Supercritical Geothermal Resources: Exploration and Development

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1. Introduction

The demand for clean, renewable energy is continuing to increase around the world. Much of that demand is being met with wind and solar power, but these resources are intermittent and therefore require balancing. Presently, developed geothermal resources are not adequate to provide the balancing that will be needed in the future thus attention is turning to supercritical geothermal resources.

Figure 1 Iceland Deep Drilling Project[1]

Utilizing supercritical fluids, geothermal could play an important role for carbon-zero energy future. These supercritical fluids provide much higher temperatures above 374 °C and pressure points above 22 MPa, providing much higher heat-content and lower density and so have the potential to generate around 10 times more energy than conventional geothermal for the same amount of extracted fluid [2].

Volcanic geothermal systems are associated with magmatic intrusions in the upper part of the Earth's crust characterized by increased temperature, specific fluid enthalpy, and convection of groundwater. Conventional exploitation of geothermal fluids from such systems typically produces an average of about 3-5 MW electric power per well with a world total exploitation of geothermal energy in 2018 corresponding to about 14.4GW [3]. Conductive heat transfer from a magmatic intrusion to the surrounding groundwater occurs in the roots of the geothermal system below the depth of typical conventional geothermal wells. Recent modelling suggests that supercritical fluids with temperatures and enthalpies exceeding 400°C and 3000 kJ

[1] https://interestingengineering.com/iddp-drills-into-new-era-steam-energy-potential

[2] http://www.thinkgeoenergy.com/utilising-supercritical-fluids-geothermal-could-play-a-crucial-role-for-nzs-carbon-zero-energy-future/

[3] A. Richter, *Global geothermal capacity reaches 14,369 MW – top 10 geothermal countries, Oct 2018*, Think GeoEnergy Geothermal Energy News, 2018.

kg^{-1}, respectively, exist at the boundary between geothermal systems and the magmatic heat source, with such fluids possibly capable of generating up to 30-50 MW of electricity from a single well or ten times more than conventional geothermal wells.

2. Supercritical Fluids

Supercritical geothermal fluids have commonly been classified based on the critical temperature Tc = 373, 976°C and pressure Pc = 22,01 MPa of pure water (H_2O). They are common defined as a single-phase vapor with a temperature above the critical temperature.

Supercritical fluids have been suggested to form by groundwater circulation near the intrusion with or without input from magmatic gas [4,5]. Magmatic intrusions emplaced into the upper parts of the Earth's crust may exsolve magmatic fluids at near litho-static pressure, resulting in fracturing of the surrounding rocks and magmatic fluid migration. Near magmatic intrusions, conductive heat addition to the surrounding groundwater system may also potentially form high-temperature supercritical fluids. However, permeability may rapidly decrease at the brittle-ductile transition (BDT), possibly limiting the formation of such supercritical fluids to lithologies with basaltic glass transition temperatures above 400-450 °C [6,7].

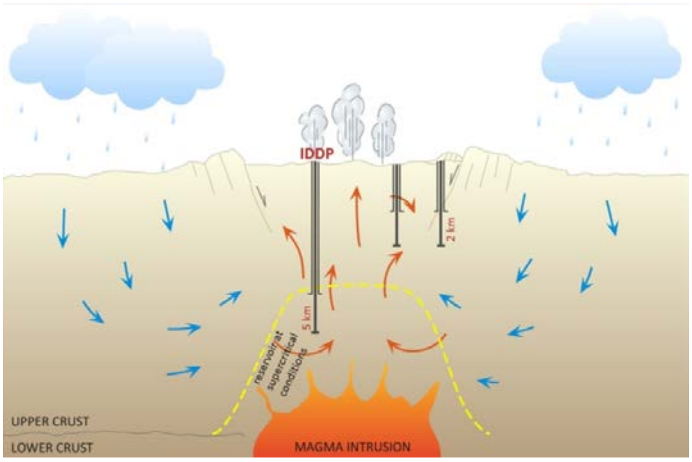

Figure 2 Molten rock level mixed with water. The ultimate heat and pressure stuck at this depth turn water to a "supercritical steam," which is neither a gas nor a liquid and holds 10 times more energy than conventional geothermal[8]

While the relations between rock permeability and brittle-ductile behavior, as well as reservoir simulations around magmatic intrusions, have received considerable interest, less attention has been drawn to the geochemical properties of such supercritical fluids. Fluids originating from degassing magma are rich in CO_2, SO_2, HCl, and HF. In contrast, supercritical fluids formed by boiling of subcritical geothermal water of meteoric or seawater origin are considered to display similar concentrations of many volatile elements (CO_2, H_2S, H_2, and B) as the original water, much lower than corresponding magmatic-gas concentrations, but negligible

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[4] S. Scott, T. Driesner, and P. Weis, "The thermal structure and temporal evolution of high-enthalpy geothermal systems," *Geothermics*, vol. 62, pp. 33–47, 2016.

[5] A. Stefànsson, "Gas chemistry of Icelandic thermal fluids," *Journal of Volcanology and Geothermal Research*, vol. 346, pp. 81–94, 2017.

[6] S. Scott, T. Driesner, and P. Weis, "Geologic controls on supercritical geothermal resources above magmatic intrusions," *Nature Communications*, vol. 6, no. 1, article 7837, 2015

[7] P. Weis, T. Driesner, and C. A. Heinrich, "Porphyry-copper ore shells form at stable pressure-temperature fronts within dynamic fluid plumes," *Science*, vol. 338, no. 6114, pp. 1613– 1616, 2012

[8] http://iddp.is/

nonvolatile element concentrations (Si, Na, K, Ca, and Mg). The formation of supercritical fluids may also produce a silica deposit around the magmatic intrusion [9] (Figure 3).

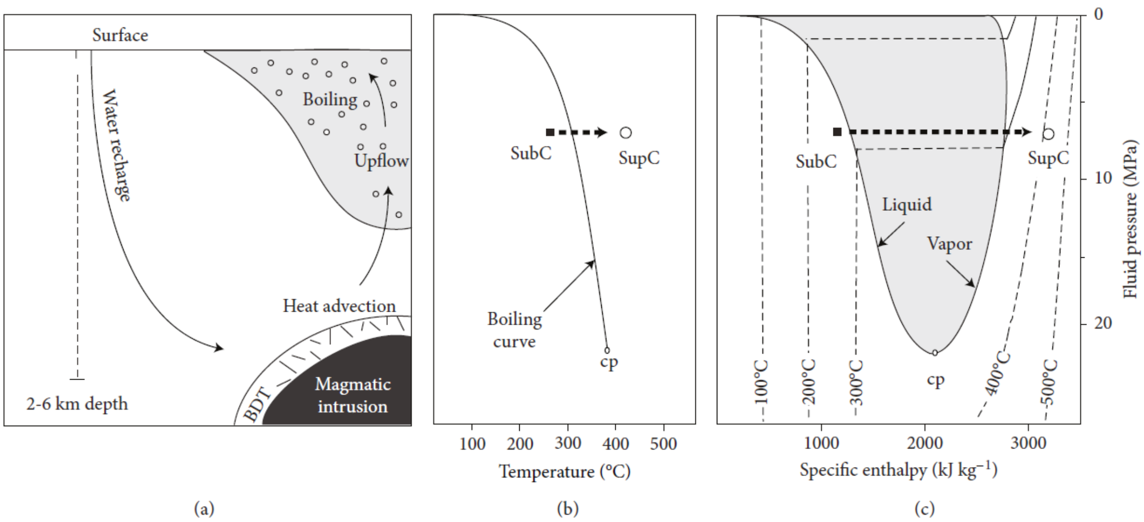

Figure 3 : Main characteristics of a volcanic geothermal system. (a) Conceptual model showing fluid flow paths, the brittle-ductile transition (BDT) between the magmatic heat source and the circulating geothermal fluid, and depressurization boiling near the surface. (b) The boiling curve of water. (c) The phase diagram of water showing pressure, specific enthalpy, and temperature relations. Also shown are the subcritical (SubC) to supercritical (SupC) conditions [10]

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

[9] M. Heřmanskà, A. Stefànsson, and S. Scott, “Supercritical fluids around magmatic intrusions: IDDP-1 at Krafla, Iceland,” *Geothermics*, vol. 78, pp. 101–110, 2019.
[10] Supercritical Fluid Geochemistry in Geothermal Systems, Matylda Heřmanská , Barbara I. Kleine, and Andri Stefánsson, Hindawi Geofluids Volume 2019, Article ID 6023534, 14 pages https://doi.org/10.1155/2019/6023534

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 have been documented [11, 12].

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 Worldwide Projects

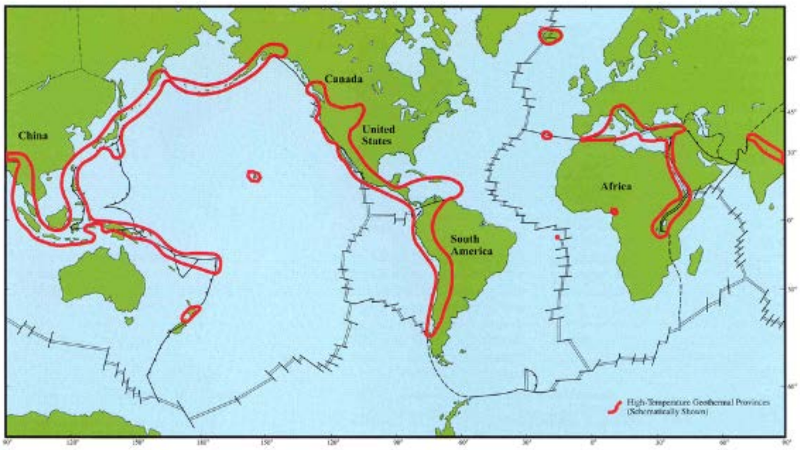

Figure 4 Outlined in red are the worldwide zones where very high enthalpy, possibly supercritical geothermal resources could exist at drillable depths. [13]

More than 25 deep wells sunk into the geothermal fields at

- Krafla, Nesjavellir, and Reykjanes (Iceland)
- Larderello (Italy);
- Kakkonda (Japan);
- The Geysers, Salton Sea, and Hawaii (USA);
- Los Humeros (Mexico);
- Taupo Volcanic Zone (New Zeland);
- Menengai (Kenya)

[11] Reinsch, T.,Huenges, E.,Bruhn, D.,Thorbjörnsson, I.,Gavriliuc, R.,andvan Wees, J.D.:Geothermal R&D, new projects and perspectives for applied as well as basic scientific research,European Geothermal Congress, (2016), 4 p

[12] www.geothermalresearch.eu

[13] https://www.researchgate.net/figure/Outlined-in-red-are-the-worldwide-zones-where-very-high-enthalpy-possibly-supercritical_fig3_274013081

have reached temperatures in excess of the critical temperature of water and, in some cases, have even encountered magma [14].

- Iceland Deep Drilling Project

Figure 5 The IDDP was founded in the year 2000 by a consortium of three Icelandic energy companies: (Hitaveita Sudurnesja (HS) (since 2008: HS Orka hf), Landsvirkjun (LV) and Orkuveita Reykjavíkur (OR)), and Orkustofnun (OS), the National Energy Authority of Iceland. [10]

The most extensive project aiming at obtaining supercritical fluids for geothermal utilization is the Iceland Deep Drilling Project [15] . In 2009, the IDDP-1 well at Krafla (NE Iceland) came to a halt after drilling into molten magma at about 2.1 km depth. After an initial heating period, the well discharged supercritical fluids with temperatures of about 440°C and eventually reached a maximum temperature of 459°C and specific enthalpy of about 3200 kJ kg^{-1}. From March 2010 until September 2011, series of flow tests were conducted; however, due to the corrosive nature of the fluids, silica scaling, and thermal damage to the well casings, utilization proved to be challenging and the fluid discharge was eventually terminated. In 2017, the second IDDP-2 well at Reykjanes (SW Iceland) reached its target depth of 4.6 km with a measured bottom hole temperature of 426°C. At present, fluid discharges from IDDP-2 at surface are not characterized by supercritical temperatures. Thus, deep reservoir fluid composition has been estimated from fluid inclusion analysis of felsic veins consisting of a vapor phase dominated by water (97.5 mol% H_2O, 1.5 mol% CO_2, 0.7 mol% H_2S, and traces of H_2), Cl-rich brine (Fe-K chlorides, sylvite-halide solid solutions), and sulfides [16].

[14] T. Reinsch, P. Dobson, H. Asanuma, E. Huenges, F. Poletto, and B. Sanjuan, "Utilizing supercritical geothermal systems: a review of past ventures and ongoing research activities," *Geothermal Energy*, vol. 5, no. 1, p. 16, 2017.

[15] http://www.iddp.is

[16] E. Bali, L. E. Aradi, Á. Szabó, Cs. Szabó, G. Ó. Friðleifsson, and R. Zierenberg, "Fluid composition in the deepest part of the IDDP-2 deep borehole in Iceland based on fluid inclusions," in *Acta Mineralogica-Petrographica Abstract series, ECROFI XXV abstract book*, p. 16, Department of Mineralogy, Geochemistry and Petrology, University of Szeged, 2019.

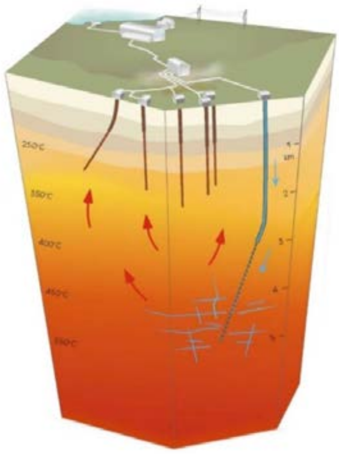

Figure 6 A conceptual model showing the EGS (Enhanced geothermal system) system in the Reykjanes field[17]

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 subsequent flow testing of the well to determine the nature of the formation fluids, their enthalpy, and flow characteristics, and hence their engineering and economic potential.

The IDDP consortium is organized and funded by an Icelandic energy consortium (HS Orka, Landsvirkjun, Reykjavik Energy, and 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 Comission 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. The International Continental Scientific Drilling Program (ICDP) and the US National Science Foundation (NSF) have also provided additional funding for this project.

- Krafla Magma Testbed project

Whereas the brittle–ductile transition zone was defined as the target for the IDDP project, the main goal of the Krafla Magma Testbed project is to closely observe, sample, and manipulate the transition zone from host rock to magma in order to test the concept of directly harnessing magmatic systems. An improved understanding of the roots of geothermal systems gained from dedicated research wells will be used to explore the potential for direct energy extraction from magma. This project plans to combine information obtained from downhole samples and subsurface measurements with surface geophysical and geochemical observations.[18] The connection zone between a hydrothermal and magma system has never been observed or sampled before. The KMT will enhance understanding of the coupling between these systems, using direct observations to infer mechanisms and fluctuations of mass and heat within a volcano [19]. The magma project,

[17] Fridleifsson, G.O., Bogason, S.G., Stoklosa, A.W., Ingolfsson, H.P., Vergnes, P, Thorbjörnsson, I.Ö., Peter-Borie, M., Kohl, T., Edelmann, T., Bertani, R., Sæther, S., and Palsson, B.: Deployment of deep enhanced geothermal systems for sustainable energy business, European Geothermal Congress 2016, (2016), 8 p

[18] Sigmundsson F, Eichelberger J, Papale P, Ludden J, Dingwell D, Mandeville C, Pye S, Markússon S, Árnason K, Ingólfsson H. Krafla magma testbed. In: GEORG geothermal workshop, Reykjavik, Iceland. 2016.

[19] https://www.kmt.is/

called Krafla Magma Testbed, will involve drilling a hole 2.1 kilometres deep directly into a magma chamber below the Krafla volcano in northern Iceland.

Figure 7 Krafla power station, Iceland

The first phase of the project is planned to start by 2020 and will cost $30 million, the British Geological Survey said in a statement on Friday about the study, which also aims to explore the mechanism of eruptions to protect communities from volcanic disasters. It said it was confident of securing the financing as a number of countries and companies had expressed interest in contributing, but did not give details.

- Larderello, DESCRAMBLE Project

Figure 8 The test site has been an existing dry well in Larderello, Italy, already drilled to a depth of 2.2 km and temperature of 350 °C, which was deepened to 2.9 km depth reaching supercritical conditions [20, 21]

The "Drilling in dEep, Super-CRitical AMBient of continentaL Europe" (DESCRAMBLE), running from May 2015 to April 2018, has developed novel drilling technologies for a proof-of-concept test of reaching deep geothermal supercritical resources. It has drilled and tested the continental-crust condition for demonstrating novel drilling techniques, the control of gas emissions and high temperature/pressure

[20] https://www.enelgreenpower.com/it
[21] http://www.descramble-h2020.eu/

conditions expected from the deep fluids. It has also improved knowledge of deep chemical-physical conditions for predicting and controlling future drilling conditions. The first-in-the-world intra-continental, mid-crustal borehole in very high temperature condition has been this test site, using an existing dry well in Larderello, Italy, already drilled to a depth of 2.2 km and temperature of 350 °C, which was deepened to 3 km depth. Larderello, the birthplace of geothermal power production, has been extensively explored and investigated for many decades. 2D and 3 seismic survey data highlighted an important deep seismic marker named “K-horizon” culminating below the currently exploited, vapor-dominated, reservoirs and recognizable throughout southern Tuscany. The high seismic impedance of this seismic marker, even resembling a bright-spot in some areas, was interpreted as due to magmatic/metamorphic fluids, possibly in super-critical conditions. Evidence strengthening this interpretation was provided by the exploratory well San Pompeo 2, drilled on 1979 to cross K-horizon. Before reaching the K-horizon, high-pressure fluids were unexpectedly encountered, and induced well blow-out and the eruption of a large amount of tourmaline-quartz breccia and vein fragments, which are typical of high temperature, magmatic hydrothermal systems occurring at the top of many granite intrusions in Tuscany. The chosen well, Venelle-2, is close to San Pompeo 2 well, and the drilling target, i.e. the pack of seismic reflections corresponding to the K-horizon, is particularly thick and shallow in this area. The site was considered perfect for such an experiment, as it is representative of deep crustal levels in Europe, is cost effective (since drilling for reaching the target is reduced to a minimum), and is practical due to the high probability of encountering extremely high temperature and pressures (supercritical condition).

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 [22].

Specific Objectives of the project were:

- Demonstrating safe drilling of a deep geothermal well and extremely high temperature and pressures (supercritical condition).
- Reducing the technical and financial risks of drilling and exploiting deep geothermal wells by improving knowledge of the physical and chemical conditions in deep geothermal formations.
- Reducing pre-drilling uncertainty in the exploration of deep geothermal wells.
- Improve in-situ characterization by developing a special tool for extremely high temperature and pressure measurements and by analyzing fluid and rocks samples of deep, supercritical conditions
- Investigating the economic potential of exploiting chemicals and minerals by analyzing fluid samples for valuable raw materials.

Innovative aspects are:

[22] Fridleifsson, G.O., Bogason, S.G., Stoklosa, A.W., Ingolfsson, H.P., Vergnes, P, Thorbjörnsson, I.Ö., Peter-Borie, M., Kohl, T., Edelmann, T., Bertani, R., Sæther, S., and Palsson, B.: Deployment of deep enhanced geothermal systems for sustainable energy business, European Geothermal Congress 2016, (2016), 8 p.

- Applied research/demonstrations of industrial component in an unconventional application
- Materials: Bottom hole assembly components, Cementing process, Drilling fluids, Well materials (casing, well head, and cement).
- Well design and control: the research will optimize new procedures, explicitly utilizing synergies with oil and gas industry.
- Predicting and controlling super-critical conditions: optimization of new procedures, explicitly using synergies with oil and gas industry. Existing simulators will be extended to the super-critical regime.
- Development of a new logging tool: suitable for measurement of pressure and temperature at supercritical conditions.
- Scientific research aspects: Seismic characterization of the super critical region, Petrophysics and log interpretation, Geochemical monitoring and Petrology.

➢ <u>Drilling of Supercritical Systems in Japan</u>

Figure 9 Kakkonda Geothermal Power Plant, Iwate, 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. This well, WD-1a, was drilled to a depth of 3729 m, and penetrated through the upper hydrothermal system int 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. 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 [23].

The Japan Beyond Brittle Project was initiated to investigate the feasibility of creating enhanced geothermal systems in the brittle-ductile transition zone [24,25].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 10). Evaluation of an uplifted young granite-porphyry system in this region [26] 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 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 be drilled into such a supercritical system.

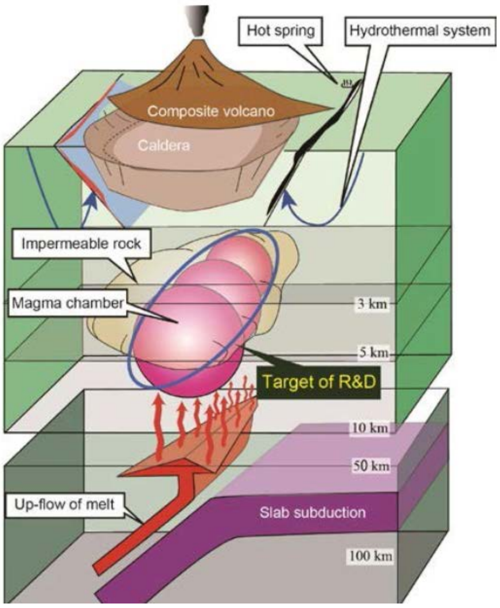

Figure 10 Conceptual model for supercritical geothermal systems in northern Honshu, Japan[25]. These systems lie above shallow magma chambers that are associated with Miocene and younger caldera complexes in the Tohoku region.

[23] Hashida, T., Hayashi, K., Niitsuma, H., Matsuki, K., Tsuchiya, N., and Nakatsuka, K.: Investigation of heat extraction from supercritical geothermal reservoirs, Proceedings, World Geothermal Congress 2000, Kyushu – Tohoku, Japan, (2000), 6 p.

[24] Muraoka, H., Asanuma, H., Tsuchiya, N., Ito, T., and the participants of the ICDP/JBBP Workshop: The Japan Beyond-Brittle Project, Scientific Drilling, 17, (2014), 51-59.

[25] Asanuma, H., Soma, N., Tsuchiya, N., Kajiwara, T., and Yamada, S.: Concept of development of supercritical geothermal resources in Japan, Proceedings, 2015 International Conference on Geothermal Energy in Taiwan, (2015), 66-68

[26] Tsuchiya, N., Yamada, R., and Uno, M.: Supercritical geothermal reservoir revealed by a granite–porphyry system. Geothermics, 63, (2016), 182-194

- Drilling of Supercritical Systems in the US

Figure 11 Geysers Geothermal Power, USA

Elevated temperatures have also been encountered in a number of geothermal systems in the United States[27]. 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 3672m [28]. 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 [29].

A temperature of 390 °C was reported for the IID-14 well in the Salton Sea geothermal field [30]. 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. 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

[27] Elders, W.A.: The potential for on- and off-shore high-enthalpy geothermal systems in the USA, Proceedings, 40th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California (2015), 9 p.
[28] https://www.conservation.ca.gov/dog/geothermal
[29] Garcia, J., Hartline, C., Walters, M., Wright, M., Rutqvist, J., Dobson, P.F., and Jeanne, P.: The Northwest Geysers EGS Demonstration Project, California Part 1: Characterization and reservoir response to injection, Geothermics, 63, (2016), 97-119.
[30] Kaspereit, D., Mann, M., Sanyal S., Rickard, B., Osborn, W., and Hulen, J.: Updated conceptual model and reserve estimate for the Salton Sea geothermal field, Imperial Valley, California, Geothermal Resources Council Transactions, 40, (2016), 57-66

thermal gradient resulting from this area representing a continental rift zone that transitions into a strike-slip plate boundary [31].

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[32] . 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 wellbeing 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.

- Drilling of Supercritical Systems in Mexico

Figure 12 GEMex project, a cooperation initiative between Mexico and the European Union

Within the Los Humeros geothermal field in Mexico, at least seven deep (> 2100 m) wells have estimated stabilized temperatures greater than 380°C [33,34]. 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. 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 is studied as part of the recently initiated GEMex project [35]. 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 uses innovative techniques and approaches of reservoir characterization, numerical modelling, and laboratory

[31] Shnell, J., Newman, J.S., Raju, A., Nichols, K., Elders, W.A., Osborn, W.L., and Hiriart L., G.: Combining high-enthalpy geothermalgeneration and hydrogen production by electrolysis could both balance the transmission grid and produce non-polluting fuel fortransportation, Proceedings, 41st Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California (2016), 6 p.

[32] Teplow, W., Marsh, B., Hulen, J., Spielman, P., Kaleikini, M., Fitch, D., and Rickard, W.: Dacite melt at the Puna geothermal venturewellfield, big island of Hawaii, Geothermal Resources Council Transactions, 33, (2009), 989- 994.

[33] Garcia, J., Hartline, C., Walters, M., Wright, M., Rutqvist, J., Dobson, P.F., and Jeanne, P.: The Northwest Geysers EGS DemonstrationvProject, California Part 1: Characterization and reservoir response to injection, Geothermics, 63, (2016), 97-119.

[34] Elders, W.A., Izquierdo-Montalvo, G., Aragon A., A., Tovar A., R., and Flores A., M.: Significance of deep zones of intense bleaching and silicification in the Los Humeros high-temperature geothermal field, Mexico: Evidence of the effects of acid alteration, Geothermal Resources Council Transactions, 38, (2014b), 497-502.

[35] http://www.gemex-h2020.eu/index.php?option=com_content&view=featured&Itemid=101&lang=en

experiments, in order to make this renewable energy source cost-effective and affordable both for electricity and heat production. The project has the goal to bring together the extended Mexican know-how of discovering, developing, and exploiting geothermal energy systems with a variety of European expertise from similar geothermal energy systems in Italy, Iceland, and other places. It also reports on main results of its activities, e.g. on preliminary 3D geological models of Los Humeros and Acolculco geothermal fields, characterising the influence of pre-existing structures on caldera evolution by analogue modelling. Further topics include: understanding from exhumed fossil geothermal systems, structure geology suitable for EGS development, geochemical characterization and origin of cold and thermal fluids, geophysical surveys in the geothermal fields, ongoing reservoir characterization studies, social impacts and public engagement on enhanced and superhot geothermal systems, ongoing research on drilling and completion in super-hot systems, and monitoring environmental impacts.

- New Zealand Hotter and Deeper Project Research

Figure 13 Wairakei geothermal facilities, Taupo/ New Zealand

Research efforts in New Zealand have included study of the deep (5-7 km) geothermal resource potential for the Taupo Volcanic Zone (Figure 13), which is estimated to have temperatures > 400 °C and a potential of 10 GWe [36]. 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. Researches used 3D MT modelling to provide evidence of deep-seated electrically conductive plumes down to 10 km depth that were interpreted to represent magmatic intrusions underlying hydrothermal systems. Were 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.

[36] Bignall, G. and Carey, B.: A deep (5 km?) geothermal science and drilling project for the Taupo Volcanic Zone – Who wants in?; Proceedings New Zealand Geothermal Workshop 2011, New Zealand, (2011), 5 p.

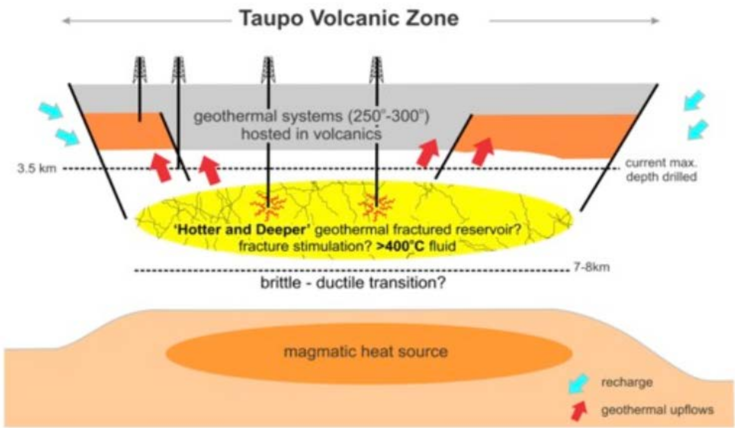

Figure 14 Conceptual model for the HADES project [37]

➢ Drilling of supercritical systems in Kenya

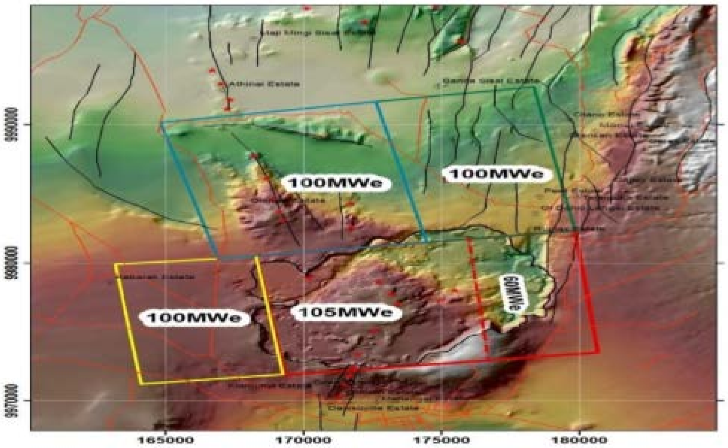

Figure 15 Menengai Development Blocks

Wells MW-04 and MW-06 in the Menengai geothermal field were drilled into magma, resulting in fresh quenched glassy cuttings at 2080 and 2172 m depth, respectively, suggesting the presence of a shallow intrusive heat source below the caldera summit [38]. The drill string got stuck while drilling these intervals. During production testing of MW-04, fluid entries were observed from overlying layers and a temperature of 390 °C was measured after 11 days of flow testing and about 1 month after the end of drilling. Pressures up to about 140 bar were observed during shut-in. At flowing conditions, bottom-hole pressure was observed to be about 20 bar. The development of the Menengai geothermal field is currently delayed due to drilling problems. Stuck pipe problems accounted for 12% of the total drilling time in this field and were often caused

[37] Bignall, G. and Carey, B.:A deep(5 km?) geothermal science and drilling project for the Taupo Volcanic Zone –Who wants in?ProceedingsNew Zealand Geothermal Workshop 2011, New Zealand, (2011), 5 p

[38] Mbia P, Mortensen A, Oskarsson N and Hardarson B. Sub-surface geology, petrology and hydrothermal alteration of the Menengai geothermal field, Kenya: case study of wells MW-02, MW-04, MW-06 and MW-07. In: Proceedings World Geothermal Congress 2015, Melbourne, Australia; 2015. p. 20

by lost circulation at permeable zones and long waits for drilling water. Drilling into liquid magma pushed the drill string up, resulting in drop of hook load. Simultaneously, circulation was blocked. Drilling at these high temperatures often leads to metal fatigue. A drill string risk management program was suggested to monitor any defects [39].

4. Exploration and Development of Supercritical Geothermal Resources On the Ocean Floor

Access to vast amounts of geothermal energy can be gained through the ocean floors, under which abundant geothermal resources can be found in a supercritical state.

According to the USGS (United States Geological Survey), the Earth's crust in continental landmasses averages approximately 30,000 meters in thickness, and can be as thick as 100,000 meters, but the thickness of the Earth's crust under the oceans averages about 6,000 meters and is less in some areas. The most promising area on the ocean floor is the oceanic rift zone, which wraps around the world "like the seams on a baseball", as described in a recent National Geographic production, "Drain the Ocean" [40].

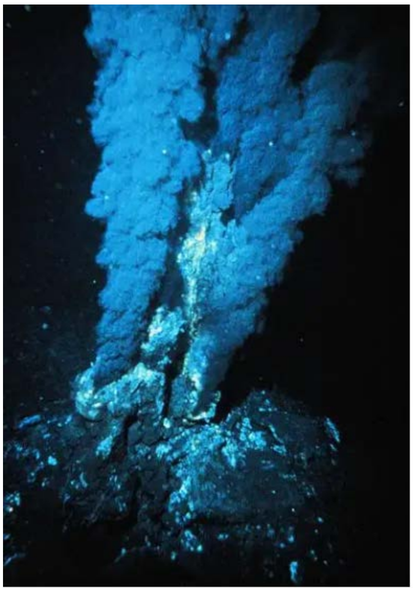

Figure 16 At over 3 kilometres beneath the surface, sitting atop what could be a huge bubble of magma, it's the hottest water ever found on Earth [41].

The development of geothermal resources is often challenged by expenses and difficulties of exploration and similar expenses and difficulties can be anticipated in the pursuit of new resources in the ocean floor. New opportunities, however, will also arise in this new context. For example, the plumes created by geothermal vents in the ocean can be detected across thousands of kilometres of ocean in exploring for active vent fields[42] .

[39] Makuk I. Reducing geothermal drilling problems to improve performance in Menengai, Geothermal Training Programme Reports 2013, Number 16. 2013

[40] Nicholls, S. and Coules, V., "Drain the Ocean," National Geographic Channel, August 9, 2009

[41] https://www.newscientist.com/article/dn14456-found-the-hottest-water-on-earth/

[42] Searle, R., Mid-Ocean Ridges, published by Cambridge University Press, 2013

The belief that plate tectonics is driven primarily by slab-pull forces has been the predominant view of experts for the past forty years. It is, however, now being replaced by the perception that half of the forces driving plate tectonics arise from the deep mantle. The earlier perception was the result of early estimates that the heat flux in the core-mantle boundary was no more than 4 TW. More recent estimates of the heat flux at the core-mantle boundary range from 14 to 20 TW, indicate that there may be much greater geothermal resources under the ocean crust than previously anticipated [43].

In addition, supercritical turbines are more efficient than steam turbines, and resource temperatures of 500 °C will enable the use of supercritical CO_2 turbines, which are much smaller (which is particularly beneficial under the pressures at the ocean floor) and even more efficient. Supercritical CO_2 in a closed-loop recompression Brayton cycle could have a plant efficiency of 50% [44]. This system combines the off-peak baseload electricity of this system with the direct use of the supercritical geothermal resource in a new style of cogeneration to produce low-cost hydrogen.

More recently, researchers have developed an analytical approach to using data from the Amphibious Array deployment of the Cascadia Initiative to show unusually high attenuation of teleseismic P and S waves and at the same time measuring P and S wave differential travel times across the array. This approach enables the gathering of significant information. For example, it shows dynamic upwelling under the Juan de Fuca Ridge from a depth of 200 kilometres below the crust. Such information could be a useful tool in determining where and how to drill geothermal wells [45].

One innovation is a self-contained, submersible, remote-controlled electric generating station that will sit on the ocean floor. This step would reduce the amount of drilling by 2,000 to 2,500 meters per well, which is the usual range of depth of the mid-ocean ridge, thus decreasing the cost and risk of drilling. The proposed approach would drill wells in the ocean floor to depths of 2,000 meters or more to access geothermal resources at supercritical temperatures and pressures. The station will use a supercritical turbine coupled to a generator for converting geothermal energy to electricity. Offshore drilling to the depths contemplated by this approach is currently practiced in the oil and gas industry. The largest oil field in the Gulf of Mexico is approximately 250 kilometres from shore. Recently, oil companies have drilled wells as deep as 8,000 meters beneath the ocean floor in water as deep as 2,800 meters.

Drilling for geothermal resources will, however, be conducted in basalt, rather than sedimentary rock, a harder formation that is more difficult to drill. Nevertheless, geothermal wells in Iceland are drilled in basalt; wells 2,000 meters deep are estimated to cost about $5,000,000 per well [46].

A significant advantage to drilling offshore is the shallower drilling depth at which supercritical geothermal resources can be accessed. Another major advantage is that the reservoirs are more sustainable, because the heat flow through the ocean floor is much higher. Also, there is a virtually unlimited supply of saline water

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[43] Rowley, D. B., A. Forte, C. Rowan, P. Glišović, R. Moucha, S. Grand and N. Simmons, "Kinematics and dynamics of the East Pacific Rise linked to a stable, deep-mantle upwelling," Science Advances, December 2016, in http://advances.sciencemag.org/content/2/12/e1601107

[44] Shnell, J., W. A. Elders, R. Kostecki,3 K. Nichols,4 W.L. Osborn ,5 M.C. Tucker ,3 J.J. Urban,3 and E.D. Wachsman, "Supercritical Geothermal Cogeneration: Combining Leading-Edge, Highly-Efficient Energy and Materials Technologies in a Load-Following Renewable Power Generation Facility," Geothermal Resources Council Transactions, Vol. 42, 2018.

[45] Eilon, Z., and Abers, G., "High Seismic Attenuation at a Mid-Ocean Ridge Reveals the Distribution of Deep Melt") Science Advances, May 2017, in https://www.researchgate.net/publication/317155367_High_seismic_attenuation_at_a_mid-ocean_ridge_reveals_the_distribution_of_deep_melt

[46] Friðleifsson, G. Ó., Iceland Deep Drilling Project, private conversation on October 1, 2013.

with which to create or enlarge geothermal reservoirs, if Enhanced Geothermal Systems (EGS) are necessary, or to recharge existing reservoirs [47]

5. 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 [48].

- The HiTI project focused on developing high temperature tools and methods for characterizing and exploiting supercritical geothermal systems. 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 and high temperature tracers.
- 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 (Integrated Methods for Advanced Geothermal Exploration) 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.
- 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.
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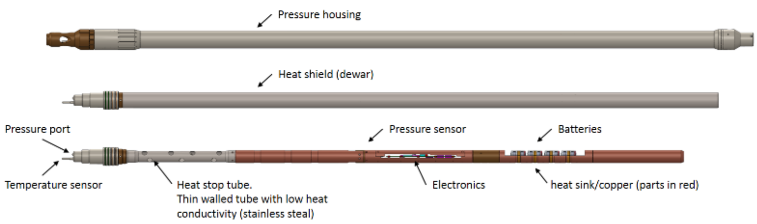

Figure 17 (Top)The complete tool with pressure housing. Temperature sensor and pressure port to the left (nose) and connection for the slick line wire to the right. (Middle)Pressure shield and nose protector removed. Picture show the nose of the tool and the heatshield. (Bottom) Heat shield removed. Pictures how the inner parts of the tool. Electronics located in the middle of the tool [49]

[47] Exploration And Development Of Supercritical Geothermal Resources On The Ocean Floor; PROCEEDINGS, 44th Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February 11-13, 2019 SGP-TR-214

[48] Patrick Dobson, Hiroshi Asanuma, Ernst Huenges, Flavio Poletto, Thomas Reinsch, et al.. Supercritical Geothermal Systems - A Review of Past Studies and Ongoing Research Activities. 42nd Workshop on Geothermal Reservoir Engineering, Feb 2017, Stanford, CA, United States. hal-01497951

[49] The First Results of the DESCRAMBLE Project; PROCEEDINGS, 43rd Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February12-14, 2018SGP-TR-213

6. Conclusion

Supercritical temperature conditions are often found at the roots of high-temperature geothermal systems. Supercritical pressure conditions are found in sufficiently deep wells or where impermeable layers were capable of trapping high-pressure conditions.

Deep geothermal heat represents a huge energy potential. The fluids contained in profound reservoirs are at supercritical thermodynamic conditions. Volumetric enthalpy of supercritical water is larger than common geothermal fluid because of its higher density [50].

- ✓ Dry steam at 370 °C and 40 bar has a density of 14.43 kg/m^3 and contains 45.354 kJ/m^3 of heat. The density of supercritical water at 350 bar and 400°C is 475 kg/m^3 and contains almost 106 kJ/m^3 of geothermal heat.
- ✓ Supercritical reservoirs at high temperature and pressure, beyond the critical point, could provide more than 20 times as much enthalpy per cubic meter as the geothermal fluids used with present current technology.
- ✓ Deep geothermal heat will be able to generate, i the next future, more electricity, more efficiently, cleaner energy, through special advanced turbine-generators adapted for supercritical fluids

Supercritical temperatures have been observed in shallower wells in cases where molten magma was hit, as in two wells in Menengai, Kenya, the IDDP-1 and K-39 wells in Iceland, and the KS-13 well in Hawaii. Pressure conditions in these wells were likely or reportedly lower than supercritical conditions. Wells encountering molten magma have been found to have a reasonable permeability in reservoir layers above the magma. For deeper high-temperature wells like the IDDP-2 and K-36 wells in Iceland, several wells at Los Humeros, Mexico, the Prati 32 well at The Geysers, IDD-14 at Salton Sea, KS-2 in Hawaii, USA, and Sasso 22 and San Vito 1 in Italy, no molten magma was found. However, zones of permeability were reported close to the bottom of some of these wells. In contrast, the deep (conductive) portion of the WD-1a well at Kakkonda or Lanipuna 1 on Hawaii did not encounter significant permeability.

For most of the wells where supercritical conditions were encountered, permeable zones were observed at depths and an inflow could be measured. For wells that encountered a magmatic intrusion, fluid emanated from the zone surrounding the magma layer, likely in a brittle state. For sites without recent intrusion, where proximity to a larger (solidifying) magma body can be assumed to be the heat source, observed permeabilities are often lower (e.g., at Kakkonda, Japan or Los Humeros, Mexico). Here, EGS-type concepts have to be considered, including stimulation technologies, thermally or hydraulically. Such concepts are currently being developed in the DEEPEGS, JBBP, and GEMex projects.

Different stress regimes and rock types may impact the ability to create and sustain open fractures under supercritical conditions. Testing and eventually producing high-temperature geothermal fluids from the current field laboratories in Iceland and Italy will help to validate new technology to handle the hostile downhole conditions.

A number of serious issues have been encountered while trying to handle and utilize fluids from geothermal reservoirs at temperature and pressure conditions exceeding the supercritical conditions of water. Early experiments in high enthalpy geothermal fields clearly identified bottlenecks in terms of exploration, drilling, completing, and monitoring.

[50] Thermodynamics of Deep Supercritical Geothermal Systems; M C Suárez-Arriaga 2019 IOP Conf. Ser.: Earth Environ. Sci.249 012019

The major engineering challenges remain valid today, although a lot of valuable experience was gained in recent drilling campaigns in Iceland. During some drilling campaigns, supercritical conditions were unexpected and therefore the well design was not appropriate to handle fluids at supercritical temperatures. This calls for better exploration and imaging technologies prior to drilling, as well as better reservoir models. To improve reservoir understanding at supercritical conditions, laboratory experiments at these conditions and numerical models capable of handling supercritical fluid conditions are also key.

Current developments to utilize supercritical geothermal reservoirs are mainly driven by the momentum from ongoing H2020 projects funded by the European Commission.

To further accelerate the development of high-temperature geothermal systems worldwide, a closer collaboration between associated research institutions and the geothermal industry is key [51].

Recent innovations described above relate to exploring for and developing supercritical geothermal resources, including the tracing of plumes from geothermal vents for thousands of kilometres across the ocean, the realization that a much greater heat flux at the core-mantle boundary creates an ongoing source of magma and hot rock to drive upwelling along the mid-ocean ridges, and the use of a more sophisticated analysis of seismic wave data to gather data on upwelling and other activity in the rift zones to a depth of 200 kilometres.

These innovations confirm the existence of and aid in the development of the supercritical geothermal resources to power supercritical Brayton-cycle turbine generators and supercritical electrolysis in cogeneration to provide electricity to balance intermittent power and hydrogen to replace fossil fuels, with energy left over to drive innovative desalination and mineral extraction processes. Together, these innovations will create a unified energy industry that operates entirely from renewable resources, on a balanced and sustainable basis [52].

[51] Utilizing supercritical geothermal systems: a review of past ventures and ongoing research activities Thomas Reinsch, Patrick Dobson, Hiroshi Asanuma, Ernst Huenges, Flavio Poletto and Bernard Sanjuan; Reinsch et al. Geotherm Energy (2017) 5:16 DOI 10.1186/s40517-017-0075-y

[52] PROCEEDINGS, 44th Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February 11-13, 2019 SGP-TR-214