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Investigating ultra high-enthalpy geothermal systems: a collaborative initiative to promote scientific opportunities

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Abstract. Scientists, engineers, and policy makers gathered at a workshop in the San Bernardino Mountains of southern California in October 2013 to discuss the science and technology involved in developing high-enthalpy geothermal fields. A typical high-enthalpy geothermal well between 2000 and 3000 m deep produces a mixture of hot water and steam at 200–300 °C that can be used to generate about 5–10 MWe of electric power. The theme of the workshop was to explore the feasibility and economic potential of increasing the power output of geothermal wells by an order of magnitude by drilling deeper to reach much higher pressures and temperatures. Development of higher enthalpy geothermal systems for power production has obvious advantages; specifically higher temperatures yield higher power outputs per well so that fewer wells are needed, leading to smaller environmental footprints for a given size of power plant. Plans for resource assessment and drilling in such higher enthalpy areas are already underway in Iceland, New Zealand, and Japan. There is considerable potential for similar developments in other countries that already have a large production of electricity from geothermal steam, such as Mexico, the Philippines, Indonesia, Italy, and the USA.

However drilling deeper involves technical and economic challenges. One approach to mitigating the cost issue is to form a consortium of industry, government and academia to share the costs and broaden the scope of investigation. An excellent example of such collaboration is the Iceland Deep Drilling Project (IDDP), which is investigating the economic feasibility of producing electricity from supercritical geothermal reservoirs, and this approach could serve as model for future developments elsewhere. A planning committee was formed to explore creating a similar initiative in the USA.

1 Introduction

This workshop was under the aegis of DOSECC (Drilling, Observation and Sampling of the Earths Continental Crust), a consortium of United States universities with investigators that are interested in research involving subsurface sampling, measurement and observation. DOSECC is actively seeking to engage a wider earth science community by sponsoring five workshops on different topics where the science being investigated requires drilling (see www.dosecc.org). This initiative is designed to foster a more integrated continental scientific drilling program that will strengthen scientific drilling in the USA and interact in more fruitful ways with the International Continental Scientific Drilling Program (see http://www.icdp-online.org/home/).

The workshop had two objectives: firstly to discuss scientific studies of active very high enthalpy hydrothermal systems and, secondly, to stimulate collaboration between academic scientists, government agencies, and industry. Such collaboration is highly desirable because the scientific study of active hydrothermal systems requires drilling and sampling boreholes whose costs far exceed budgets normally available to academic scientists; it is industry that drills wells to access geothermal resources. Although drilling into these deep unconventional geothermal reservoirs is more expensive, the higher productivity per well should offset this by reducing the number of wells needed for a given power output (Friðleifsson and Elders, 2005). Developing these resources would make available new large and environmentally benign sources of alternative energy. In addition, such developments would make important scientific contributions. It would permit major advances in our understanding of active hydrothermal processes that are important on a global scale but are not otherwise available for direct investigation (Elders and Friðleifsson, 2010). These include the coupling of magmatic and hydrothermal systems and their mass and energy transfer, hydrothermal ore formation in magma-ambient conditions, the transition from low to higher grade metamorphism, and aspects of volcanic hazards.

The participant list and program of the workshop appear as appendices to this report, and the talks presented at the workshop are available on the workshop website: http://csdworkshops.geo.arizona.edu/Lake_Arrowhead_CA.html. Two scientists from New Zealand, two from Mexico, and one from each of Iceland, Italy, Philippines, and Russia participated in the workshop. This led to discussions of programs in various countries that are currently investigating, or planning to investigate, "ultra high-enthalpy" geothermal systems.

Plans for deep drilling to explore for deeper, much higher enthalpy, geothermal resources are already underway in Iceland (Iceland Deep Drilling Project), in the Taupo Volcanic Zone of New Zealand (Project HADES), and in northeast Japan the Beyond-Brittle Project (JBBP), which is an ambitious program attempting to create an enhanced geothermal system (EGS) reservoir in ∼ 500 °C rocks. Although there is a significant undeveloped potential for developing high-enthalpy geothermal systems in the western USA, Hawaii and Alaska, there is no comparable national program to develop such resources. The main difficulty in implementing such programs is the very high cost in drilling deep into hostile environments.

2 The Iceland Deep Drilling Project

One approach to mitigating the cost issue is to form a consortium of industry, government and academia to share the costs and broaden the scope of investigation. An excellent example of such collaboration is the Iceland Deep Drilling Project (IDDP). The aim of IDDP is to produce geothermal energy from magma-hydrothermal systems at *supercritical* conditions, similar to environments found at depth on mid-ocean ridges. It is funded by an industry–government consortium (Friðleifsson et al., 2014). The drilling and well completion was funded by an industry–government consortium and the science sampling program by the ICDP and the US National Science Foundation (Friðleifsson et al., 2014).

In 2009 this industry–government consortium drilled a well in the volcanic caldera of Krafla in NE Iceland (Fig. 1).

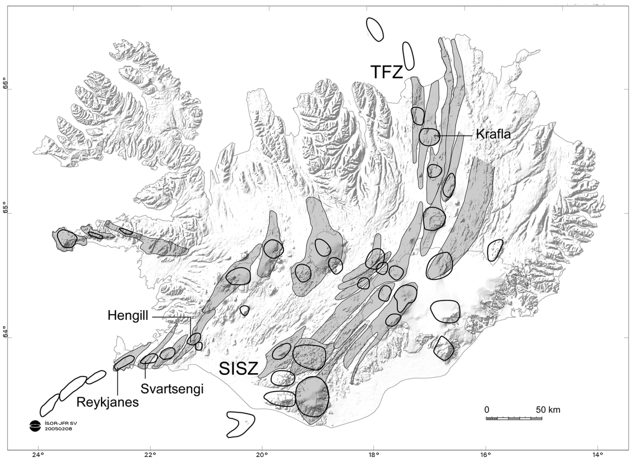

Figure 1. The location of rifting (shaded) in the neovolcanic zone of Iceland, an extension of the Mid-Atlantic Ridge. The map shows the location of the three high-enthalpy magma-hydrothermal systems – Krafla, Hengill, and Reykjanes – that are sites that were chosen for deep drilling by the Iceland Deep Drilling Project (IDDP). The irregular ellipses are active central volcanoes.

Continuing the search for supercritical geothermal resources in Iceland in 2014–2015, the IDDP will drill a new deep well on the Reykjanes Peninsula in SW Iceland that is the continuation of the Mid-Atlantic Ridge on land (Fig. 1; Friðleifsson et al., 2013). In the future, a third deep well will be drilled at Hengill, another high-temperature system.

The critical point for pure water occurs at 220 bar and 374 °C. Exceeding such pressure–temperature conditions, for likely pressure–temperature gradients, requires drilling to depths of 4 to 5 km (Fournier, 1999). Supercritical fluids have higher enthalpy and greatly enhanced rates of mass transfer relative to conventional lower-temperature geothermal resources (Dunn and Hardee, 1981; Hashida et al., 2001). Figure 2 shows that water at supercritical conditions with a temperature of 400 °C and a pressure of 250 bar has more than five times the power-producing potential than that of liquid water at 225 °C (Tester, 2006).

Geothermal wells in Iceland typically range up to 3.0 km in depth and produce a < 300 °C mixture of steam and water, at a rate sufficient to generate between 4 to 10 megawatts (MWe) of electricity. Modeling suggests that producing superheated steam from a supercritical reservoir could potentially increase the power output of geothermal wells by an order of magnitude relative to the output of lower enthalpy wells (Friðleifsson and Elders, 2005). A conventional dry-steam well with a downhole temperature of 235 °C and pressure of 30 bar with a volumetric flow rate of 0.67 $m^3\,s^{-1}$ can generate ∼ 5 MWe, whereas we estimate that a supercritical well at the same volumetric flow rate but with a downhole temperature of 430–550 °C and pressure of > 200 bar could generate ∼ 50 MWe. The IDDP aims to produce supercritical

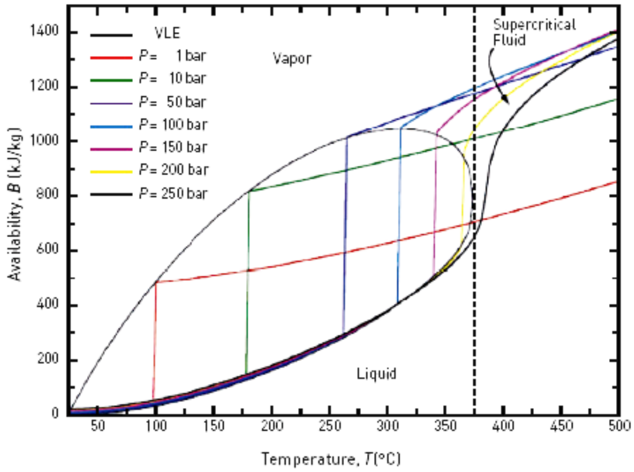

Figure 2. The availability diagram for pure water, i.e., its power-producing potential at specified specific-state conditions of temperature and pressure (Tester, 2006, Fig. 1.10).

Figure 3. The flow of the IDDP-01 into a rock muffler produced dry superheated steam with only 0.1–0.2 % of non-condensable gases. Initially corrosion products gave the steam a dark color, but after a few minutes it became clear and transparent. The condensate had a pH of 2.5–3 due to its HCL content. However, experiments on wet scrubbing to remove acid gases from the dry steam were very successful (Hauksson et al., 2014) (photograph courtesy of Kristján Einarsson).

fluid to the surface such that it transitions directly to superheated steam.

The IDDP-1 well

In 2009 the first IDDP well was drilled in the Krafla geothermal field within a volcanic caldera in the central active rift zone of NE Iceland (Fig. 1). At Krafla production wells drilled since 1971 supply steam to a 60 MWe geothermal power plant. During 1975–1984, a rifting episode occurred at the Krafla volcano, involving nine volcanic eruptions. A large magma chamber, believed to be the heat source of the active geothermal system, was detected by S wave attenuation at 3–7 km depth within the center of the caldera, and this was confirmed by a recent magnetotelluric survey. The well IDDP-1 was sited to reach 4.5 km depth close to the margin of this magma chamber (Friðleifsson et al., 2014). Difficulties were encountered during drilling this well due to caving that required cementing due to enlargement of the borehole, and getting stuck twice at 2100 m depth (Pálsson et al., 2014). The reason for these problems became clear when it became apparent that we were dealing with very high temperatures, as, at a depth of 2104 m, > 900 °C rhyolitic magma flowed into the drill hole and filled the bottom 9 m. Our studies indicate that this magma formed by partial melting of hydrothermally altered basalts within the Krafla caldera (Elders et al., 2011; Zierenberg et al., 2013). The decision was made to terminate drilling, cement production casing, allow the well to heat, and to flow test the well (Hauksson et al., 2014) (photograph courtesy of Kristján Einarsson).

The resultant well had very high enthalpy and produced superheated steam from the contact zone above the intrusion (Fig. 3). With a well-head temperature of ∼ 450 °C and a well-head pressure of up to 138 bar, it became the hottest producing geothermal well in the world, and, with a flow rate of 45 kg s^{-1} of dry superheated steam, it was estimated to be capable of generating > 35 MWe (Hauksson et al., 2014). In July 2012, after 10 months of full-scale flow, the well was shut down to recondition some of the surface equipment.

The future utilization of this magmatic resource at Krafla is still being discussed. It may be possible to recondition the IDDP-1, or several new wells could be drilled towards the contact zone of the magma. Ideally building completely new high-enthalpy turbines would be preferable, as the existing turbines at Krafla have an inlet pressure of only 7 bar. In the future it may even be possible to produce energy directly from the magma, either utilizing a downhole heat exchanger or by creating the world's first EGS production and injection wells in magma.

3 Wider applications

The IDDP-1 well engendered considerable international scientific and engineering interest. A special issue of the journal *Geothermics* was published in January 2014 reporting some of this work. In contrast to the freshwater system at Krafla, the Reykjanes geothermal system, which lies directly on the landward extension of the Mid-Atlantic Ridge, produces hydrothermally modified seawater. Processes at depth at Reykjanes should be quite similar to those responsible for black smokers on oceanic rift systems (Elders and Friðleifsson, 2010; Friðleifsson et al., 2013). If new IDDP wells at Reykjanes and Hengill prove successful, this could trigger similar activities elsewhere. In the future such very

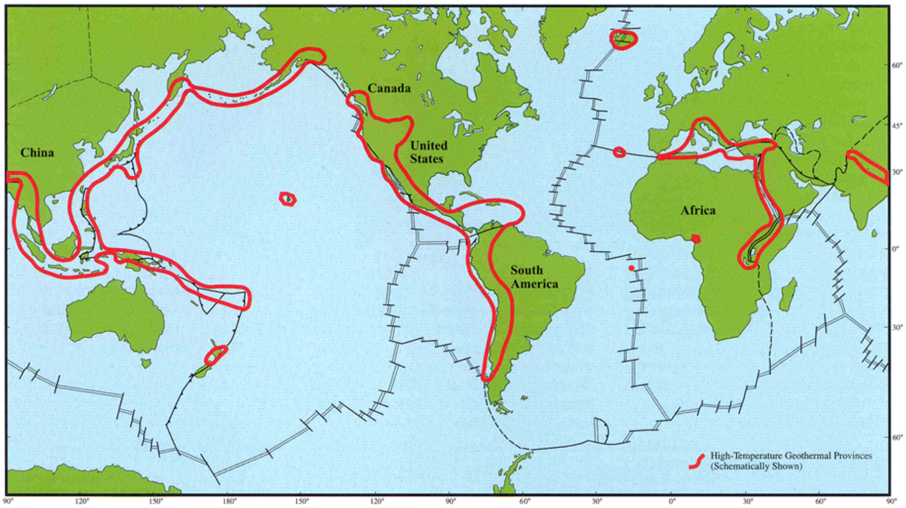

Figure 4. Outlined in red are the worldwide zones where very high enthalpy, possibly supercritical geothermal resources could exist at drillable depths.

high enthalpy geothermal systems could become significant resources worldwide, wherever suitable young volcanic geothermal systems occur (Fig. 4).

3.1 Developing "ultra" geothermal resources

Developing such ultra high-enthalpy supercritical geothermal resources at drillable depths is most credible

- at young volcanic rocks along plate boundaries and at hot spots
- near shallow, still hot (or partially molten) igneous intrusions
- at well-established high-enthalpy geothermal fields – for example in
  - Iceland – Reykjanes, Hengill, Krafla
  - Northeast Japan (JBBP)
  - New Zealand in the Taupo Volcanic Zone (HADES)
  - Philippines, Indonesia, Italy, Mexico (Cerro Prieto, Los Humeros)
  - USA – Hawaii, California, the Cascade Volcanic Chain, the Basin and Ranges, Alaska, etc.

In fact, projects comparable but differing in approach to the IDDP are already underway in both Japan and New Zealand. The plan in Japan is to drill beyond the brittle ductile transition in a 500 °C or hotter neo-granite and to thermally fracture the rocks to form permeability in the ductile zone and thus create a contained EGS system (Fig. 5) as is explained on the website (http://www.icdp-online.org/fileadmin/icdp/projects/doc/jbbp/JBBP_Concept_poster_En.pdf). The expectation is that a combination of government and industry funding will permit drilling to begin in 2 or 3 years.

A similarly ambitious project is underway in New Zealand, although possibly not so far advanced as the IDDP or the JBBP. Hotter and Deeper Exploration Science (HADES) is a long-term program of exploration and assessment in the Taupo Volcanic Zone in the North Island of New Zealand that aims to use geological, geochemical and geophysical data to assess the resource potential of deep geothermal systems in the Taupo Volcanic Zone (Fig. 6). Preliminary indications of this "Hotter and Deeper" project suggest that by 2025 New Zealand's deep geothermal resources (3–7 km) could supply at least 20 % of New Zealand's electricity requirement. Conservative estimates point to the total potential of accessible deep geothermal resource in the Taupo Volcanic Zone (TVZ) exceeding 10 000 MWe (see www.gns.cri.nz/Home/Our-Science/Energy-Resources/Geothermal-Energy/Research/Hotter-and-Deeper).

3.2 The potential for ultra geothermal resources in the USA

In contrast to the activities in Iceland, Japan, and New Zealand, there is no systematic activity in the USA directed towards developing ultra geothermal resources. This is not because valid targets for exploration for high-enthalpy geothermal resources are lacking. As shown in Fig. 7, an early estimate of the geothermal resource base of magma-ambient systems in the USA suggested that the potential of that resource was huge, exceeding even the estimate of enhanced geothermal systems ("hot dry rock resources" = EGS).

For more than a decade the US Department of Energy had a *magma energy program* aimed at extracting high-enthalpy energy directly from magma, using a downhole heat exchanger. A special issue of the *Bulletin of the Geothermal*

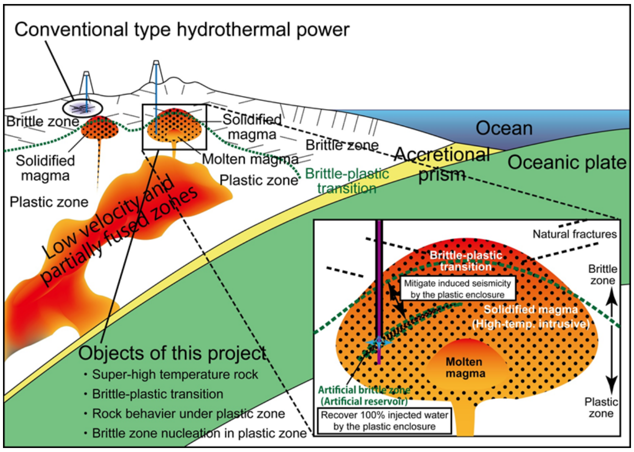

Figure 5. The principles behind the Japan Beyond the Brittle Project (JBBP). Figure courtesy of H. Asanuma (National Institute of Advanced Industrial Science and Technology, AIST), Japan.

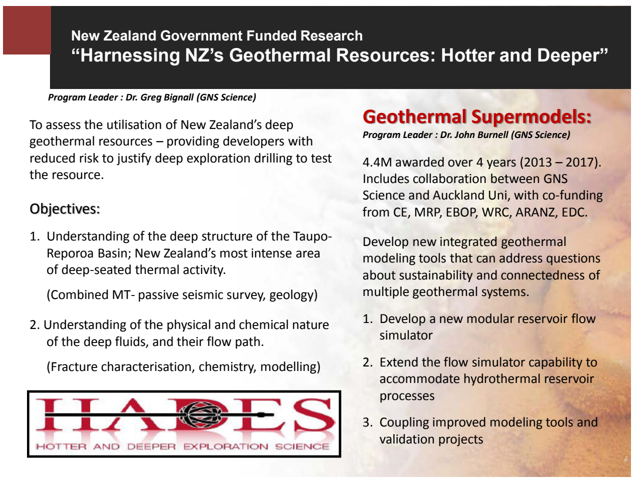

Figure 6. The aims of Project HADES in New Zealand. Figure courtesy of Ted Bertrand (GNS-Science, New Zealand).

Resources Council in 1990 was devoted to discussing that concept (Eichelberger and Dunn, 1990). After a nation-wide study (Finger and Eichelberger, 1990), the Long Valley Caldera in California was chosen as the optimum site in the USA to drill into magma. A drilling rig began drilling a well designed to reach a depth of almost 7 km to reach a magma chamber believed to exist below the caldera. However, due to funding problems, it was abandoned far short of its target, at less than 3 km depth where the temperature was only 120 °C (Bender-Lamb, 1991). A more recent assessment of geothermal resource base to 10 km depth in the USA is shown in Table 1 for different categories of geological environment as reported in Tester (2006). The major thrust of that report was to assess the potential of enhanced (or engineered) geothermal systems (EGSs) in the USA, and it greatly increased the assessment of the EGS resource base of the USA in crystalline

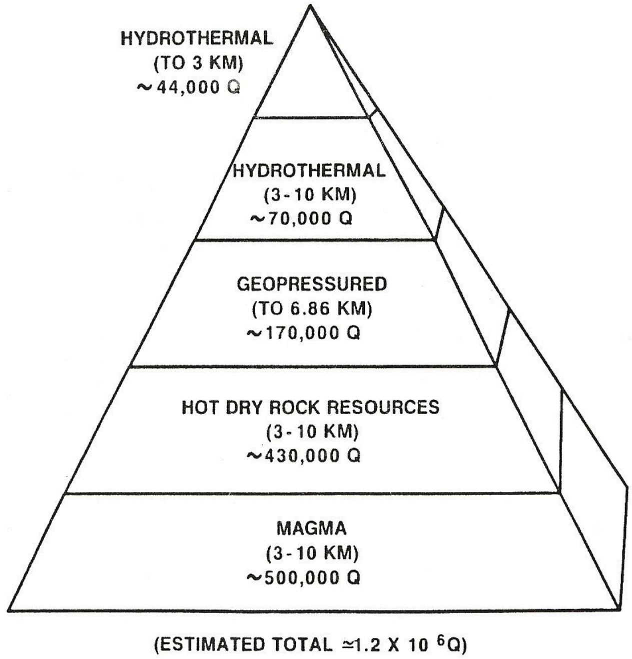

Figure 7. An early estimate of the resource base in various geothermal environments indicated that magma-ambient systems have a very large potential. Q = quad or 10^{15} BTU or about 1 exajoule = 10^{18} J (source: White and Williams, 1975, USGS Circular 726).

basement rocks over the estimate made in 1975. The overall conclusion of that comprehensive assessment was clearly that the largest part of the EGS geothermal resource base resides in the form of thermal energy contained in sedimentary and basement rocks that are heated by radiogenic heat sources and conductive heat transfer. The size of its resource base is orders of magnitude greater than the resource base of "conventional" geothermal systems in permeable rocks that are associated with volcanic-related hydrothermal temperature anomalies. However, as Table 1.1 from Tester (2006) shows, *supercritical volcanic* EGS also has a large potential in the USA.

Although field experiments to create EGS in crystalline rocks began in the USA in the 1970s, at present *all* of the 3400 MWe of geothermal power currently generated in the USA comes from conventional hydrothermal systems. Since the early experiments in the USA, development of EGS resources has been attempted in the UK, France, Japan, Australia, Sweden, Germany, and Switzerland. However today the total world installed generating capacity from EGS is less than about 10 MWe, and in each case its development has required large government subsidies. These EGS experiments have largely focused on systems with temperatures less than 300 °C (and in some cases only 200 °C as deep as 5 km). This slow development is a function of both some of the inherent technological difficulties and economic limitations of low to moderate enthalpy EGS.

Table 1. Estimated US geothermal resource base to 10 km depth by category.

Category of resource	Thermal energy in exajoules (1 EJ = 10^{18} J)	Reference
Conduction-dominated EGS		
Sedimentary rock formations	100 000	Tester (2006)
Crystalline basement rock formations	13 300 000	Tester (2006)
Supercritical volcanic EGS[1]	74 100	Muffler et al. (1979)
Hydrothermal	2400–9600	Muffler et al.(1979)
Coproduced fluids	0.0944–0.4510	McKenna et al. (2005)
Geopressured systems[2]	71 000–170 000	White et al. (1975)

[1] Excludes Yellowstone Park and Hawaii
[2] Includes methane content
Source: Table 1.1, Tester (2006)

3.3 Developing a project to develop "ultra" geothermal system

One outcome of the workshop was the formation of a planning committee (consisting of the authors of this report) to develop a project similar to the IDDP in the USA. Implementation of such a plan will require formation of a consortium with participation from industry, government agencies, and universities. The planning committee is tasked with the creation and implementation an "ultra geothermal development project in the USA". Ultra geothermal resources are magma-ambient and/or supercritical geothermal systems that have much higher enthalpy and pressures than the geothermal systems that are currently utilized to generate electricity today.

Unlike the situation in the UK, France, Australia, Germany and Switzerland, as Table 1 shows, there is a large potential to develop supercritical volcanic EGSs in the USA. In addition supercritical hydrothermal geothermal systems not requiring EGS technology could be developed where convective heat transfer operates due to the existence of appropriate combinations of pressure, temperature and lithology. In basaltic terrains, such as in Iceland, the brittle ductile transition occurs at much higher temperatures than in the granitic terrains such as those being investigated by the JBBP. Today there is revived and growing interest in investigating high-enthalpy geothermal systems in the USA (Elders, 2013; Elders et al., 2014).

3.4 The aims of ultra geothermal development projects

- improve the economics and efficiency of base load electrical power production from sustainable geothermal resources without increasing their environmental footprint
- explore and demonstrate the feasibility of increasing geothermal electrical power production by approximately an order of magnitude through production of ultra high-enthalpy geothermal fluids
- create projects for developing ultra high-enthalpy resources that build upon those already underway in Iceland (IDDP), Japan (JBBP), and New Zealand (HADES)
- promote and enhance collaboration amongst governmental agencies, industry, and academia in the USA and internationally, to advance the capitalization, study, and development of ultra high-enthalpy as sustainable geothermal resources
- through such collaboration, to develop multidisciplinary approaches and best practices for site selection in the exploration for ultra high-enthalpy geothermal resources in the USA
- identify candidate sites where a drilling project targeting ultra high-enthalpy fluids has the greatest potential for transforming the ability of geothermal energy to contribute to sustainable, electrical power production
- explore the potential of using EGS technology to optimize electrical power production from ultra high-enthalpy geothermal resources
- develop the science and technology for ultra high-enthalpy exploration and development that is transferable to other earth and materials science applications
- enhance our understanding of fundamental problems in the earth sciences including ore genesis, very high-temperature fluid–rock interactions, and magmatic/hydrothermal transitions
- educate and train the future work force and create new employment opportunities in this field of green sustainable energy.

3.5 The criteria for site selection for the UGDP include

- The site must contain ultra high-enthalpy resources at depths attainable by current drilling technology on the basis of existing surface and subsurface data.

- The site must have substantial infrastructure, access, and permitting, as well as availability to power and testing facilities.

- The site must have an existing operator *willing* to be an *active partner* in this project.

- The site should maximize the scientific and technological benefits and transferability for a given capital investment.

- The initial site must be one in which this project could readily demonstrate the proof of concept that the development of ultra high-enthalpy resources is viable.

3.6 Some advantages and potential barriers to creating an UGDP

The principal barrier to creating programs to develop magma-ambient and supercritical geothermal resources is their high costs. The obvious solution therefore is to share the costs between industry and government, with involvement of national laboratories and university scientists and engineers participating and providing scientific and technical input.

Among the potential advantages of such collaboration with strong industrial involvement is that industry can furnish access to the following:

- "holes of opportunity", i.e., deepening boreholes that are sited and drilled by industry in geothermal areas

- large and flexible funding sources

- industry databases relevant to site selection

- industry leasing and permitting

- industry technical expertise, equipment, and infrastructure.

Among the reasons why such collaborations have previously not been more common are the following:

- industry's concern with protecting propriety data and leaseholds in competitive situations

- it is complicated and time-consuming

- the long lead time for return on investment for the industry partner

- it requires coordination of multiple funding sources and timetables.

To overcome these disadvantages requires good faith by all parties, patience, flexibility, mutual understanding, backup plans, and an optimism that continued progress will overcome obstacles with collaboration. This requires having clearly enunciated and understandable scientific and technical goals, seizing opportunities, building working relationships based on trust, stressing benefits to both parties, being flexible, and educating funding agencies about timetable constraints and drilling contingencies. This can be done, as was demonstrated by the IDDP.

4 Conclusions

Approaches to improving the economics of the geothermal industry development of ultra geothermal resources could reduce the number of wells needed and increase the power output of each well, by producing supercritical fluid and/or high-enthalpy dry superheated steam. The potential impact of utilizing geothermal resources at supercritical conditions could become quite significant. This would call for re-evaluation of the geothermal energy resource base not only on a local scale but also on a global scale. Accessing supercritical fluids within drillable depths could yield a significant enlargement of the accessible geothermal resource base.

The *practical significance* of attempting to implement an ultra geothermal development project in the USA, and elsewhere in the world, includes the following:

- Fewer wells are needed for a given power output.

- The power cycle has a higher thermodynamic efficiency.

- For a given power output, the "environmental footprint" is smaller.

- Already developed geothermal fields would have increased sustainability.

The *scientific significance* of investigating ultra geothermal systems is that it allows direct study of active

- supercritical phenomena

- coupling of hydrothermal and magmatic systems

- hydrothermal alteration and ore formation

- fluid circulation at continental rift systems analogous to that at mid-ocean ridges and black smokers

- related volcanic hazards.

Supercritical zones are most important for the practical goals of the ultra geothermal development project. It is predominantly there that mobile fluids are heated and interact chemically with their host rocks, where most of the geologically important heat flow, chemical alteration, and hydrothermal ore formation take place. Supercritical fluid–rock interactions are important in the overall heat and fluid budgets of mid-ocean ridges. Studying analogous systems on land is much more practical than drilling from a ship in 3 km of water. And finally supercritical fluid and/or superheated steam represent an attractive source of electric power generation.

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