International Collaboration on Research into Deep Superhot Roots of Geothermal Resources through IEA Geothermal

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ABSTRACT

Research into the deep, superhot roots of geothermal systems, which potentially host supercritical fluids, has been actively pursued by several member countries of the International Energy Agency Geothermal Technology Collaboration Program (IEA-Geothermal TCP), including New Zealand, Iceland, USA, Italy and Japan. To date the work has been focused on: a) identification and delineation of superhot geothermal resources that are prospective and accessible by drilling; b) advancing technology to enable reliable energy production from these superhot prospects; and c) a realistic assessment of the potential thermal energy that might be available from these deeper geothermal resources to sustainably support the low carbon energy futures that member countries are all actively pursuing.

Recent advances have seen significant improvements in knowledge of the geochemical and physical conditions to be expected in these superhot settings through experiments in fluid-rock interactions and advanced simulation models. Improvements in deep drilling and well completion technology are also progressing. This paper discusses these aspects, especially from a New Zealand perspective, and summarizes lessons learnt from past superhot geothermal projects, seeking to share knowledge acquired, inform interested parties and direct future enquiry.

In addition, this paper introduces a new collaboration task that was initiated by IEA-Geothermal in 2025. The purpose of the new task is to encourage further collaborative activity to help accelerate novel geothermal energy technology development. Although the focus is on >400 ºC, the scope is inclusive of >300 ºC where novel fracture stimulation efforts are informative. Key components will include: a) develop reliable and cost-effective technology that can be used in the superhot energy production infrastructure; b) inform appropriate regulatory regimes and economic frameworks that will provide adequate certainty to support the investment needed; c) construct a shared data repository; and d) promote global testbed activities. The overall goal is to achieve expanding impact by reducing costs and increasing deployment through innovation and demonstration.

1. INTRODUCTION

The technical potential for geothermal energy at depth has long been recognized; a recent report "The Future of Geothermal Energy" by the International Energy Agency (IEA, 2024) suggests that the global technical geothermal power potential, at conservative depths of up to 5 km, amounts to 21,000 EJ (equivalent to 42 TWe of power generation for 20 years). Of this potential, superhot (>400 ºC) resources constitute a relatively low-cost, high-enthalpy production option, if existing technical challenges can be overcome.

Superhot temperatures have been measured in deep drillholes in several countries, including Iceland, Italy, Japan, Kenya, Greece, USA and Mexico. Some have even accidently drilled into molten rock, and a few drilling projects have confirmed both fluid pressure and temperature conditions that are higher than the critical point (22 MPa and 374 ºC for pure water). However, none of these deep drillholes have so far been successfully and sustainably discharged. This is due to a number of technical issues, mostly related to well completion problems, chemical issues and thermal stresses (sometimes leading to casing failures).

The International Energy Agency Geothermal Technology Collaboration Program (IEA-Geothermal, Working Group 12, Bromley & Carey, 2023, Bromley et al., 2020) has members collaborating on the topic of deep, high-temperature roots of geothermal systems. These roots potentially host either supercritical or superhot geothermal fluids. (Superhot fluids are similar to supercritical fluids, having temperatures exceeding the critical point of 374 ºC, but are inclusive of fluids, such as super-heated vapour, that are at subcritical pressures, see Figure 1).

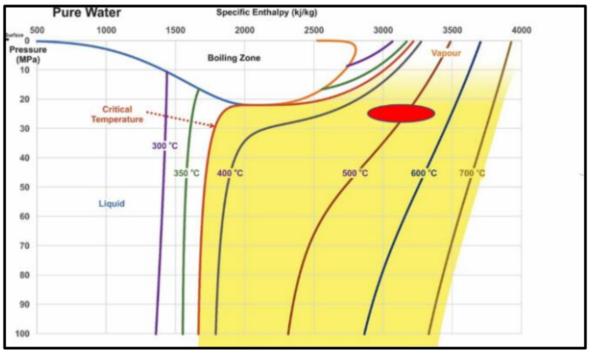

Figure 1. Simplified representation of the super-critical region (shaded yellow), and main area of interest (red oval) in 'enthalpy-pressure' phase space for pure water. Super-hot vapour develops at lower pressure and shallower depths. Adapted from Bromley et al (2023).

The main topics for consideration by the working group when assessing the potential for exploration and development of the 'deep roots' of geothermal systems are listed below:

a) Reservoir properties: the temperatures, permeability range (seismicity & ductility), recovery factors, production cut-off (minimum) temperature and pressure, and tolerable fluid chemical properties (e.g., gas content, acidity, mineral saturation) appropriate for a superhot resource capacity assessment,

b) Geophysics: interpretation of geophysical models to establish a resource volume and conceptual model using: MT (resistivity), magnetics (Curie Point depth), gravity (density and topographic stress), seismic (reflections, P and S wave velocity tomography and attenuation), and geodetics (creep, inflation & deflation),

c) Resource modelling: at a conceptual level, establish the knowledge required for sizing and planning sustainable operations. Quantify the heat input that is needed into the base of the reservoir and relate to the heat output from the wells. Investigate the parameters that most strongly affect sustainability, including heat in place per unit volume, acceptable temperature change over the project life and appropriate recovery factors,

d) Development strategies: provide optimized choices for production and reinjection wells to sustainably utilize the available resource,

e) Engineering challenges: investigate appropriate materials for pressure containment that achieve adequate well and plant longevity and improve procedures for cementing well casings, managing well expansion with temperature change, initiating and maintaining well flow, controlling well bore scaling and corrosion, and choosing the appropriate process plant for energy transformation,

f) Regulatory issues: assist regulators to adjust policies, without inadvertently imposing excessive compliance costs, to address the following: imprecise 3D resource boundaries, the need for flexibility so learnings through time can lead to adaptation, management of land access over the most desirable resource volumes, and management of possible resource interference between users (proving cause and effect when there are multiple tappers).

In Section 2, we summarize some recent advances in superhot geothermal projects around the world, and then, in Section 3, we discuss a selection of lessons learnt so far.

2. KEY PROJECTS OF IEA-GEOTHERMAL GROUP

2.1 United States of America

Summaries of past USA projects, learnings, challenges and future plans for superhot geothermal research and demonstration projects are found, for example, in Dobson et al. (2017), Cladouhos & Callahan (2024) and a series of recent online reports commissioned or accessed by Clean Air Task Force (CATF, 2024).

A leading example, the FORGE (Frontier Observatory for Research in Geothermal Energy) program, was supported by the DOE Geothermal Technologies Office and was designed to assist in enabling the building of large-scale, economically sustainable Enhanced Geothermal System (EGS) systems for heat extraction from deep underground formations. The FORGE project, at the Milford site in Utah, has resulted in many published results and has demonstrated improvements (especially cost reductions) in deep well drilling, stimulation, injection-production, micro-seismic monitoring and subsurface imaging technologies. Such advances are required to establish and sustain continuous fluid flow and commercially viable energy transfer from a deep high-temperature EGS reservoir (Moore et al, 2021, Simmons et al., 2025). A spin-off from this research has been advancement of the closed-loop geothermal technology (White et al., 2024) and projects such as that of Fervo Energy at nearby Cape Station (https://fervoenergy.com/).

Newberry Super-Hot EGS Project intends to demonstrate an EGS proof of concept at a location where very hot rocks are close to the surface (~5 km). Drilling into the brittle-ductile transition aims to test the efficiency of thermally induced fracturing and reservoir creation as well as the development of drilling techniques, borehole instrumentation adapted to high temperature and optimized exploration methods (e.g. Bonniville et al, 2020, Taverna, et al, 2024).

In addition, the joint DEEPEN project (USA, Icelandic and European partners, 2021-2024) has recently been completed. Its stated aim was to **DE**risk **E**xploration for geothermal **P**lays in magmatic **EN**vironments (**DEEPEN**). An increase in the probability of success when drilling for geothermal fluids near magmatic systems was sought through the development of improved exploration methods and frameworks for the joint interpretation of exploration data using a Play Fairway Analysis methodology (www.or.is/en/about-or/innovation/deepen/).

2.2 Iceland

The Icelandic Deep Drilling Program's (IDDP) superhot drilling project is summarised in Gunnarsson et al. (2025a), with a particular focus on past progress and future plans. At the location of the next proposed superhot deep drillhole (IDDP3, Hengill, Hellisheiði), Icelandic geoscientists conceptualise that the deep superhot resource is hydraulically connected to the shallower sub-critical conventional reservoir. In this setting, reinjection of brine deep into superhot conditions is considered as a means to support shallower pressures. Mass extracted will substantially be replaced by the fluid reinjected into the deep upflow. Such a strategy is proposed to avoid the potential adverse chemical effects of producing from a deep zone potentially containing high concentrations of non-condensable gases (NCGs) and/or silica. Also, production enthalpy enhancement will be achieved by more efficient re-heating of the injected water in the high temperature environment (relative to conventional peripheral reinjection or shallow/marginal groundwater recharge). Once re-heated, the injected water at depth is expected to rise and bring additional energy into the shallower reservoir. For this to occur there must be open and connected fluid pathways between the deeper and shallower parts of the reservoir, and these pathways must remain free from mineral precipitation that could impede flow. Yapparova et al. (2023) have quantified the effects through modelling studies which, in their assessment, shows that the underlying superhot parts of the resource are likely to be hydraulically connected to the shallower sub-critical geothermal reservoir. There is some evidence of such a connection from data collected during the drilling of IDDP2 in Reykjanes (Weisenberger et al., 2019). Hence, a deep injection strategy using the superhot 'roots' is supported at Hengill.

In addition, recent work through the HORIZON, EU-funded COMPASS project (Gunnarsson et al. 2024b) focusses on solving casing damage and well completion issues. These studies concentrate on casing corrosion, thermal expansion of casings, and behaviour of trapped fluids between casing strings. Solutions for these issues include corrosion-resistant cladding or protective coatings, thermally expandable casing couplings, and improved cementing technology.

Laboratory experiments were also undertaken to test for potential superhot chemical corrosion and scaling problems (Lamy-Chappuis et al., 2022). Corrosion of L80 carbon and 13Cr stainless steel have been autoclave tested in superhot (>400 ºC) conditions, containing H_2O, H_2S and CO_2 gases. The results (Karlsdottir et al., 2025) showed relatively low background corrosion rates (<0.1 mm/yr), but some localised pit corrosion. Scales that formed locally included iron-chromate, magnetite and iron-silicate. These scales were observed when silicate residue was present in the vapour.

2.3 Japan

Since 2017, research and development of superhot geothermal resources in Japan has progressed through funding from the New Energy and Industrial Technology Development Organization (NEDO). The final objective is to utilize 400 °C to 500 °C supercritical or super-heated fluid from a depth shallower than 5 km, in Japan's subduction-zone geological setting (Asanuma et al., 2022). Earlier work, for example deep drilling at Kakkonda (Suzuki et al. 2022), suggested supercritical geothermal resources may exist around and within many of the volcanic zones in Japan, with the potential capacity of several tens of gigawatts. NEDO has released a powerful incentive for supercritical geothermal through their Green Innovation Fund; if a company pays some portion for a supercritical geothermal development, the government will cover the remaining costs. Four potential promising sites for supercritical geothermal development in Japan are under exploration. The operation of an initial pilot plant has been targeted for 2040. Phases of the project included exploration, site selection and plans for deep drilling (Asanuma et al, 2020). Many of the superhot exploration outcomes were summarized within papers collected into a Special Issue of Geothermics (Asanuma & Bromley, 2022).

2.4 Italy

Efforts in Italy have previously focused on DESCRAMBLE which was an international project (2015-2018), undertaken within the Larderello geothermal field. Its aim was to encounter supercritical geothermal conditions. The Venelle-2 well, a dry well drilled to 2200m was extended to 2810 m, encountering temperatures of more than 500 °C (Bertani et al., 2018). Unfortunately, due to a technical issue with the well casing, caused, in part, by the extreme downhole temperature gradients, no superhot fluids were able to be discharged or sampled. However, the extensive learnings from this ambitious project have assisted subsequent superhot projects with identifying issues and developing solutions through improvements in well design and measurement technologies.

Other European 'Horizon2020' funded research efforts into superhot resource exploration technologies were discussed in Bruhn et al. (2018).

2.5 New Zealand

Superhot geothermal research efforts in New Zealand (NZ) developed during the recently concluded 5-year GNG project (www.geothermalnextgeneration.com/). These studies have focused on: a) deep geophysical and geological exploration technologies (Chambefort et al. 2024) and reservoir simulation modelling (Kissling et al. 2024, O'Sullivan et al. 2024), b) understanding superhot thermochemistry, mainly through laboratory experiments (e.g. Mountain et al. 2024, Rendel et al. 2024, Rendel & Mountain 2023), supercritical tracer testing (Sajkowski et al. 2022, 2025) and mineral solubility investigations (Rendel et al 2024), and reactive transport modelling of fluid-NCG reinjection (e.g. Altar et al. 2023, Siahaan et al. 2024), and c) integrating the acquired knowledge to provide an inventory of NZ superhot resources with an economic assessment of their future development potential (Bromley et al, 2024). In addition, within the integration theme, a review was conducted of regulatory planning provisions (Kissick et al. 2024), modelling was undertaken of well-bore supercritical fluid flow (Rivera et al. 2023) and potential communicating opportunities to engage local communities were addressed. The promising outcome of this entire program has been a commitment from the NZ Government (as announced in November 2024) to support and fund (up to NZ$60M) a superhot geothermal deep drilling project (3.5-6 km depth). This project is intended to test the inferred superhot resource potential of parts of the Taupō Volcanic Zone and is based on the GNG research efforts to date. Ongoing efforts involve design and planning work before deep drilling commences.

3. GENERAL OBSERVATIONS AND LEARNINGS

Learnings from the international research and demonstration projects to date have been wide-ranging and productive. Here, we select and summarize discussions from several topics that have recently been of considerable interest to the superhot collaborating group: deep to shallow vertical connectivity, permeability inferred from modelling efforts, semi-ductile permeability, and high temperature silica transport (deposition and dissolution).

3.1 Deep connectivity – from superhot to sub-critical

Energy must transfer in some manner from the deeper superhot geothermal resources (the 'deep roots') into the overlying 'sub-critical' geothermal reservoirs. The transfer mechanisms must involve conduction of heat, along with fluid advection and convection. The relative contribution of these heat transfer mechanisms will depend on the local geological setting within which the geothermal resources are hosted (Dreisner et al., 2021, Scott et al., 2024).

There are competing processes at depth between those that reduce vertical permeability, and those that enhance vertical permeability. Over time, these processes occur at the interface between superhot and sub-critical geothermal conditions. The processes include silica deposition or dissolution and the effects of transient thermal or tectonic stress under dynamic strain, resulting in either fracture enhancement (seismicity), or fracture healing, even in semi-ductile rock.

3.2 Permeability controls from modelling

In a 2D fluid-flow model of the Taupō Volcanic Zone (TVZ), an actively rifting zone of New Zealand, Kissling et al (2024) has a 20 km wide hot-plate heat-source (0.7 W/m^2) at 10 km depth, producing 'unsteady' convection within the rifted faulted) basement (at 2-10 km depth). This creates localised and transient 'buoyant plumes' over lifetimes of ~10,000 to ~100,000 years. The plume locations are determined by permeability in overlying 'cap-rock' volcanics: higher values cause downflows of cool fluid from the surface and low temperature gradients, while lower values allow up-flow plumes to form. Vertical permeability in the deeply rifted basement needed to be ten times higher (~10^{-16} m^2) than horizontal permeability (10^{-17} m^2), which is enough to permit slow convection, and some advection, of fluids into the base of the sub-critical (300-350 ºC) geothermal reservoirs. However, conduction is dominant at great depth, within ~1 km of the hot-plate in regions between the geothermal systems with steep vertical temperature gradients of ~300 °C/km.

In a 3D 'representative' super-critical model of a typical natural-state TVZ system (O'Sullivan et al, 2024) the pressure gradients at depth needed to be greater than hydrostatic, implying overall low vertical matrix permeability. However, the model allowed for some advective and convective up-flow through faults linking superhot (374-600 ºC, 50-70 MPa) to subcritical (330 ºC at -2 km) regions. In the bottom layers of the TVZ model (at 8 km depth) fluids rise from a zone of elevated heat flux (2-4 W/m^2) through a few faults. A larger scale 3D TVZ model, also by O'Sullivan et al (2020), shows the complexity and transient behaviour (on a geologic timescale) of the convecting plumes. Controls on plume location include: a) deep influxes of high heat flow, b) surface topography controlling hydrostatic pressure, c) heterogeneous permeability distribution and d) the formation of capping structures above the plumes.

3.3 Permeability in semi-ductile supercritical conditions

Even in semi-ductile rock, elevated permeability at supercritical reservoir conditions is still likely, allowing for slow convective and advective processes, particularly in regions of high strain rate such as back-arc rift zones (e.g. TVZ). This conclusion is based on the laboratory and modelling studies of Watanabe et al. (2017) and Meyer et al (2024).

3.4 Silica deposition and dissolution

Rendel & Mountain (2023) experimentally determined the solubility of quartz in supercritical fluid, and Stefansson et al (2025) observed that "silica transport and deposition play a critical role in the geochemistry of superhot geothermal systems". Quartz solubility typically varies from ~0.6 mg/kg in superheated vapor to ~6000 mg/kg in supercritical water at low pressures (0.01 MPa), with even higher solubilities at greater pressures. In conventional geothermal systems, hosting subcritical fluids, quartz solubility is highly temperature-dependent, with cooling and boiling leading to silica precipitation. In superhot geothermal environments, rapid pressure and temperature changes can also significantly reduce quartz solubility leading to severe silica scaling. This has been observed in IDDP-1 borehole (Iceland), where decompression of superhot hydrothermal fluids caused severe silica precipitation within the well. The transition from magmatic to hydrothermal conditions may also significantly influence silica transport. Initially confined at near-lithostatic pressures, these fluids depressurize as they migrate into the geothermal system, triggering silica precipitation, reducing permeability and restricting fluid flow. As Stefansson et al. (2025) note, "the interplay between temperature, pressure, and fluid composition dictates silica transport and deposition, with temperature exerting a stronger influence in liquid dominated systems and pressure changes playing a more critical role in superhot systems".

The results of experimental studies of superhot temperature water-rock reactions in laboratory settings (Rendel et al., 2024, Sajkowski et al., 2025) and through modelling (Altar et al., 2023) have also demonstrated some important geochemical processes at superhot conditions.

4. NEW SUPERHOT GEOTHERMAL TASK GROUP

The focus of a new IEA-Geothermal Superhot Task Group, initiated in 2025, is to establish a pathway to commercialization of superhot geothermal energy by addressing key challenges. Details can be found at www.iea-gia.org/superhot and www.superhotrock.org/. Specifically, the task focuses on geothermal technology advancements at temperatures > 400˚C, but it also includes studies collecting relevant learnings from any projects > 300˚C, with an emphasis on findings relevant to geothermal energy extraction from deep, hard-rock, high-temperature settings. The goal is to achieve the lowest possible cost and highest possible market penetration of geothermal energy production in these challenging, but potentially widely applicable, geological settings. Conventional hydrothermal and oil/gas exploration researchers are encouraged to participate, as many of their advancing technologies can be applied to improved development of deep superhot resources in relatively low-permeability rock. Participants will be asked to share learnings relevant to superhot geothermal, particularly in low-permeability settings, so that the work remains useful to a broader number of countries across more-diverse geological environments.

The objectives of the Task Group are as follows:

a) To facilitate cross-border information-sharing and ensure shared learnings between global pilot projects, so that groups can collaborate and build from each other's successes and failures,

b) To leverage ingrained knowledge from global technology leaders on multiple projects,

c) To build from a shared understanding of technology development needs and a shared vision of the pathways forward,

d) To coordinate global activities to reduce cost, de-risk development, and standardize tools;

e) To support Superhot testbed and pilot projects

f) To lay the groundwork for joint resource commitment toward the commercialization of Superhot resources globally. This could include a shared data repository, a shared venue for information exchange, a shared global testbed, shared financial resources, and more.

The task is led by Jenna Hill of the Clean Air Task Force (CATF, www.catf.us/superhot-rock) in the USA. As of July 2025, participants include New Zealand, Iceland, Norway, Japan and Italy.

5. CONCLUSIONS

It is undisputed that there is a large amount of energy in place in the 'deep roots' of high temperature geothermal systems and beneath areas of relatively heat high flow across the globe. In places, these potentially contain superhot fluids.

To accelerate development of these superhot resources, an active, collaborative, collegial group is hosted by IEA-

Geothermal, to share relevant ideas, outputs and proposed investigative activities. The work discussed in this paper is the result of part of that collaboration between members of the IEA Geothermal Working Group focusing on 'Deep roots' of geothermal systems. We also introduce the proposed forward work program for a new collaborative task with broader objectives on 'Superhot' geothermal energy.

Overall, the work is focused on collaboration to assist: a) delineation and identification of locations of supercritical geothermal resources that might be prospective and accessible by drilling, b) evaluation of the energy that might be available long term, c) advancing technology to enable reliable energy production from the high temperature prospects, and d) developing appropriate regulatory regimes and economic frameworks that will provide adequate certainty to support the needed investment in superhot geothermal.

This paper reflects on the foundational work undertaken by members of the IEA Geothermal Working Group on 'Deep Roots'. The new Superhot Task Group builds from this by facilitating testbed collaboration, standardizing performance indicators, and creating shared technical infrastructure to advance technology readiness and deployment across countries.

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