assessment of supercritical reservoirs that are presumed to overlie partially-molten, magmatic heat sources. In Europe the "favourability" map of geothermal resources at super-critical condition was obtained in the frame of the IMAGE Project (Manzella et al., 2019). After defining three main indicators, i.e. the depth of 400 °C isotherm, the crustal thickness, and the earthquake density combined with the estimated depth of the Brittle-Ductile Transition in Europe, their spatial correlation was established by Geographic Information System (GIS) models, and a super-critical resource map was then organized by prioritizing favourable conditions using GIS spatial analysis methods.

Contrary to previous assumptions, Watanabe et al. (2017) conclude that the permeability at the brittle-ductile transition (BDT) does not reduce drastically; there is no step reduction in permeability. Therefore, supercritical reservoirs are theoretically feasible at BDT depths in crustal rocks, whether the host rock composition is basaltic (which has a relatively high BDT temperature), or granitic or rhyolitic (relatively low BDT temperatures). Laboratory studies from Watanabe et al. (2017) reveal the permeability behaviour of fractured granite samples at 350-500 °C and under effective confining pressures (up to 100 MPa) creating a transition from elastic to plastic deformation (simulating ductile behaviour). It was noted that rocks that are ductile in compression can be brittle in extension, and intensive tensile fracturing has been observed in metamorphic and plutonic rocks from the middle crust beneath the BDT. Therefore, Watanabe et al. (2017) infer that, even though permeability generally decreases with depth, some permeability remains in the brittle-ductile transition zone, and potentially exploitable resources probably exist in the granitic crust at temperatures of 375-460 °C and at depths of 2-6 km. Also, Fournier (1991) noted that at temperatures > 370 °C, pore fluid pressures encountered in such deep hot geothermal wells often exceed hydrostatic. It is not unreasonable to infer that such conditions may also exist in other crustal lithologies (such as rhyolite), although experiments and drilling projects are needed to test such inferences. Furthermore, tectonic earthquake swarms in volcanic areas are frequently located at depths that coincide or underlie the inferred BDT, further supporting the inference that brittle failure enhancing fracture permeability is present even at supercritical conditions where dominantly ductile deformation is expected. Note, however, that the existence of earthquakes in the tectonically active crust does not in itself guarantee good permeability in the long term. Ingebritsen and Manning (2010) show that, for example, rock-fluid interaction such as hydrothermal alteration and retrograde metamorphism act slowly but steadily to destroy permeability created by intermittent rock failure or escape of lithostatic-pressured fluids. Permeability in this setting is highly dynamic.

2.2 DESCRAMBLE (Italy)

The Italian Larderello project (DESCRAMBLE) was undertaken between May 2015 and April 2018 (Bertani et al., 2018, Manzella, 2017). The chosen area is the hottest within the Larderello geothermal field, with heat flow exceeding 800 mW/m^2. Drilling improvement was a key focus of this project because previous deep drilling experience at Larderello (1980 to 1983), to 4.1 km depth, had encountered severe problems due to elevated temperatures (thermal stresses), tool deviation, drill-pipe corrosion, pipe breakage, fishing, side-tracking, and casing cement failures. The target for deep drilling was a horizon of strong seismic reflectors named the K-horizon at 3-4 km depth in the explored area, which was inferred to contain or cap a reservoir of supercritical fluid. Seismic properties in such super-hot systems were discussed by Farina et al. (2019) and de Franco et al. (2019). The geological host is a fractured contact zone in meta-sediment above a large granitic intrusive which is the inferred heat source. Available geophysical data (seismic reflection, passive seismic, MT resistivity) suggested that the K-horizon marks a transition to supercritical and BDT conditions. The supercritical reservoir conditions were estimated to be about 450 °C and >240 bar.

During the project an existing high temperature, but low permeability, well, Venelle-2, was deepened from 2.2 km (originally 350 °C) to about 3 km. At a depth of 2.7 km, a loss of circulation zone, with temperature > 400°C and pressure of about 300 bars, was the first evidence of the existence of super-hot conditions in the deep system. Static formation temperature at 2.8 km depth was estimated by mechanical Kuster tool and synthetic fluid inclusions. Moreover, a novel logging tool able to withstand super-hot temperatures was developed for the project and tested. All methods indicate a temperature > 504 °C, which was significantly higher than anticipated, and exceeded some of the well design parameters. A significant and unexpected issue was the behaviour of drilling mud at these extreme temperatures. Since it was impossible to cement the bottom-hole fluid-loss zone for further drilling in safe conditions, the drilling was halted at 2.9 km. After the last data-logging and coring activities, the well was closed in a safe condition through a temporary cement plug. Perhaps due to the fact that the K horizon seismic reflectors were only partially crossed, the drilling has not unequivocally proven the presence of supercritical reservoir fluids at these depths.

2.3 IDDP (Iceland)

Evidence for super-critical reservoir conditions in Iceland has been found at three high-enthalpy, producing, geothermal fields. International collaboration on 'Deep Roots' research has been coordinated through the GEORG Deep Roots Geothermal (DRG) project which was completed in late 2017 (GEORG, 2017). This has been crucial to the IDDP project whose objective has been to validate the concept that supercritical fluids at temperatures of ~450-600 ºC could be encountered and produced from depths of 3.5-5 km and used to generate power. Three sites were initially chosen for deep drill-holes: Krafla (IDDP-1, 2008), Reykjanes (IDDP-2, 2016) and Hengill (IDDP-3, proposed). Seismicity is observed at the target depths, indicating that brittle failure and therefore permeable fractures probably occur at supercritical conditions. A well bore collapse during testing of the first candidate well to be deepened in Reykjanes (RN-17) led to a move to Krafla. Here, the target was 4.5 km but 900 ºC rhyolitic magma was unexpectedly encountered at 2.1 km, so the well was completed early, tested and discharged. Superheated steam was produced at wellhead temperatures of up to 450 ºC, enthalpies of 3200 kJ/kg, and well head pressures of up to 140 bar. Flowrates of 10-12 kg/s suggested potential generation capacity of 25-35 MWe (Fridleifsson et al., 2014). Unfortunately, the well casing and surface pipes suffered from corrosion by acid gases (HCl, HF and H_2S), along with erosion and silica scaling. The well was eventually shut in and abandoned after failure of the well-head master-valve. However, field and laboratory tests using the discharged fluids had already shown that chemical scrubbing techniques could be employed to mitigate the corrosion and erosion effects of the produced fluids, at least at the surface (Hauksson et al., 2014). Supercritical resources around magmatic intrusions, such as at IDDP-1, were discussed by Hefmanska et al. (2019). Some of the engineering challenges of drilling into magma and extracting its energy were discussed by Holmgeirsson et al. (2018).

The second well, IDDP-2, was drilled at Reykjanes in 2016-17 to 4.65 km depth (Weisenberger et al., 2019, Stefansson, 2017) and reached supercritical conditions even for seawater. The measured bottom-hole temperature in January 2017 was 426 ºC and pressure of 340 bar, although, when measured, the well was still heating up following drilling with water. Measurements made during the warm-up period were used to estimate the likely stable bottom hole temperature, yielding an estimate of about 540 ºC. (Tulinius and Níelsson, 2020). The original objectives of the drilling were to: (i) explore the deep roots of the Reykjanes hydrothermal reservoir to find superheated or supercritical fluids; (ii) investigate options for injection to exploit such deep heat sources; (iii) explore for permeability in the deep, fault-related, up-flow zone; (iv) test whether or not a supercritical reservoir exists at 4–5 km depth; (v) investigate the geological nature of the heat source (dyke complex or gabbroic intrusion) and the geochemistry of the recharge of the saline seawater recharged hydrothermal system. Coring of IDDP-2 revealed the host rock to be a sheeted basalt dyke complex, which is highly fractured, intensely hydrothermally altered (including high temperature mineral amphibolite) and highly permeable. Blind drilling (total loss of fluid, with no return of cuttings) occurred from 3.2 to 4.6 km depth, representing a loss of 53 m^3 of cuttings into open fractures (at the major loss zone at 3.3 km depth, and minor loss zones at 4.4 and 4.5 km). The primary heat transfer mechanism at great depth is thought to consist of periodic dyke and sill injections from a primitive magma source within the underlying oceanic crust. Thermal and tectonic stresses associated with these intrusions probably result in brittle rather than ductile deformation and facilitate the deep persistence of open fractures at such high temperatures. Thermal stimulation of the bottom (supercritical) part of the well was attempted using a 3½" drill-string and by injecting cold water (IDDP, 2018). Problems with a packer inserted to block the primary loss zone at 3.3 km depth, to stimulate the deepest section, resulted in unintended rapid heating up (and expansion) of the production casing and a casing failure occurring at 2.3 km depth. Severe corrosion was also noted on the lower part of the 3½" drill string after it had been withdrawn. The casing damage has significantly limited the planning and progress of subsequent downhole surveys and has thus far thwarted planned flow-tests.

During the IDDP "Way Forward Workshop" in March 2018 it was concluded that some useful lessons have already been learnt from the problems experienced. They are paraphrased as follows: a) The temperatures being exposed to deep sections of wells IDDP-1 and IDDP-2 reflect an environment where available casing materials and cementing technologies are at, or exceed, their limits. b) Significant thermal movement of steel should be expected at extreme temperatures and wells may end up having to be operated with deformed casings or liner sections. c) Such wells may nevertheless be able to transport injected fluid to their deepest feed zones, so one objective for a supercritical well (as an injector) can still be achieved. d) Due to such casing problems, future supercritical drilling projects should prepare for the potential problem of insufficient deep well thermal recovery data to accurately assess the deepest reservoir undisturbed pressure and temperature conditions. e) In this situation, various logging data sets collected during drilling and well completion can still be coupled together and matched in an appropriate (supercritical capable) inverse modelling suite, to determine an accurate and stable temperature-depth profile.

In the future, IDDP-3 drilling is planned to investigate the deep roots and potential supercritical resources near Nesjavellir on Hengill volcano. In 1985, a maximum temperature of >380 ºC was recorded at 2.2 km depth (in NJ-11) with feed zone permeability at a similar depth. The lower limit of seismicity extends to 6-7 km, and other geophysical evidence (MT resistivity and seismic properties) points to the probable existence of an intrusive heat source and overlying supercritical reservoir beneath Hengill.

2.4 Kakkonda (Japan)

The 1994 Kakkonda project in Japan involved the drilling of a 3.7 km deep exploration hole into a high temperature granitic pluton. A bottom hole temperature of 500 ºC was encountered (Ikeuchi et al., 1998). A temperature inflection was also found at 3.1 km depth (380 ºC) with a convective profile above, and a conductive (linear) temperature gradient below this depth. The minimum quartz solubility depth was estimated at 3.4 km. It was therefore deduced that this depth approximately marked the brittle-ductile temperature boundary; there was reduced fracture density and no permeable fluid entries observed deeper in the pluton (Okamoto et al., 2019). MT resistivity models show a low resistivity structure (<10 ohm-m) located near the centre of the Kakkonda granite, from 2.5 km depth, and anomalies also underlie two local volcanic peaks, implying the presence of magmatic brines or partial melts at relatively shallow depths. Local micro-seismic monitoring in 1994-1999 indicated that most events were concentrated at 1.5 to 3 km depth across the top of the intrusive.

Asanuma et al. (2017) summarised the progress made with the Japanese supercritical geothermal projects. Furthermore, in a recent assessment of the power potential (to 5 km depth) of the 'ultra-high-temperature' resources in north-east Japan (Tohoku), Okamoto et al. (2019) suggested that a large amount of crustal fluid at supercritical state occurs within intrusive rocks deep beneath these volcanoes and calderas. If such fluids prove to be extractable and useable, then a high level of energy productivity is expected.

2.5 USA & Mexico

In the USA, Stimac et al. (2017) provided a review of exploitable supercritical geothermal resources (to about 5 km depth), based on deep temperature and pressure information from conventional resources associated with known magmatic intrusions, at three sites: The Geysers-Clear Lake, Salton Sea and Coso. Deeper drilling in several operating geothermal fields has revealed the presence of ultra-hot conditions: 400 °C steam at 3.4 km depth (Prati-32 well, The Geysers), 390 °C at 2.1 km depth (IID-14, Salton Sea) and molten dacitic magma (~1050 °C) at 2.5 km depth (KS-13, Puna, Hawaii). Various drilling and completion problems related to the presence of such high temperatures, such as casing collapse, extreme bit wear (when air drilling), extreme pressures or stuck drill-pipe, led to their abandonment or re-configuration as injection wells. Hence it has not yet been feasible to test supercritical fluid discharges for their chemical and physical properties and their energy utilisation potential.

It was noted that the Northwest Geysers area contains accurately located seismic events down to about 5 km depth (implying some brittle failure to this depth) and that this is ~1.5 km below the static conductive rock temperature of 400 °C measured at 3.4 km depth, where a transition to supercritical conditions has been inferred. The heat source for The Geysers is inferred to be a series of young silicic intrusions, and the reservoir is vapour-dominated and hosted in greywacke. MT resistivity modelling (Peacock et al., 2019) suggests a slightly lower resistivity zone in the deeper part of NW Geysers (below 5 km) which might be indicative of a partially molten intrusive. Despite vapour-dominated fluid conditions in the existing production reservoir, some higher than hydrostatic pressures were estimated at 3.6 km depth from mud pressure measurements during drilling.

Interestingly, by comparison, at Reykjanes, Hengill and Krafla (Iceland), the depth below which a sharp drop in seismicity occurs (base of the seismogenic zone), implying dominantly ductile conditions in basalt, is also at 4-5 km. Comparing this with induced and natural seismicity depths recorded within seven other large operating (non-basaltic) geothermal systems in South-East Asia and New Zealand (Bromley, 2018), it is suggested here that 3-5 km is a common base depth for seismicity in high-temperature geothermal systems, especially where underlying magmatic intrusive heat sources are inferred. Two exceptions, where deeper base-levels of seismicity have been documented (6.5 to 7 km), are found at Wairakei (New Zealand) and at Olkaria (Kenya). A possible explanation, in these two cases, is that the magmatic heat sources and associated ductile conditions are also deeper.

Stimac et al. (2017) used volumetric stored heat and power density assessments based on temperature contouring of the inferred supercritical resources, and a range of conservative heat recovery factors (0.1 to 4 %) and power-plant energy-conversion efficiencies (0.7 to 0.8 exergy efficiency at expected enthalpies), to estimate electrical power potential over a 30 year project life-span. As was noted, there are many caveats related to the simplistic assumptions in the stored heat method. For example, the method assumes a complete heat sweep across the resource volume, achieved by reinjection cooling over time. With real reservoirs, active management minimizes adverse cooling effects, and encourages heat and mass recharge from beyond the assumed resource boundaries. Over time, permeability may be stimulated to increase heat recovery. Also, the real project lifetime is typically greater than the assumed 30 years. Nevertheless, the study resulted in probability power generation estimates, despite some conservative assumptions, of approximately 0.9 and 1.2 GWe (50% probability) for the supercritical roots (down to 5 km depth) of The Geysers and Salton Sea fields respectively. The anticipated high productivity of individual wells, assumed from the beneficial physical properties of the supercritical fluid, will improve the economics (in terms of required number of production wells) rather than the overall sustainable capacity calculations.

At Los Humeros, which is an operating geothermal field in Mexico, several wells 2.2 to 2.5 km depth (H8, H28, H29) have estimated bottom hole temperatures of 350 to 394 °C, and two wells (H26 and H12) appear to have been drilled into a young intrusive. The supercritical part of the reservoir is the subject of a joint European-Mexican research project (GEMex, 2019, Bruhn et al., 2018).

3. MODELLING AND LABORATORY STUDIES

The use of specialist software (e.g. CSMP++, COTHERM project, Switzerland) to numerically simulate the formation of supercritical resources associated with magma-driven systems was described by Scott et al. (2015). It was noted that potentially exploitable resources can form at supercritical conditions in rocks where the brittle-ductile transition temperature is higher than 450 °C (such as basalt). Rocks with higher silica content (e.g. rhyolite) are likely to have a lower brittle-ductile transition temperature (~360 °C), and therefore less likely to host a thick supercritical fluid reservoir. Permeability of the interface between a magmatic heat source and overlying reservoir fluid is a key parameter that controls fluid enthalpy, as well as heat and mass transfer rates. At permeabilities less than about 10^{-16} m^2 the heat transport mechanism switches from convection- to conduction-dominated, and fluid production into wells is generally uneconomic. Hence, the search for supercritical fluid reservoirs relies on encountering relatively high permeability (>10^{-16} m^2) as well as high temperatures (>374 °C), and high enthalpy fluid (>2086 kJ/kg). If the fluid pressure is below the critical pressure (22 MPa), that is, it is sourced at hydrostatic conditions from less than 2.7 km depth, or from deeper fluids at less than hydrostatic conditions, then it is termed ‘super-heated’. However, Scott et al. (2015) argue that supercritical fluid properties vary gradually across this critical isobar, so reservoir conditions for resource assessment purposes are also a gradual continuum, whereas super-critical temperature and enthalpy are more crucial parameters for characterizing resource potential.

Another aspect of supercritical conditions that is difficult to couple into modelling studies is the permeability change effect of silica deposition and dissolution within fractures. The transition from brittle to ductile behaviour of most silicic rocks occurs near the critical point (370-400 °C), and this is also where quartz develops retrograde solubility. Thus, quartz may precipitate and seal fracture permeability (Stimac et al., 2017). Codes that simulate geochemical, thermal and hydrological processes include TOUGHREACT, but there remain challenges in bringing this to supercritical state. A key aspect of this ongoing work with TOUGHREACT (for example, at LBNL, California) is implementing a higher temperature thermodynamic data base. In this regard, recent autoclave measurements in New Zealand of stibnite solubility at supercritical conditions have been reported by Olsen et al. (2019). Mountain et al. (2017) describe the results of flow-through laboratory experiments (water-rock interaction) at supercritical conditions to measure the devolitisation of chloride, sulphur and carbon-dioxide from host rocks such as greywacke and rhyolite. Reaction rates were found to be rapid and differences in resulting fluid chemistry (e.g. Cl/S ratio) could be correlated with the rock lithology. Clearly, dissolution and deposition rates at supercritical conditions will have significant impact on transient permeability values.

The geological conditions under which magma intrusions create supercritical reservoirs are typically transient (e.g. Fournier, 1999). They have been studied using relict systems, such as exhumed epithermal gold and copper deposits. Precious metals can be favourably emplaced under transient phases of high energy input into otherwise stable hydrothermal systems. This has been termed 'punctuated equilibrium' (Lawless, 1988). Heat influx creates vigorous boiling, brecciation and mineral deposition along fractures. The permeability thus created, in a quasi-cyclic or episodic manner, serves to temporarily enhance fluid circulation into rock that is close to magmatic temperature, which heats the fluid to supercritical conditions. Permeability then gradually reduces in the aureole or contact zone around the intrusion as silica and other minerals deposit and block up the fractures created by stress changes during the emplacement of the intrusive.

Modelling studies into the likely effects of cool water injection into a hypothetical supercritical fluid reservoir have also been undertaken. An example is described by Newman (2018) using numerical modelling code AUTOUGH2. The objective was to test whether such injection could help create an effective heat sweep of deep, super-critical energy resources and thereby augment the fluid and heat recharge into an overlying hydrothermal resource, developed using conventional technology. Such a strategy has been proposed as a possible end use for the IDDP-2 well drilled into supercritical conditions at Reykjanes, Iceland (Fridleifsson, 2017). In relation to this possibility, Thorgilsson et al. (2020) study an abrupt change in the chemical content of fluid produced from production wells in Reykjanes observed during drilling of well IDDP-2 as an analogy of a tracer test between the deep part of the geothermal system and the shallower production reservoir.

Within the TOUGH2 modelling community further efforts in Iceland, Italy and New Zealand have improved the handling and reliability of supercritical fluid transport using the EOSIsc Module of iTough2 (Magnusdottir & Jonsson, 2018) while O'Sullivan et al. (2016) provided details on improvements to the AUTOUGH2 supercritical fluid simulator with an extension to allow for the equation-of-state for an air-water interface. A new equation-of-state (EOS) for TOUGH2, capable of working in the range 1-1000°C, 0.1-1000 bar, and including water, CO_2 and NaCl, was developed within the DESCRAMBLE project (Bertani et al., 2018; Montegrossi & Burnell, 2018). Furthermore, a new, more efficient, and more-stable, reservoir simulator was developed in New Zealand, 'WAIWERA' (O'Sullivan et al., 2019). Applications of AUTOUGH2 to modelling supercritical geothermal reservoirs were previously reported by O'Sullivan et al. (2015) and modelling of the deep roots of volcanic geothermal systems was discussed by Thorgilsson et al. (2018), in particular, progress made through the DRG-project of GEORG.

4. COLLABORATION OPPORTUNITIES

Further collaboration under the IEA-Geothermal umbrella is anticipated and encouraged. Some novel suggestions for supercritical resource exploration and assessment have recently been proposed and discussed. This will hopefully facilitate future new developments and international collaborative research opportunities.

The ideas include a theoretical study on the use of seismic imaging to identify, locate and monitor supercritical geothermal reservoirs (Kasahara et al., 2019). The method applies full waveform inversion to datasets from active and passive seismic surveys with instrumentation that includes continuous fibre-optic DAS (distributed acoustic sensor) arrays deployed downhole at temperatures of up to 500 °C. With sufficient data the tomography inversion method can resolve seismic velocity anomalies (Vp, Vs) of about -5% and density anomalies of about -2%, that theoretically should be linked to the extent and fluid properties of supercritical reservoirs, and then track changes in these properties through time. Examples of innovative drilling technology to handle supercritical conditions were also discussed in Naganawa et al. (2017), and a discussion on the effects of supercritical conditions on resistivities in Iceland deep roots projects was addressed in Nono et al. (2017). Each of these research leads could result in fruitful advances through international collaboration.

Another example of a novel proposal was presented by Shnell et al. (2019). It involves exploring for and utilizing supercritical geothermal resources located beneath the deep ocean floor (typically at mid-ocean ridges and submarine volcanoes). Advanced technology to generate power, perhaps using supercritical CO_2 as a working fluid, in combination with supercritical water electrolysis for hydrogen, desalination, and mineral extraction, could find an economic use for these deep sea-bed resources. The concept is a self-contained, submersible, remote-controlled, electric-generating station at depths of 2 km or more, supplied with supercritical fluid by directionally drilled wells. A similar submersible concept was proposed by Hiriart et al. (2010) for directly tapping the energy from ocean-floor hot-water vents. Elders et al. (2018) discussed ways of improving the economics of marginal geothermal projects by utilizing super-hot and supercritical fluids for power generation in combination with hydrogen electrolysis, and mineral separation (e.g. lithium).

5. CONCLUSIONS

The key challenges to address before significant advances can occur in supercritical geothermal resource use are summarised below:

1. Solving drilling problems at extremely high temperature and pressure (casing, drill-string, cement and mud fluids).
2. Finding or stimulating, and maintaining, sufficient permeability to sustain production from the supercritical reservoir.
3. Reliably predicting the competing effects of water-rock interaction (deposition) and thermal stimulation (tensile fractures).
4. Demonstrating mitigation methods for handling aggressive fluids (vapour, salt, magmatic gases, and acid condensate).

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REFERENCES

Asanuma, H., Mogi, T., Tsuchiya, N., Watanabe, N., Naganawa, S., Ogawa, Y., Fujimitsu, Y., Kajiwara, T., Osato, K., Shimada, K., Horimoto, S., Sato, T., Ito, T., Yamada, S., Watanabe, K., Gotoh, Y., Nagasawa, Y., Kohyama, A.: Status report on the Japanese Supercritical Geothermal Project for FY2017, *Transactions* Geothermal Resources Council, October (2018).

Bertani, R., Buesig, H., Buske, S., Dini, A., Hjelstuen, M., Luchini, M., Manzella, A., Nybo, R., Rabbel, W., Serniotti, L., and the DESCRAMBLE Science and Technology Team: Drilling technology, supercritical resource, logging tools, resource characterization, modelling. *Proceedings* 43rd Stanford Geothermal Workshop. February (2018).

Bromley, C.: The role of advanced geophysical monitoring in improved resource expansion and make-up drilling strategy. *Proceedings* 43rd Stanford Geothermal Workshop, 8p, February (2018).

Bruhn, D., Jolie, E., Huenges, E.: European Research Efforts on Engineered and Superhot Geothermal Systems within Horizon2020. *Transactions* Geothermal Resources Council, October (2018).

de Franco, R., Petracchini, L., Scrocca, D., Caielli, G., Montegrossi, G., Santilano, A., Manzella, A.: Synthetic seismic reflection modelling in a supercritical geothermal system: an image of the K-horizon in the Larderello field (Italy), *Geofluids*, 2019, Article ID 8492453, 21p. (2019).

Einarsson, K., Sveinsson, K.E., Ingasson, K., Kristjansson, V., Holmgeirsson, S.: Discharge testing of magma well IDDP-1. *Proceedings* World Geothermal Congress 2015, Melbourne, Australia. (2015).

Elders, WA., Shnell, J., Fridleifsson, GO., Albertsson, A., Zierenberg, RA.: Improving Geothermal Economics by Utilizing Supercritical and Superhot Systems to Produce Flexible and Integrated Combinations of Electricity, Hydrogen, and Minerals. *Transactions* Geothermal Resources Council, October (2018).

Farina, B., Poletto, F., Mendrinos, D., Carcione, JM., Karytsas, C.: Seismic properties in conductive and convective hot and super-hot geothermal systems, *Geothermics*, 82, 16-33. (2019).

Fournier, RO.: The transition from hydrostatic to greater than hydrostatic fluid pressure in presently active continental hydrothermal systems in crystalline rock. *Geophysical Research Letters*, 18, 955-958. (1991).

Fournier, RO.: Hydrothermal processes related to movement of fluid from plastic to brittle rock in the magmatic-epithermal environment. *Economic Geology*, 94, 1193-1211. (1999).

Fridleifsson, GO., Elders, WA., Albertsson, A.: The concept of the Iceland deep drilling project. *Geothermics*, 49, 2-8. (2014).

Fridleifsson, GO., Elders, WA.: Successful drilling for supercritical geothermal resources at Reykjanes in SW Iceland. *Transactions* Geothermal Resources Council, 41, October (2017).

GEMex, http://www.gemex-h2020.eu. (2019).

GEORG Deep Roots Geothermal project final workshop, Reykjavík, Iceland, http://georg.cluster.is/thank-you-for-attending-drg-final-meeting/ December (2017).

Hauksson, T., Markusson, S., Einarsson, K., Karlsdóttir, S.N., Einarsson, Á., Möller, A., Sigmarsson, Þ.: Pilot testing of handling the fluids from the IDDP-1 exploratory geothermal well, Krafla, N.E. Iceland. *Geothermics*, 49, 76–82. (2014).

Heřmanská, M., Stefánsson, A., Scott, S.: Supercritical fluids around magmatic intrusions: IDDP-1 at Krafla, Iceland, *Geothermics*, 78, 101-110. (2019).

Hersir, GP.: Geothermal exploration and reservoir assessment in magmatic systems. IMAGE Final Conference Akureyri, Iceland, October (2017).

Hiriart, G., Prol-Ledesma, R., Alcocer, S., Espindola, S.: Submarine Geothermics; Hydrothermal Vents and Electricity Generation. *Proceedings* of the World Geothermal Congress, April (2010).

Holmgeirsson, S., Ingolfsson, HP., Eichelberger, J., Pye, S., Normann, R., Kaldal, GS., Blankenship, D., Mortensen, A., Markusson, S., Paulsson, B., Karlsdottir, SN., Wallevik, SO., Gardarsson, SM., Tester, J., Lavallee, Y.: Krafla Magma Testbed (KMT): Engineering Challenges of Drilling into Magma and Extracting its Energy. *Transactions* Geothermal Resources Council, October (2018).

IEA-Geothermal: Working Group 12: Deep Roots of Volcanic Systems, Chapter in series of Annual Reports; http://iea-gia.org/publications-2/annual-reports/ (2019).

IDDP: http://iddp.is/wp-content/uploads/2018/04/Way-Forward-Workshop-20-21-March-2018-SAGA-REPORT-No-11.pdf https://www.landsvirkjun.com/researchdevelopment/research/iddpproject (2018).

Ikeuchi, K., Doi, N., Sakagawa, Y., Kamenosono, H., Uchida, T.: High-temperature measurements in well WD-1a and the thermal structure of the Kakkonda geothermal system, Japan. *Geothermics*, 27, 591–607. (1998).

Ingebritsen, S.E., Manning, C.E.: Permeability of the continental crust: Dynamic variations inferred from seismicity and metamorphism: *Geofluids*, 10, p. 193-205. (2010).

Jacobsen, W.: Beyond 300 °C: reliable long-term measurement of temperature for super-critical geothermal systems. *Transactions* Geothermal Resources Council Meeting, Salt Lake City, p 704, September (2017).

Jolie, E., Bruhn, D., Lopez Hernandez, A.: The GEMex Team and The CFE Team: GEMex – A Mexican-European Research Cooperation on Development of Superhot and Engineered Geothermal Systems. *Proceedings* 43rd Stanford Geothermal Workshop. February (2018).

Kasahara, J., Hasada, Y., Yamaguchi, T.: Seismic Imaging of Supercritical Geothermal Reservoir Using Full-waveform Inversion Method. *Proceedings* 44th Stanford Geothermal Workshop, 5p, February (2019).

Lawless, JV.: Punctuated equilibrium and paleohydrology. *Proceedings* 10th New Zealand Geothermal Workshop, 165-169. (1988).

Magnusdottir, L., Jonsson, MT.: Increased Reliability of Supercritical EOS1sc Module in iTOUGH2. *Proceedings* 43rd Stanford Geothermal Workshop. February (2018).

Manzella, A.: Conceptual model of the super-critical geothermal system in the Larderello area (Italy) using multidisciplinary exploration data. IMAGE Final Conference Akureyri, Iceland, October (2017).

Manzella, A., Botteghi, S., Flovenz, O., Gola, G., Hersir, G.P., Limberger, J., Liotta, L., Santilano, A., Trumpy, E., van Wees, J-D.: Mapping super-critical geothermal resources in Europe, *Proceedings* European Geothermal Conference (EGC), Den Haag, The Netherlands (2019).

Montegrossi, G., Burnell, J: TOUGH2 modelling from EOS for supercritical fluids to Venelle 2 regional and local models. DESCRAMBLE Final Conference, Pisa, Italy, March (2018).

Mountain, BW., Chambefort, I., Sajkowski L.: Progressive devolitisation of New Zealand reservoir rocks from sub-critical to supercritical conditions. *Proceedings* 39th New Zealand Geothermal Workshop, paper 88. (2017).

Naganawa, S., Tsuchiya, N., Okabe, T., Kajiwara, T., Shimada, K., Yanagisawa, N.: Innovative drilling technology for supercritical geothermal resources development. *Proceedings* 42nd Workshop on Geothermal Reservoir Engineering, Stanford University, California, February (2017).

Newman, R.: Numerical Modelling of Cold Water Injection into Supercritical Geothermal Reservoirs. MSc thesis in Sustainable Energy Engineering; Reykjavik University, Iceland (2018).

Nono, F., Gibert, B., Parat, F., Loggia, D., Cichy, SB., Violay, M.: Electrical conductivity of Icelandic deep geothermal reservoirs up to supercritical conditions: Insight from laboratory experiments. *Journal of Volcanology and Geothermal Research*, 2018, ISSN 0377-0273, https://doi.org/10.1016/j.jvolgeores.2018.04.021. (2018).

Okamoto, K., Asanuma, H., Ishibashi, T., Yamaya, Y., Saishu, H., Yanagisawa, N., Mogi, T., Tsuchiya, N., et al.: Geological and engineering features of developing ultra-high-temperature geothermal systems in the world. *Geothermics,* 82, p.267-281 https://doi.org/10.1016/j.geothermics.2019.07.002 (2019).

Olsen, NJ., Mountain, BW., Seward, TM.: Antimony (III) Speciation in hydrosulphide solutions from 70 to 400 °C and up to 300 bar. *ACS Earth Space Chem.*2019361058-1072.

O'Sullivan J, Kipyego E, Croucher A, Ofwona C, O'Sullivan M.: A supercritical model of the Menengai geothermal system. *Proceedings*, World Geothermal Congress 2015, Melbourne, Australia (2015).

O'Sullivan, J., O'Sullivan, M., Croucher, A.: Improvements to the AUTOUGH2 supercritical simulator with extension to the Air-Water Equation-of-State. *Transactions* Geothermal Resources Council Meeting, 40, p 921-929, (2016).

O'Sullivan, J., Croucher, A., Yeh, A., O'Sullivan, M.: Working with Multi-million Block Geothermal Reservoir Models. *Proceedings* 44th Stanford Geothermal Workshop. 11p, February (2019).

Peacock, JR., Mangan, M.T., Walters, M., Hartline, C., Glen, J., Earney, T., Schermerhorn, W.: Geophysical characterization of the heat source in the Northwest Geysers, California. *Proceedings* 43rd Workshop on Geothermal Reservoir Engineering, Stanford University, February (2019).

Ratouis, TMP., O'Sullivan, MJ., O'Sullivan, JP., McDowell, JM., and Mannington, WI.: Holistic approach and recent advances in the modelling of the Ohaaki geothermal system. *Proceedings* 39th New Zealand Geothermal Workshop, Rotorua, November (2017).

Reinsch, T., Dobson, P., Asanuma, H., Huenges, E., Poletto, F., and Sanjuan, B.: Utilizing supercritical geothermal systems: a review of past ventures and ongoing research activities. *Geothermal Energy*, 5, DOI 10.1186/s40517-017-0075-y (2017).

Scott, S., Driesner, T., Weis, P.: A New Conceptual Framework for the Deep Roots of Magma-Driven Geothermal Systems. *Proceedings* 43rd Stanford Geothermal Workshop. February (2018).

Scott, S.: The Hydrology of 'Superhot' and 'Supercritical' Geothermal Resources in Magma-Driven Geothermal Systems, *Transactions* Geothermal Resources Council, October (2018).

Scott, S., Driesner, T., Weis, P.: Geologic controls on supercritical geothermal resources above magmatic intrusions, *Nature Communications*, 6:7837 doi: 10.1038/ncomms8837, (2015).

Shnell, J., Elders, WA., Kostecki, R., Nichols, K., Osborn, WL., Tucker, MC., Urban, JJ., Wachsman, ED.: Supercritical Geothermal Cogeneration: Combining Leading-Edge, Highly-Efficient Energy and Materials Technologies in a Load-Following Renewable Power Generation Facility. *Transactions* Geothermal Resources Council, October (2018).

Shnell, J., Elders, WA., Orcutt, J., Osborn, WL.: Exploration and development of supercritical geothermal resources on the ocean floor. *Proceedings* 44th Stanford Geothermal Workshop, 10p, February (2019).

Stefansson, A.: The drilling of RN-15/IDDP2 Research well at Reykjanes, SW Iceland. *Transactions* Geothermal Resources Council Meeting, Salt Lake City, p502. September (2017).

Stimac, J., Wilmarth, M., Mandeno, PE., Dobson, P., Winick J. : Review of exploitable supercritical geothermal resources to 5 km at Geysers-Clear Lake, Salton Sea and Coso. *Transactions* Geothermal Resources Council Meeting September 2017, Salt Lake City, September (2017).

Thorgilsson, G., Óskarsson, F., Galeczka, IM., and Axelsson, G.: Tracking Fluid Flow Between IDDP-2 and the Current Production Reservoir in the Reykjanes Geothermal System in SW-Iceland, Using Drilling Fluid as a Tracer. *Proceedings* World Geothermal Congress 2020, Reykjavík, Iceland, (2020).

Thorgilsson, G., Axelsson, G., Berthet, J.C., Magnúsdóttir, L., Árnason, K.: Modelling of the Deep Roots of Volcanic Geothermal Systems. *Proceedings* 43rd Stanford Geothermal Workshop, 15p, February (2018).

Tulinius, H., and Níelsson, S.: How Hot Is the Deepest Part of the IDDP2 Well in Iceland? *Proceedings* World Geothermal Congress 2020, Reykjavík, Iceland, (2020).

Watanabe, N., Numakura, T., Sakaguchi, K., Saishu, H., Okamoto, A., Ingebritsen, SE., Tsuchiya, N. : Potentially exploitable supercritical geothermal resources in the ductile crust. *Nature Geoscience* DOI: 10.1038/NGEO2879. (2017).

Weisenberger, TB., Harðarson, BS., Mesfin, KG., Einarsson, GM., Níelsson, S., Zierenberg, RA., Friðleifsson, GO.: The Iceland Deep Drilling Project at Reykjanes - 4.5 km Deep Drilling into Supercritical Conditions. *Proceedings* 44th Stanford Geothermal Workshop, 11p, February (2019).