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A Proposal to Promote the Development of Higher Enthalpy Geothermal Systems in the USA

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ABSTRACT

In the USA, after more than 50 years of development, only about 0.33% of the country's total installed electrical capacity is currently being produced from geothermal resources and the growth rate of this environmentally "green" energy resource is overshadowed by that of wind and solar energy. However, most of the new geothermal developments in the USA involve only relatively small, moderate-temperature, geothermal systems. In contrast, 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 a smaller environmental footprint for a given size of power plant. Unfortunately locations of suitable very high enthalpy geothermal systems are restricted to young volcanic terrains. Furthermore,, production of very high enthalpy fluids usually requires drilling deeper wells and may require enhanced geothermal (EGS) technology. Similarly drilling deep into hot hostile environments is technologically challenging. None-the-less, there is considerable undeveloped potential in the USA that could yield very favorable economic returns and this suggests that we should begin to develop such a program.

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 an investigation. An excellent example of such a collaboration is the Iceland Deep Drilling Project (IDDP) which is investigating the economic feasibility of producing electricity from *supercritical* geothermal reservoirs. At Krafla in northeast Iceland the IDDP developed the world's hottest geothermal well, capable of generating >35 MWe from superheated steam at a well-head temperature of ~450°C. Plans for deep drilling to explore for much higher enthalpy, geothermal resources are also underway in the Taupo Volcanic Zone of New Zealand (Project HADES), and in northeast Japan the "Beyond Brittle Project" (Project JBBP) is an ambitious program attempting to create an EGS reservoir in ~500 C rocks. However, there is no comparable national program to develop such resources in the USA, in spite of the fact that there is significant undeveloped potential for developing high-enthalpy geothermal systems in the western USA, Hawaii and Alaska, both on and offshore. Forming a consortium to systematically explore, assess, and eventually develop such higher-enthalpy geothermal resources and to stimulate the necessary scientific and engineering investigations is a necessary first step.

1.0 INTRODUCTION

The aim of this paper is to encourage the formation of programs designed to investigate the geothermal resources that are beyond the upper temperature range of those currently produced in the USA along the lines of 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, Elders and Albertsson, 2014). The IDDP's drilling and well completion activities are funded by an industry-government consortium and the science sampling program has been funded by the ICDP (International Continental Scientific Drilling Program) and the US NSF (National Science Foundation (Friðleifsson, Elders and Albertsson, 2014).

In 2009, this industry-government consortium drilled a well in the volcanic caldera of Krafla in NE Iceland (Figure 1). Continuing the search for supercritical geothermal resources in Iceland in 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 (Figure 1; Friðleifsson, Elders, and Bignall, 2013; Elders et al., 2014). In the future, a third deep well will be drilled at Hengill, another mid-ocean ridge type high- temperature system on land.

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

In Iceland geothermal wells typically range up to 3.0 km in depth and produce a <300^{o}C mixture of steam and water, at flow rates sufficient to generate between 4 to 10 megawatts (MW) of electric power. 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). According to Albertsson et al.(2003) a conventional dry-steam well with a down hole temperature of 235°C and a wellhead pressure of 25 bar$_a$ with a typical volumetric flow rate of 0.67 m^3/s (or about 3.6 x 10^4 bpd) can generate ~5 MWe, whereas they estimate that a supercritical well at the same volumetric flow rate, but with a down hole temperature of 430-550°C and a wellhead pressure of 230-260 bar$_a$ could generate ~50 MWe. A supercritical well may thus afford a tenfold improvement in power output over that from a typical conventional well. The IDDP aims to produce supercritical fluid so that it transitions directly to superheated steam as it flows to the surface.

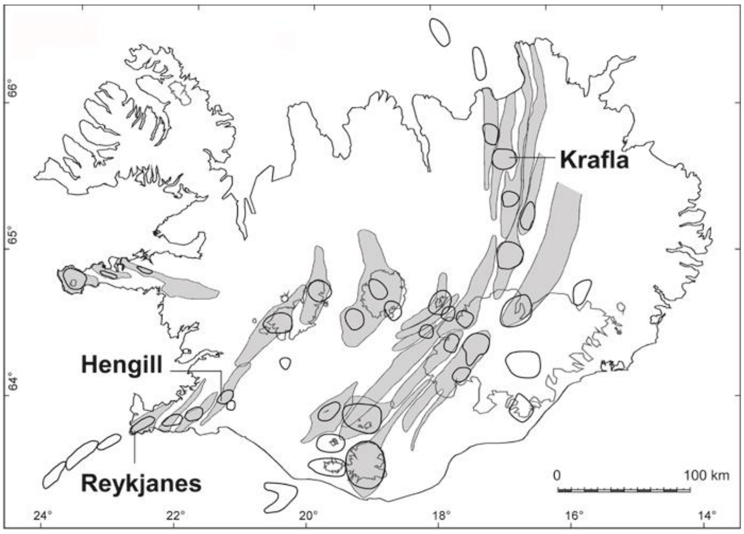

Figure 1. The location of rifting (shaded) in the neovolcanic zone of Iceland, an extension of the Mid-Atlantic Ridge. The map shows the location of three high-enthalpy magma-hydrothermal systems, Krafla, Hengill, and Reykjanes that are sites that were chosen for deep drilling by the Iceland Deep Drilling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

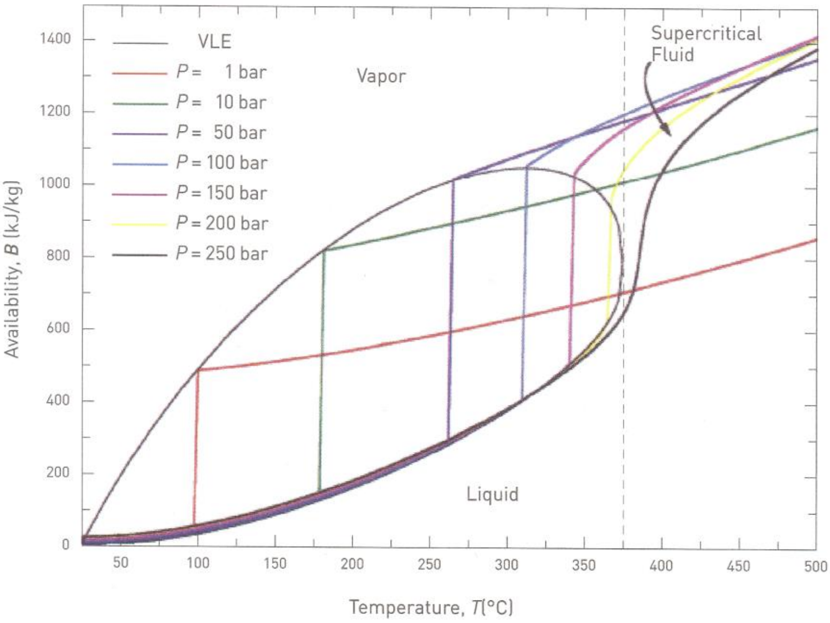

Figure 2. The availability diagram for pure water, i.e. its power-producing potential at specified specific-state conditions of temperature and pressure (Tester, 2006, Figure 1.10).

1.1 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 (Figure 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 9 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 more recent MT-survey.

The well IDDP-1 was sited to reach 4.5 km depth close to the margin of this magma chamber with the aim of reaching supercritical conditions (Friðliefsson, Elders and Albertsson, 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^{o}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. The resultant well had very high enthalpy and produced superheated steam from the contact zone above the intrusion (Figure 3). With a well-head temperature of ~450°C and a well-head pressure of up to 138 bar$_a$, it became the hottest producing geothermal well in the world. With a flow rate of 45/kg/s of dry superheated steam, it was estimated to be capable of generating >35 MWe (Hauksson et al., 2014).. In July 2012, after ten months of full scale flow, the well was shut down as it was necessary to replace some of the surface equipment.

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 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).

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_a. In 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 directly in molten magma.

2 WIDER APPLICATIONS

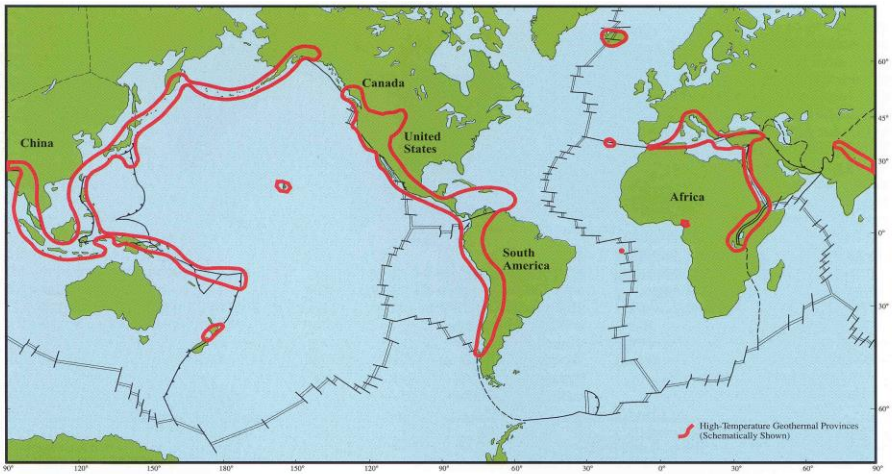

Figure 4. Outlined in red are the world-wide zones where very high-enthalpy, volcanic-related, and possibly supercritical geothermal resources could exist at drillable depths.

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 fresh water 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, Elders and Bignall, 2013). If new IDDP wells at Reykjanes and Hengill prove successful, this could trigger similar activities elsewhere. In the future such very high enthalpy geothermal systems could become significant resources worldwide, wherever suitable young volcanic, high-enthalpy, "ultra" geothermal systems occur (Figure 4).

2.1 Developing ULTRA Geothermal Resources:

The term "ultra geothermal resources" is used here to refer to 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. The development of such high-enthalpy, magma ambient and 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 & Ranges, Alaska, etc.

In fact, projects comparable but differing in approach to the IDDP are already underway in both Japan and New Zealand (Figures 5 and 6). The plan in Japan is to drill beyond the brittle ductile transition in a 500^{o}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 (Figure 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 two or three years.

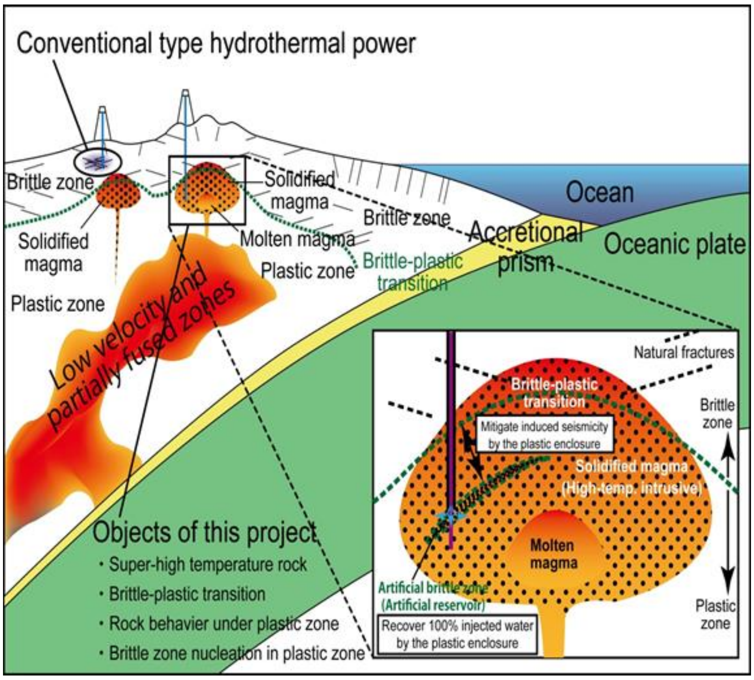

Figure 5. The principles behind the Japan Beyond the Brittle Project (JBBP). Figure courtesy of H. Asanuma, (National Institute of Advanced Industrial Science and Technology (AIST), Japan.

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 (Figure 6). Preliminary indications of this "Hotter and Deeper" project suggest that by 2025, New Zealand's deep geothermal resources (3-7km) 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).

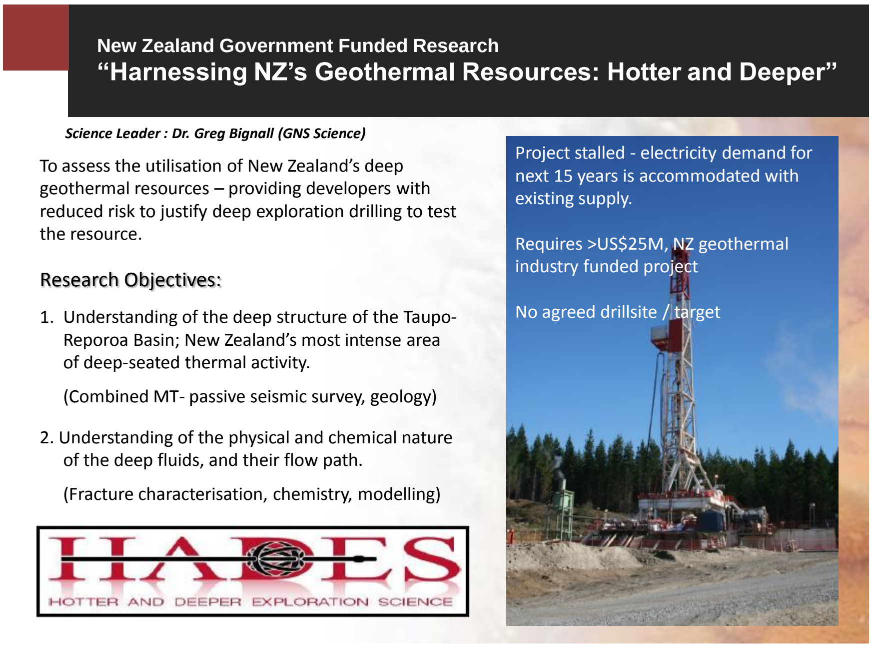

Figure 6. The aims of Project HADES in New Zealand. Figure courtesy of Ted Bertrand (GNS-Science, New Zealand).

3.0 THE POTENTIAL FOR "ULTRA GEOTHERMAL RESOURCES" IN THE USA:

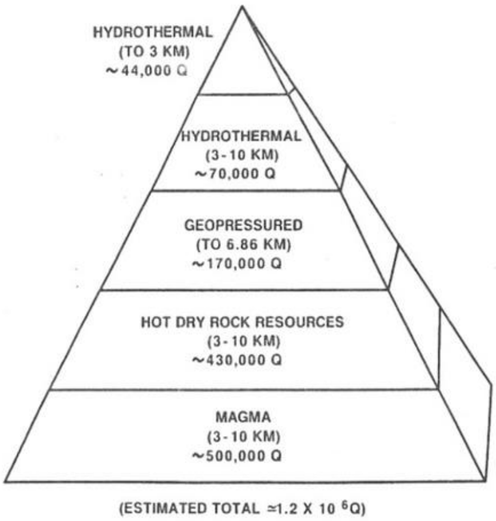

Figure 7. An early estimate of the resource base in various geothermal environments indicated that magma-ambient systems have a very large potential. Q = Quad or 10^{15} BTU or about 1 Exajoule = 10^{18} J. (Source White and Williams, 1975- USGS Circular 726).

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 Figure 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 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. The project 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 1.1 for different categories of geological environment as reported in Tester, (ed.), 2006. The major thrust of that report was to assess the potential of Enhanced (or Engineered) Geothermal Systems (EGS) in the USA, and it greatly increased the assessment of the EGS resource base of the USA in crystalline 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 (ed.), 2006 shows, *supercritical volcanic* EGS also has a large potential in the USA.

Table 1. The estimated geothermal resource base to 10 km depth by category (from Tester, 2006, Table 1.2)

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)

Although field experiments to create EGS in crystalline rocks began in the USA in the 1970's, 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 almost all cases its development has required large government subsidies. These EGS experiments have largely focused on systems with temperatures less than 300^{o}C (and in some cases only 200^{o}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.

3.1 A Program to Develop "ULTRA Geothermal Resources" in the USA

Today there is revived and growing interest in investigating high-enthalpy geothermal systems in the USA where, as Table 1 demonstrates, there is a very large, as yet undeveloped, high-enthalpy geothermal power potential (Elders, 2013; Elders, et al., 2014). . Unlike the situation in the UK, France, Australia, Germany and Switzerland, as Table 1 shows, there is a large potential to develop *supercritical* volcanic EGS 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, lithology, and permeability. 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.

3.2 The aims of the ULTRA Geothermal Development Program (UGDP).

- 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 in for developing ULTRA high enthalpy resources that builds 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 Material 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.

3.3 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.

3.4 Some potential sites in the USA meeting these criteria

Table 2 shows some of the likely sites in the continental USA that should be considered initially for the UGDP that meet the criteria listed in section 3.3, and where additional renewable electrical capacity could find a ready market. At Puna in Hawaii, on the southern flanks of the active volcano Kilauea, drilling has also penetrated a magma body at shallow depth (Teplow, et al, 2009). However, its development as a resource in the near future is limited by the market for additional electric power on the island of Oahu. In addition, to the developed high-enthalpy resources in California, there is also future potential in the Cascade Volcanic Chain, the Basin & Ranges, and in Alaska.

Table 2. Some potential sites for the development of ULTRA Geothermal Resources in the USA

Geothermal Field	Current Installed Generating Capacity	Geological Environment	Highest Temperatures Reported
The Geysers, California	1517 MWe	Meta-greywacke and rhyolites	>350 C at 3,000 m
Coso, California	350 Mwe	Granite, basalt and rhyolite	~350 C at 3,000 m
Salton Sea, California	420 MWe	Deltaic sediments and rhyolites	~390 C at ~2 km

Source of data: 2014 Annual U.S. and Global Geothermal Power Production Report. Geothermal Energy Association, (2014) 1-25.

In the intermediate to long term, there is an even larger potential for Ultra geothermal resources in *offshore* regions of western North America. For example, one estimate of the high-enthalpy geothermal resources of the Gorda Ridge, offshore Oregon and northern California, suggests that its geothermal resource base is sufficient to generate thousands of GWe (Ajito Chada, personal communication, 2014). Further north, on the Juan de Fuca Ridge, at 3 km depth beneath an axial volcano, a magma body measuring 14 km long by 3 km wide and 1 km thick has recently been identified (Arnulf et al., 2014). The barrier to the development of such offshore ULTRA geothermal systems is the technical difficulty and cost of deep drilling offshore and building the necessary transmission cables needed. However, given the large size these offshore systems they remain attractive targets for future development,

3.5 Some advantages and potential barriers to creating an UGDP:

The practical significance of attempting to implement an Ultra Geothermal Development Project in the USA, and elsewhere in the world, are:

- 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 & 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

The principal barrier to creating programs to develop magma ambient and supercritical geothermal resources are 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 “Holes of Opportunity”, i.e. deepening boreholes that are sited and drilled by industry in geothermal areas;
- to large and flexible funding sources;
- to industry data bases relevant to site selection;
- to industry leasing and permitting;
- to industry technical expertise, equipment, and infrastructure.

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

- 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, back-up plans, and an optimism that continued progress and collaboration will overcome these obstacles. 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

Amongst approaches to improve the economics and size of the geothermal industry, the 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 impact of utilizing geothermal resources at supercritical and magma ambient conditions could become quite significant. Not only would this call for re-evaluation of the geothermal energy resource base on a local scale, but also on a global scale. Accessing such environments within drillable depths could yield a significant enlargement of the accessible geothermal resource base and future electric power production in the USA.

Magma ambient and especially 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 for electric power generation.

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