Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

Investigating a Mid-Ocean Ridge Hydrothermal System on Land: the Iceland Deep Drilling Project on the Reykjanes Peninsula in SW Iceland.

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Keywords: Iceland, magma, supercritical resources, Reykjanes, mid-ocean ridges, black smokers.

ABSTRACT

The Iceland Deep Drilling Project (IDDP) is investigating the production of geothermal energy at supercritical conditions. This requires drilling to depths of 4 to 5 km where temperatures can reach 450–600°C. Modeling studies suggest producing superheated steam from a geothermal well at supercritical temperatures >450°C could increase power output up to tenfold relative to a well producing a two phase mixture of steam and water from a <300°C reservoir. The first attempt to drill an IDDP well was in 2009 at Krafla within a volcanic caldera in the active rift zone of NE Iceland. However, drilling the IDDP-1 had to be terminated at only 2100 m depth when 900-1000^{o}C rhyolitic magma flowed into the drill hole. The well was completed with a casing cemented a few meters above the magma and was the allowed to heat slowly and then to flow superheated steam for the next two years. Throughout that time various investigations at utilizing this resource were carried out and the IDDP-1 became the world's hottest producing geothermal well, with a well head temperature of more than 450°C, flowing dry superheated steam at high pressures (4–14 MPa), and capable of producing up to 36 MWe.

To continue the search for supercritical geothermal resources the second deep IDDP well, IDDP-2, is expected to be drilled to 4-5 km depth in 2015, into the seawater-dominated Reykjanes high-temperature geothermal field in SW-Iceland on the Reykjanes Peninsula. This peninsula is the landward continuation of the Mid-Atlantic Ridge with a subsidence rate is 6.0-6.5 mm/year and a spreading rate is 18-19 mm/year. Currently 100 MWe of electric power is produced at Reykjanes from some 20 wells but additional wells need to be drilled to support the current production and potential expansion of the field. Temperatures in the production zone range from 250-320^{o}C with the highest subsurface temperature measured to date of 345°C. The hydrothermal alteration pattern is characterized by zeolite to greenschist facies mineralogy.

This saline geothermal system is characterized by ocean floor geology from near surface downwards, closely resembling mid-ocean ridge lithologies. The geological succession depicts a steady buildup of volcanic strata within a submarine environment. The deepest units so far drilled consist of sheeted dike swarms and pillow basalts overlain by submarine eruptive units characterized by hyaloclastites and relatively shallow-water rocks composed of phreatic tuffs, interbedded with shallow marine fossiliferous sediments closer to the surface. Subaerial Holocene lavas cover most of the present surface.

As well as its practical goals, the IDDP-2 will be an ideal situation to study the roots of a high-temperature magma-hydrothermal system analogous to those responsible for the black smokers at submarine divergent plate margins. Studying an analog of a black smoker system on land at Reykjanes in a deep drillhole will be an unprecedented opportunity. There is an enormous unrealized geothermal resource potential in ocean hydrothermal systems. We invite the international scientific community to join us by participating in the drilling and testing the IDDP-2 and in post-drilling scientific studies.

1. INTRODUCTION

Various different strategies can be employed to improve the economics of producing geothermal electric power. The approach espoused here is being used by the Iceland Deep Drilling Project (IDDP), that is to utilizing very high enthalpy resources in temperature-pressure regimes where supercritical conditions exist (Friðleifsson, Elders and Albertsson, 2014). The critical point for pure water occurs at a temperature of 374^{o} C and 22.2 MPa pressure. According to Tester et al. (2006), an aqueous geofluid at supercritical conditions with a temperature of 400 ^{o}C and a pressure of 25 MPa has more than five times the power producing potential than a hydrothermal liquid water geofluid at 225 ^{o}C. In Iceland a typical geothermal well, 2 km deep, yields sufficient steam to generate ~ 4-7 MWe. However, Suárez and Samaniego (2012, p.8) give even higher estimates of the increased potential of using supercritical water stating that, "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 in the current technology". The IDDP estimate is more conservative. Modeling, as part of an IDDP feasibility study, indicated that a well yielding steam at the inlet to the turbine with a flow rate of 0.67 m^3s^{-1} at 235^{o} C and 3 MPa could have a power output of about 5 MWe, whereas supercritical water at 430-550^{o} C and 23-26 MPa, with the same volumetric flow rate, could have a power output of about 50 MWe (Friðleifsson et al. 2003).

The down side of this approach is that reaching supercritical conditions requires drilling deep, more expensive wells in regions of high heat flow to reach the necessary pressures and temperatures. Iceland is a favorable site to take this next step forward in geothermal resource development because of its high heat flow due to abundant volcanic activity generated by its location on the Mid-Atlantic Ridge (Figure 1).

1.1 Geothermal Systems in Iceland

With an exposed area of more than 103,000 km^2, Iceland is the largest landmass straddling a divergent plate boundary, with the Reykjanes Ridge to the south and the Kolbeinsey Ridge to the north (Figure 1). The surface expression of this plate boundary on land manifests itself in narrow central rift zones, 20 to 50 km wide, with active rifting and frequent volcanic eruptions. Both paleomagnetic and geodetic investigations indicate that it has a spreading rate of 2 cm/a, in the direction ~ N 105 ^{o} E, consistent with it being part of the slow-spreading Mid-Atlantic Ridge system (Sigmundsson and Sæmundsson, 2008). Because of its location at the center of a large igneous province stretching from Greenland to northwest Britain, since the early days of plate tectonics Iceland has been considered to be the product of the interaction of this plate boundary with a mantle plume (Wilson, 1963).

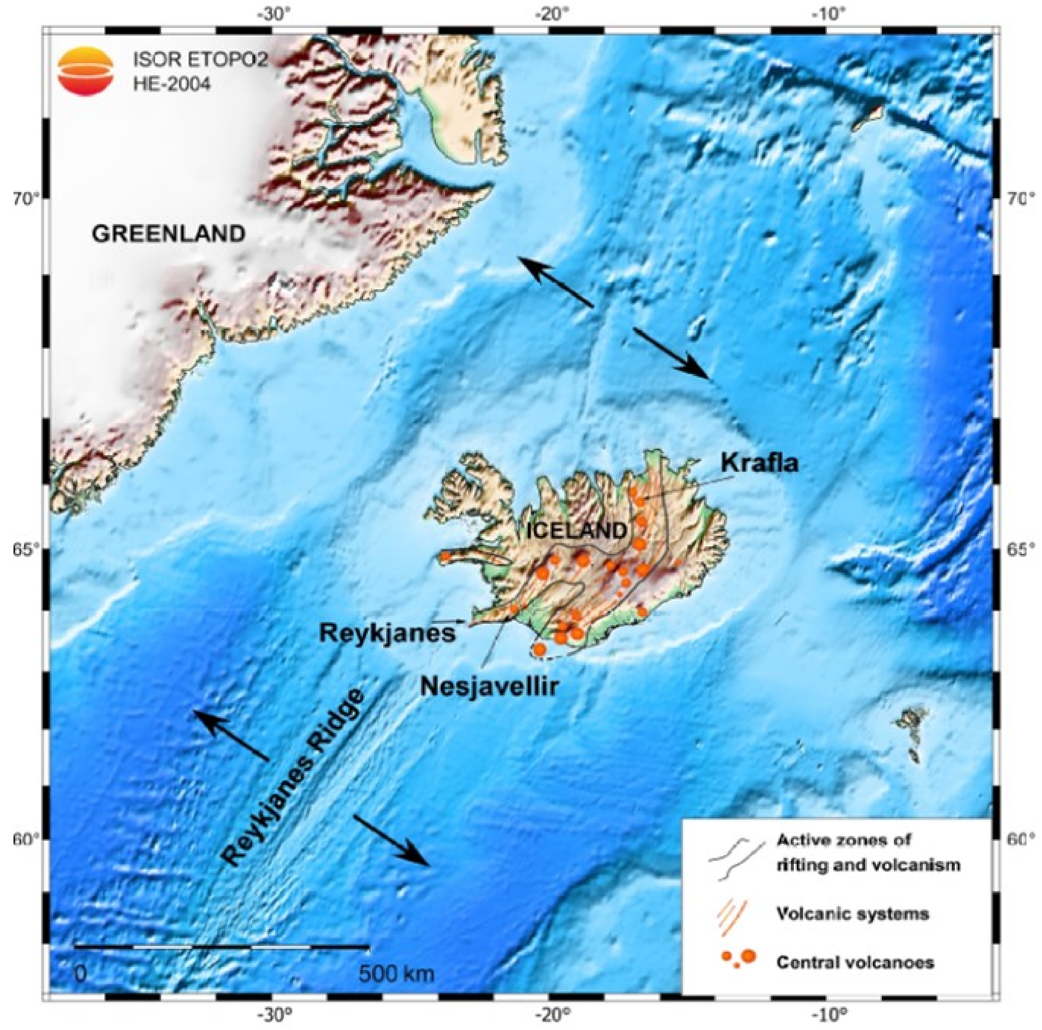

Figure 1: Iceland is located at the juncture of a mantle hotspot and the Mid-Atlantic Ridge spreading center. The arrows show the spreading directions on the Reykjanes ridge to the south and the Kolbeinsey Ridge to the north. Also shown are Iceland's neovolcanic zone, with its central volcanoes, and the sites where the IDDP is carrying out deep drilling, the high-temperature hydrothermal systems of Krafla, Nesjavellir (on the Hengill volcano), and Reykjanes (Friðleifsson and Elders, 2005).

The numerous low- and high-temperature hydrothermal systems in Iceland are the basis of a geothermal industry that supplies space heating to 87% of its buildings and generates a third of its electric power. High-temperature systems (>180 ^{o}C) are restricted to the neovolcanic zones of Upper Pleistocene and Holocene age (< 0.8 Myr) rifting and volcanism, where more than twenty-four volcanoes have erupted in post-glacial time with about 20-25 eruptions each century (Figure 2). Thus the crust of Iceland has high heat flow associated with the very frequent volcanicity, frequent seismicity, and high permeability.

Major power companies in Iceland are further developing existing high-temperature geothermal resources primarily to supply the electrical needs of energy intensive industries such as aluminum smelting. The motivation of the Iceland Deep Drilling Project (IDDP) is to develop new, potentially much larger, sources of geothermal energy, by drilling deeper into >450 ^{o}C supercritical water to produce superheated steam (Friðleifsson and Elders, 2005; Friðleifsson, Elders and Albertsson, 2014). The IDDP planned to drill a 4.5-5.0 km deep well in each of three different high-temperature hydrothermal systems with the aim of investigating supercritical conditions (Friðleifsson et al., 2003). After careful review three developed high-temperature geothermal areas, Reykjanes, Hengill, and Krafla, were selected for drilling by the IDDP (Figure 2). Each displays a different stage in the tectonic development of the mid-ocean ridge. The Reykjanes site represents an immature stage of rifting with a heat source that is probably an active sheeted dike swarm. The Hengill central volcano is the heat source for a geothermal reservoir in a graben that has temperatures of > 380^{o}C at 2.2 km depth. The Krafla high-temperature geothermal field is developed above a magma chamber in a mature, active, volcanic caldera where numerous wells have reached temperatures of > 300 ^{o}C at depths of 2 km (Friðleifsson et al., 2003).

Drilling such deep wells is of course much more expensive than drilling conventional geothermal wells in the depth range of 1.5 to 3.0 km. For this reason the Icelandic geothermal industry formed a consortium to organize and support the IDDP, that consists of the three principal energy companies, Landsvirkjun, Orkuveita Reykjavíkur, HS Orka, together with Orkustofnun (the Icelandic Energy Authority). Later, two international companies, Statoil and Alcoa joined the consortium.

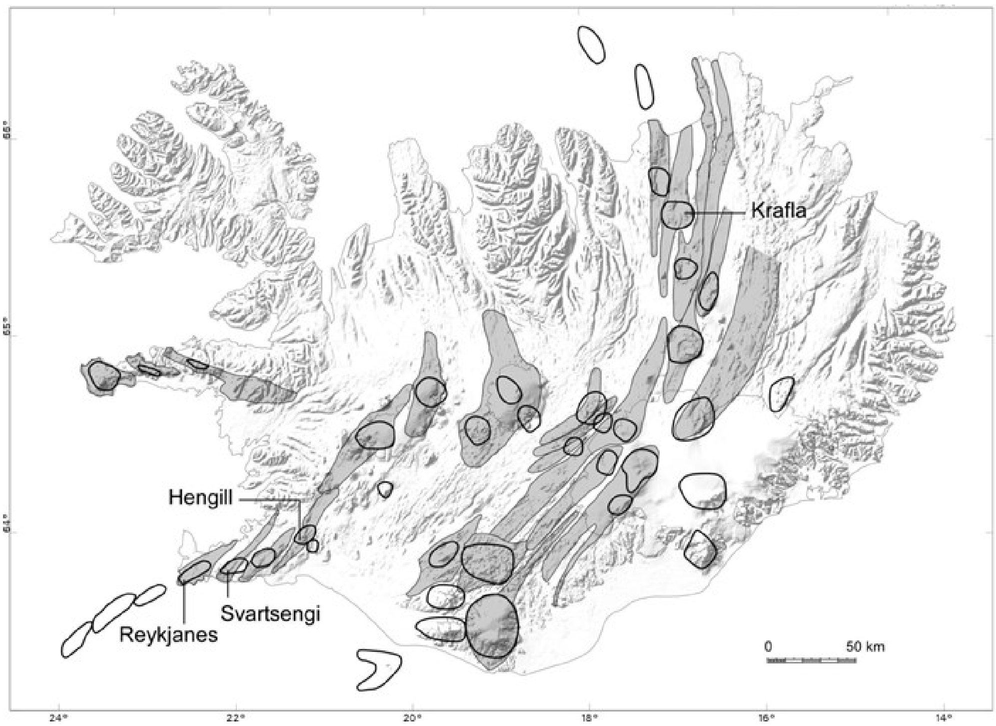

Figure 2: Shaded relief map of Iceland showing the neovolcanic systems of fissure swarms and central volcanoes and the locations of the hydrothermal systems of Reykjanes, Svartsengi, Hengill and Krafla, mentioned in the text (Modified from Sigmudsson and Sæmundsson, 2008, Figure 7).

1.2 Supercritical geothermal systems

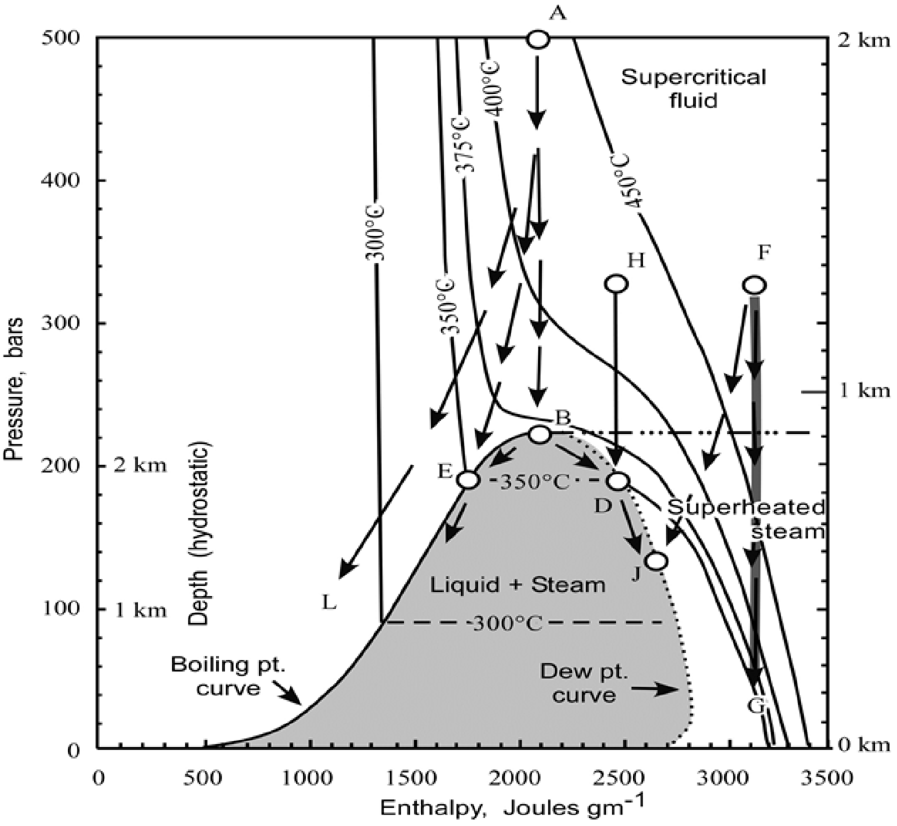

Figure 3: Pressure enthalpy diagram for pure H_2O with selected isotherms. The conditions under which steam and water coexist is shown by the shaded area, bounded by the boiling point curve to the left and the dew point curve to the right. The arrows show various different possible cooling paths; see text (Fournier, 1999).

Instead of the usual practice of producing <300 °C hot water and flashing part of it to steam for the turbines, the plan is to drill deeper into >450 °C supercritical water to produce single phase supercritical and/or superheated steam. Figure 3 shows the pressure-enthalpy diagram for pure water, showing selected isotherms (Fournier 1999). If a supercritical hydrothermal fluid (at A) with an enthalpy of about 2100 Jg^{-1} flows upward and decompresses and cools adiabatically, it would reach the critical point (at B), and with further decompression separate into two phases, water and steam (E and D). The arrows to the left of the vertical line AB (AE and AL) show possible pathways where upward flow is accompanied by conductive cooling so that supercritical fluid transitions into hot water with, or without, boiling. This situation is representative of many high-temperature, water-dominated, geothermal reservoirs where typically boiling, induced by decompression, drives thermo-artesian flow in a well bore. Similarly the pathway H-D represents supercritical fluid that separates into steam and water at D and E, a situation representative of a vapor-dominated geothermal reservoir.

Steam turbines in geothermal plants generate electricity by condensing the steam separated from the two phase system which, depending upon the enthalpy and pressure at which steam separation occurs, is often only 20-30% of the total mass flow. The concept behind the Iceland Deep Drilling Program is to produce supercritical fluid to the surface in such a way that it transitions directly to superheated steam along a path like F-G in Figure 2, resulting in a much greater power output than from a typical geothermal well.

The depth scales marked at the left and right sides of Figure 3 correspond to pressures in hydrothermal systems – respectively controlled by cold pure water hydrostatic conditions and by lithostatic load. Cold water is much denser than superheated steam. Where the pressure is controlled by cold water the critical pressure would be reached at about 2.3 km depth. This is the case on the ocean floor on mid-ocean rifts where 400 °C hydrous fluids can be expelled directly into the oceans from the black smokers without boiling occurring. On the other hand, hot water is less dense than cold. If a natural hydrostatic hydrothermal system is boiling from the surface down to the critical point, the maximum pressure and temperature at each depth is determined by the boiling point to depth curve (BPD-curve), and the critical point would be reached at about 3.5 km depth. Although the hydrostatic BPD-curve controls the maximum P-T in many high-temperature geothermal systems, exceptions are common. This can be simply due to the dominance of conductive cooling (such as the enthalpy pressure path A-L in Figure 3). On the other hand, other scenarios are possible, depending on how the hydrothermal system couples with a magmatic system, the only credible heat source for such high-temperature hydrothermal systems. Another important factor is the chemistry of the fluid, as the boiling point and critical point of water is strongly affected by the amount and nature of dissolved components in the fluid. The critical point of pure water at 22.1MPa and 374 °C, is higher in waters with dissolved components (Figure 4). For example, the critical point for seawater is at ~30MPa and ~ 411 °C (Driesner, 2007; Driesner and Heinrich, 2007).

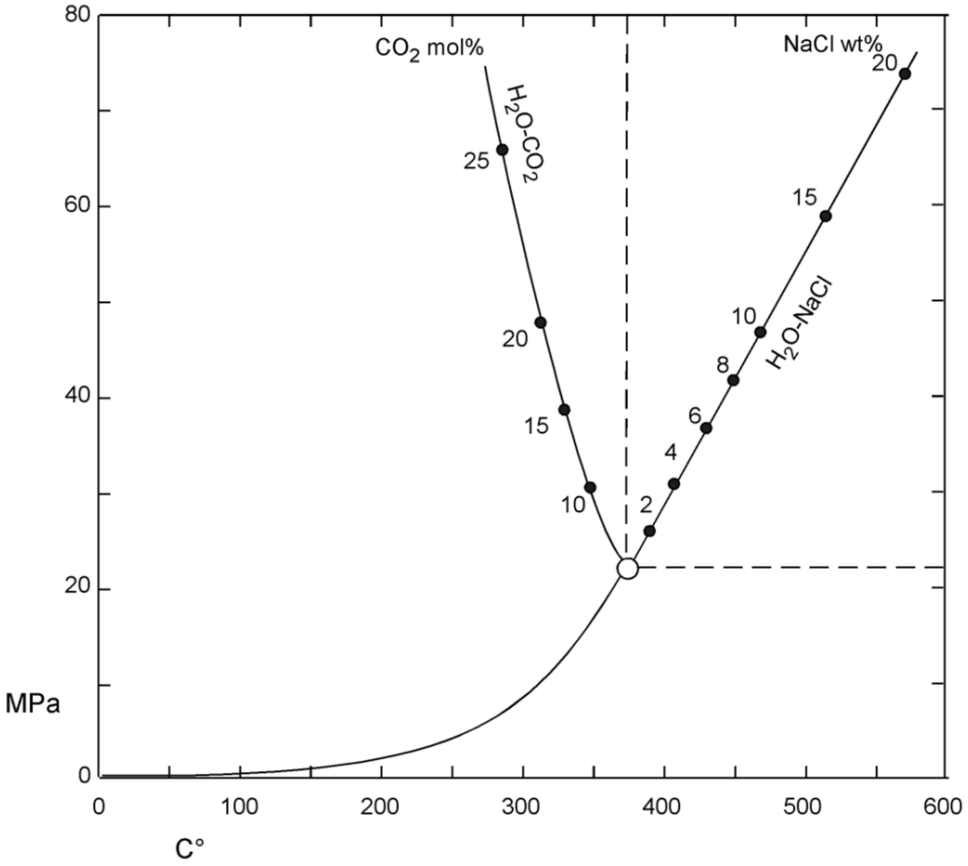

Figure 4: The boiling point curve of critical point curves for water. The critical point for pure water is indicated by the open circle at 374° C and 22.1 MPa. As is shown by the relevant critical curves for H_2O-NaCl and H_2O-CO_2, dissolved salt increases the temperature and pressure of the critical point whereas dissolved gas reduces the temperature and elevates the pressure of the critical point (Hashida et al., 2001).

While supercritical hydrothermal fluids in the Earth's crust are of scientific interest, there have not yet been any attempts to put natural supercritical fluids to practical use, even though for a long time there have been discussions of their potential as a source of high grade energy (e.g. Yano and Ishido, 1998; Hashida, et al., 2001; Suarez and Sameniego, 2012). However large changes in physical properties of fluids occur near the critical point in dilute systems. Orders of magnitude increases in the ratio of buoyancy forces to viscous forces occur that can lead to extremely high rates of mass and energy transport (Dunn and Hardee, 1988; Norton, 1984). Supercritical conditions have been encountered while drilling in a small number of geothermal fields worldwide, as far apart as Larderello, Italy, and Kakkonda, Japan, where they have presented problems for commercial exploitation. These problems include low permeability, borehole instability due to thermal creep, and the presence of acid volcanic gases. However, in these cases, the available drilling technology was not designed to handle the conditions encountered as supercritical hydrous fluids were penetrated usually unexpectedly while using conventional drilling.

2.0 THE IDDP-1 AT KRAFLA.

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 2). 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 recent MT-survey. The well IDDP-1 was sited to reach 4.5 km depth close to the margin of this magma chamber (Friðleifsson, Ármannsson, 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^{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 in a sacrificial 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. With a well-head temperature of ~450°C and a well-head pressure of up to 13.8 PPa, it became the hottest producing geothermal well in the world and, 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 shutdown 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 0.7 MPa. 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.

3.0 PLANS FOR DRILLING THE IDDP-2 AT REYKJANES

The energy company HS Orka hf is the operator of the Reykjanes field at the SW peninsula of Iceland (Figures 1 & 2). This peninsula is the landward continuation of the Mid-Atlantic Ridge with a subsidence rate is 6.0-6.5 mm/year and a spreading rate is 18-19 mm/year (Friðleifsson, Elders, and Bignall, 2013; Friðleifsson, Sigurdsson, et al., 2014). At Reykjanes the power plant is rated at 100 MWe but the operating company is reviewing plans to add a third 50 MWe turbine and an additional 30 MWe low pressure plant. This expansion will require several new deep production wells within the next 2-3 years, as well as deep re-injection wells. The operator would make one of these new 3.0 km deep production wells available to the IDDP consortium to become the IDDP-2 well by deepening it to 4.5 km. Spot coring for scientific studies will be attempted below 2.5 km depth, to the extent that scientific funds allow.

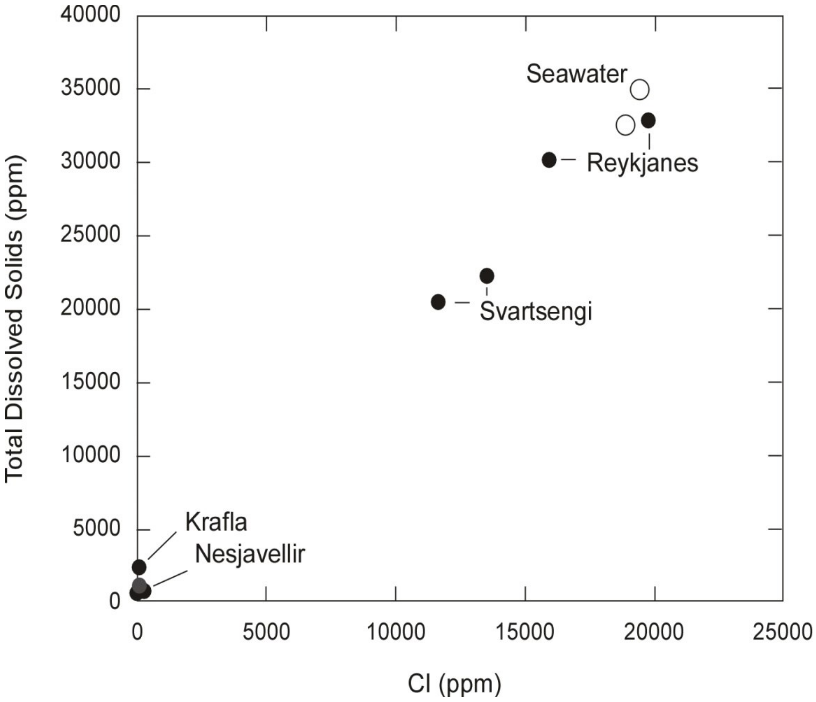

Figure 6. Chemistry of reservoir fluids from four Icelandic geothermal fields (closed circles) compared with seawater (open circles) (Data from Pope et al., 2008).

Unlike other geothermal systems in Iceland where geothermal fluids are modified meteoric water, the geothermal systems of Svartsengi and Reykjanes are more saline and contain modified seawater as befits their location on a narrow peninsula with the ocean on three sides(Figure 6). Furthermore these saline geothermal systems are characterized by ocean floor geology from near surface downwards, and so closely resemble the geology of mid-ocean ridges, with extrusive or pillow basalts and hyaloclastics, near the surface, passing downwards into sheeted basalt dikes with diabase or gabbro intrusions below.

As far as HS Orka is concerned drilling the IDDP-2 will address several basic questions of economic interest concerning the nature of the deep heat source, the permeability at depth and if a supercritical reservoir exists at 4-5 km depth under Reykjanes or does it lie deeper still. It is important to know if the heat source of this hydrothermal system is a sheeted dyke complex or a major gabbroic intrusion. Individual dykes cool to ambient temperatures in a few years, whereas a large gabbro intrusion may act as a heat source for several thousands of years, or longer.

4.0 WIDER APPLICATIONS OF THE IDDP CONCEPT TO OCEAN HYDROTHERMAL SYSTEMS

The IDDP-01 has engendered considerable international scientific and engineering interest. A special issue of the journal Geothermics was published in January 2014 reporting some of this work. Similarly although the challenge of 4-5 km deep drilling in the Reykjanes field is an important part of the HS Orka's exploration strategy for the Reykjanes system, it will also provide valuable information for the international scientific community at large. Processes at depth at Reykjanes could be quite similar to those responsible for black smokers on oceanic rift systems (Elders and Friðleifsson, 2010). An important feature of the coupling of hydrothermal and magmatic systems on mid-ocean ridges is that venting of fluids can occur at varying rates, but the maximum temperatures seem generally to be limited to 350-400°C (Kelley, et al. 2002). However hotter supercritical discharges have been observed. The highest reported temperature at the ocean floor black smoker is 464°C, is at hydrothermal vents 5°S in the on the Mid-Atlantic Ridge (Koschinsky et al., 2008).

The waters discharged at marine hydrothermal vents are seawater modified by reactions with basalt and gabbro, presumably due to seawater penetrating the thermal cracking front (Lister, 1980) at temperatures of 350-550°C, but extending up to 800°C (Manning and McCleod, 2000). As expected, the salinity of these high temperature discharges is usually that of seawater, but an interesting feature is that it can be either more, or less, saline than seawater by a factor of two or more (Von Damm, 1995; Kelly and Fruh-Green, 2000). The best explanation of this phenomenon is that these vents are discharging fluids that are derived from fluids that have suffered phase separation of dilute and hypersaline solutions in the supercritical state (Driesner, 2007; Driesner and Heinrich, 2007).

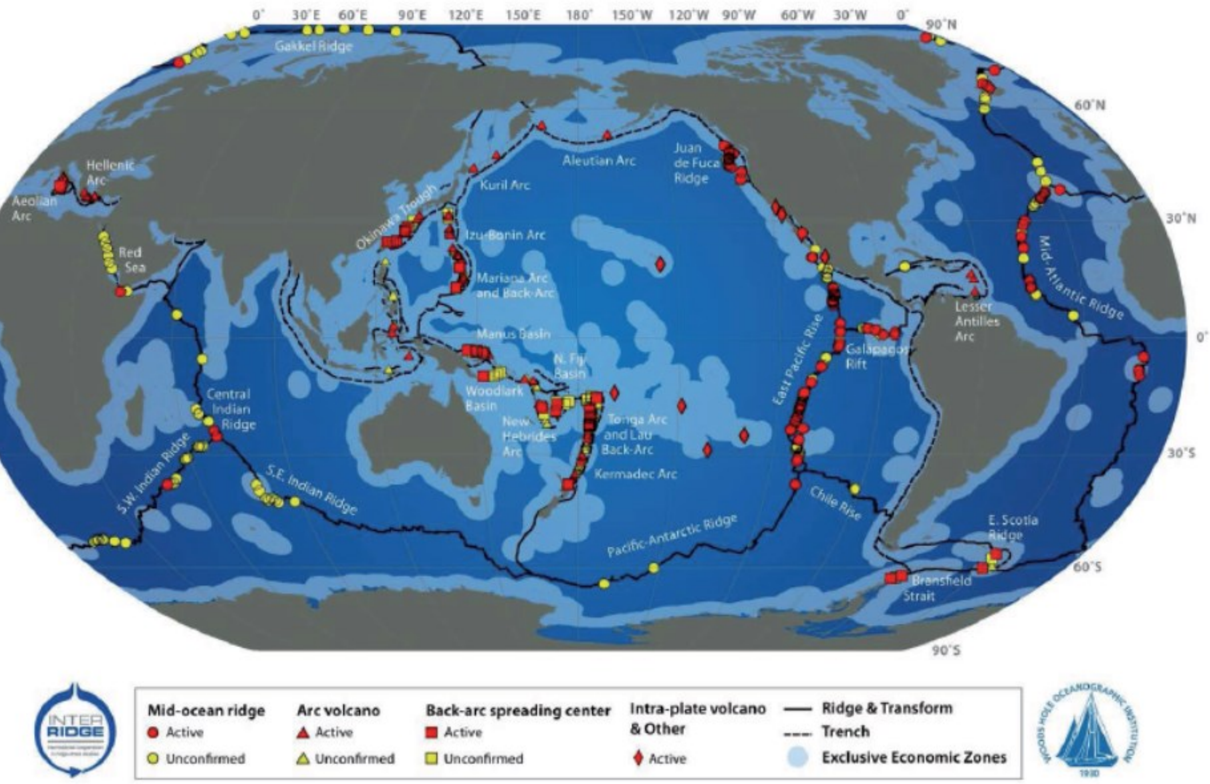

Figure 7. Submarine hydrothermal venting identified on mid-ocean ridges, arc volcanoes, back arc spreading centers, and intra-plate volcanoes (Source: The InterRidge Cruise Database, http://www.interridge.org/)

Although commercial production of ocean hydrothermal systems is hindered by the high cost of marine operations and subsea power transmission lines, the huge future potential of seafloor geothermal resources continues to attract attention (Figure 7). Oceanic rift zones have a length of more than 65,000 kilometers and exhibit very high convective heat fluxes. The global hydrothermal heat flux from ocean venting is estimated to be as large as 18 TWt and rates of discharge of hot fluids in concentrated areas of the mid-ocean ridges can be as high as $2.6 \text{ X } 10^6 m^3 s^{-1}$ (Parada et al., 2012). The geothermal resources in these narrow areas of the ocean floor are concentrated in zones that are relatively easily detected, and would require relatively shallow drilling into the crust because of the high heat flows. The cost of drilling will be high because of the depth of seawater (2 to 3 km) covering the resource. However, this seawater cover also maintains pressure in and recharge to the hydrothermal systems. Locations of black smokers closest to land such as the Red Sea, the Gulf of California, the Juan de Fuca Ridge and the Gorda Ridge, etc., are the most accessible likely candidates for such developments. A number of authors have discussed different strategies to generate electricity from such marine resources (Hiriart and Hernández, 2010; Hiriart et al, 2010; Shnell, 2009; Parada et al., 2012).

5.0 DISCUSSIONS

If the goals of economically producing geothermal energy from supercritical reservoirs in Iceland are achieved, then the IDDP could usher in a new era in geothermal development. Fewer wells would be needed for a given power output leading to a smaller environmental foot print; there would be a higher thermodynamic efficiency of the power cycle, and existing producing geothermal fields would have increased sustainability. This approach would not be limited to environments like mid-ocean ridges but also on land where supercritical and still molten, igneous intrusions occur at drillable depths. Deep high-enthalpy geothermal resources in supercritical and magma-ambient environments could be developed on land in environments wherever young volcanic rocks occur. However the high costs and risks of drilling deep very hot wells suggest that at least initially such activities should begin in well explored high-enthalpy geothermal fields in areas with known volcanic activity, such as New Zealand, the Philippines, Indonesia, Italy and Japan, and Hawaii and California in the USA (Elders, 2013).

6.0 CONCLUSIONS

Studying an analog of a black smoker system on land at Reykjanes, through a deep drill hole will be an unprecedented opportunity that the geothermal industry and the scientific community at large should not miss. We invite the scientific community to join forces with IDDP to participate in the funding of the drilling and testing operation, as well as in detailed post-drilling studies. The international science community has made investigation of hydrothermal systems at mid-ocean ridges a high priority as demonstrated through programs like RIDGE and InterRidge, and by the extensive scientific drilling conducted by the Ocean Drilling Program (DSDP/ODP/IODP). Crucial aspects of lithosphere-hydrosphere interaction are the formation of ocean crust, and the nature of thermal boundary zones and cracking fronts, and the transition from subcritical to supercritical conditions in the hydrothermal environments near magma chambers on mid-ocean ridges. Although the coupling of hydrothermal and magmatic systems, and seawater/basalt reactions at mid-ocean ridges where ocean crust is created are important aspects of lithosphere-hydrosphere interaction, they are the least accessible and least understood.

There have been almost no direct observations of the active high temperature zones near the magma/hydrothermal interface, yet such observations are critical to understanding processes such as derivation of ore fluids, instabilities that lead to volcanic eruptions, and extraction of higher-yielding geothermal energy. The Icelandic energy industry has invited the scientific community to participate. Thus a major share of the costs of drilling wells as deep as 5 km is being borne by industry and the scientific program will also benefit from the extensive practical experience of the industrial partners. We should seize this rare opportunity for collaboration between the applied and basic science communities.

ACKNOWLEDGEMENTS

We thank the Deep Vision for the opportunity to participate in the challenge represented by the concept of the IDDP. Colleagues at ISOR, HS Orka hf, Landsvirkjun and Orkuveita Reykjavikur receive our sincere thanks for assistance and the unlimited use of their data, published and unpublished. Many thanks are also due to the members of our science advisory group, SAGA who have given freely of their time and experience. We are also grateful for the contributions made by our collaborators for their contributions to the science program. Financial support from the International Continental Scientific Drilling Program to Friðleifsson and Elders, and from the US National Science Foundation grant EAR-0507625 to Elders have made the research program of the IDDP possible.

REFERENCES

Driesner, T.: The System H_2O-NaCl. II. Correlation Formulae for Phase Relations in Temperature Pressure-Composition Space from 0 to 1000°C, 0 to 5000 bar, and 0 to 1 X_{NaCl}. *Geochimica et Cosmochima Acta* **71**, (2007) 4902-4919.

Driesner, T., and Heinrich, C.A.: The System H_2O-NaCl. I. Correlations for Molar Volume, Enthalpy, and Isobaric Heat Capacity from 0 to 1000 Degrees C, 1 to 5000 Bar, and 0 to 1 X_{NaCl}. *Geochimica et Cosmochima Acta* **71**, (2007) 4880-4901.

Dunn, J.C. and Hardee, H.C.: Superconvecting Geothermal Zones. *Journal Volcanology Geothermal Research.* **11***,* (1981) 189-201.

Elders, W.A. and Friðeifsson, G.Ó.: 2010 . Implications of the Iceland Deep Drilling Project for Improving Understanding of Hydrothermal Processes at Slow-Spreading Mid-Ocean Ridges. (*In)* P. Rona, C. Devey, J. Dyment and B. Murton (Eds) Diversity of Hydrothermal Systems on Slow-spreading Ocean Ridges. *Geophysical Monograph Series* **118**. American Geophysical Union , (2010) 91-112.

Elders, W.A.: 2013 Proposed Collaborative Initiative to Promote Development of Higher-Enthalpy Geothermal Systems in the USA. *Geothermal Resources Council Transactions* **37** (2013) 263-270.

Elders, W.A., G.Ó. Friðleifsson and Albertsson, A.: Drilling into Magma and the Implications of the Iceland Deep Drilling Project (IDDP) for High-temperature Geothermal Systems Worldwide. *Geothermics* **49** (2014) 111-118.

Elders, W.A., Friðleifsson, G.Ó., Zierenberg, R.A., Pope, E.C., Mortensen, A.K., Guðmundsson, Á., Lowenstern, J. B., Marks, N.E, Owens, L., Bird D.K., Reed, M., Olsen, N. J. and Schiffman, P.: 2011. Origin of a Rhyolite that Intruded a Geothermal Well while Drilling at the Krafla Volcano, Iceland. *Geology,* **39**, (2001) 231-234.

Fournier, R.O.: Hydrothermal Processes Related to Movement of Fluid From Plastic into Brittle Rock in the Magmatic-Epithermal Environment. *Economic Geology,* **94***,* no 8 (1999) 1193-1211.

Friðleifsson, G.Ó., Ármannsson, H., Árnason, K., Bjarnason, I.Þ. and Gíslason, G.:Part I: Geosciences and Site Selection, 104 p. *In*: Iceland Deep Drilling Project, Feasibility Report, ed. G.Ó. Friðleifsson. *Iceland Energy Authority, Orkustofnun Report* OS-2003-007. Reykjavik, Iceland. (2003) (See also http://www.idddp.is).

Friðleifsson, G. Ó., and Elders, W.A.:The Iceland Deep Drilling Project: a Search for Deep Unconventional Geothermal Resources. *Geothermics* **34**, (2005) 269-285.

Friðleifsson, G.Ó., Ármannsson, H., Guðmundsson, ,Á., Árnason, K., Mortensen, A.K., Pálsson, B., Einarsson, G.M.: Site selection for IDDP-1 at Krafla. *Geothermics*, Special Issue, **49,** (2014), 9-15.

Friðleifsson, G.Ó., Elders, W.A. and Albertsson, A.: The concept of the Iceland Deep Drilling Project. *Geothermics,* Special Issue, **49** (2014) 2-8.

Friðleifsson, G.Ó., Elders, W.A. and Bignall, G.: A Plan for a 5 km-deep Borehole at Reykjanes, Iceland, into the Root Zone of a Black Smoker on Land. *Scientific Drilling*, **16,** (2013) 73-79.

Friðleifsson G.Ó, Sigurdsson, Ó., Þorbjörnsson, D., Karlsdóttir, and Gílason. Þ.: Preparation for drilling well IDDP-2 at Reykjanes. *Geothermics,* Special Issue,**49, (**2014) 119-126.

Hashida, T., Bignall, G., Tsuchiya, N., Takahashi T. and Kanifuji, K.: Fracture Generation and Water Rock Interaction Processes in Supercritical Deep-seated Geothermal Reservoirs. *Geothermal Resources Council Transactions*, **25** (2001) 225-229.

Hauksson, T., Marksson, K., Einarsson, S. N., Karlsdóttir, A., Einarsson Á ., Möller, A. and Sigmarsson Þ.: Pilot Testing of Handling the Fluids from the IDDP-1 Exploratory Geothermal Well, Krafla, N.E. Iceland. *Geothermics,* **49**, (2014) 76-82.

Hiriart, G. and Hernández, I.: Electricity from Hydrothermal Vents. *Geothermal Resources Council Transactions* **34** (2010) 1033-1037.

Hiriart, G., Alcocer, S., Prol R. M., and Espíndola, S.: Submarine Geothermics: Hydrothermal Vents and Electricity Generation. *Proceedings of the World Geothermal Congress (2010),* Bali, Indonesia 25-29 April, 2010

Kelley, D. S. and Fruh-Green,S. D.: Volatiles at mid-ocean ridge environments. *Geological Society America*, Special Paper **349** (2000) 237-260.

Kelly. D.S., Baross, J.A. and Delaney, J.R.: Volcanoes, Fluids, and Life at Mid-Ocean Ridge Spreading Centers. *Annual Reviews Earth & Planetary Sciences.* **30** (2002) 385-491.

Koschinsky, A.D., Garbe-Schonberg, S., Schmidt, H., Gennerich, H-H., and Strauss, H.: Hydrothermal Venting at Pressure-temperature Conditions above the Critical Point of Seawater at 5^{o}S on the Mid-Atlantic Ridge. *Geology,* **30**, no 8, (2008) 615-618.

Lister, C.R.B.: Qualitative Models of Spreading-center Processes, including Hydrothermal Penetration *(In) Ocean Ridges and Arcs: Geodynamic Processes.* M.N. Toköz, S. Ueyda, and J. Francheteau, (*Eds)* Elsevier Scientific Publishing Co. Amsterdam, (1980) 143-158.

Manning, C. E., and MacLeod, C.J.: Lower-crustal Cracking Front at Fast-spreading Ridges: Evidence from the East Pacific Rise and the Oman Ophiolite. *Geological Society of America* Special Paper **349** (2000) 261-272.

Norton, D.L.: Theory of Hydrothermal Systems. *Annual Reviews Earth & Planetary Sciences* **12**, (1984) 155-77.

Parada, J., Feng, X., Hauerhof, Suzuki, E.R. and Abubakar U.: The Deep Sea Energy Park: Harvesting Hydrothermal Energy for Seabed Exploration, *The LRET Collegium*, **3**, (2012).1-128.

Pálsson B., Hólmgeirsson, S., Guðmundsson, Á., Bóasson, H.Á., Ingason, K.H, Sverisson H. and Þórhallsson, S.:.Drilling of the well IDDP-1 *Geothermics* **49** (2014) 23-30.

Pope E.C., Bird, D.K., Arnórsson, S., Fridriksson, Þ., Elders, W.A., and Friðleifsson, G. Ó.: Fluid Origin and Evolution in the Reykjanes Geothermal System, Iceland: a Stable Isotope Study of Hydrothermal Epidote. *Geochimica et Cosmochimica Acta*, **15,** (2008) 4468-4488.

Shnell, J. Global Supply of Clean Energy from Deep Sea Geothermal Resources. *Geothermal Resources Council Transactions*, **33** (2009) 137-142.

Sigmundsson, F. and Sæmundsson, K.: Iceland: a Window on North-Atlantic Divergent Plate Tectonics and Geologic Processes. *Jökull, Icelandic Journal of Earth Sciences,* **31**, (1) (2008) 1-6.

Suárez A., M. C. ,and Samaniengo V., F. Deep Geothermal Reservoirs at Supercritical Conditions. *Proceedings, Thirty-seventh Stanford Geothermal Workshop*, Stanford, California, Jan. 30-Feb. 1 2012, Paper SG-TR-194, p.1-8.

Tester, J.W., (Ed), : The Future of Geothermal Energy: Impact of Enhanced Geothermal Energy (EGS) on the United States in the 21st century. *MIT Panel Report to the US Department of Energy* (2006) 1-54. (see also http: //geothermal.inel.gov, DOI, May 2112).

Von Damm, K.: Controls on the Chemistry and Temporal Variability of Seafloor Hydrothermal Fluids. *American. Geophysical Union, Geophysical Monograph* **91** (1995) 222-247.

Wilson, T.J.: Evidence from Islands on the Spreading of the Ocean Floor. *Canadian Journal of Physics* **41**, (1963) 863-868.

Yano Y., and Ishido, T.: Numerical Investigation of Production Behaviour of Deep Geothermal Reservoirs at Super-critical Conditions. *Geothermics* **27,** No. 5/6 (1998) 705-721.

Zierenberg, R.A., P. Schiffman, P., Barfod, G.H., Lesher, C.E., Marks, N., Lowenstein, J.B., Mortensen, A.K., Pope, E.C., Bird D.K., Reed, M.H., Friðleifsson G.Ó. and Elders, W.A.: Composition and Origin of Rhyolite Melt Intersected by Drilling in the Krafla Geothermal Field, Iceland. *Contributions to Mineralogy and Petrology* **165**, (2013) 327.