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# The Science Program of the Iceland Deep Drilling Project (IDDP): a Study of Supercritical Geothermal Resources

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## ABSTRACT

The main goal of this development and research program in Iceland is to investigate interaction of high-temperature, supercritical (400-600 °C) hydrothermal fluids with basaltic crust in Iceland, where the Mid-Atlantic Ridge emerges from the ocean. The Iceland Deep Drilling Project (IDDP) is a long-term collaboration between a consortium of Icelandic power companies and the Icelandic government, together with two international partners, formed to investigate the economics of deeper, hotter, geothermal resources. The consortium agreed that the operators on the Reykjanes, Hellisheidi, and Krafla geothermal fields would each fund the drilling of a well 3 to 4 km deep and that the IDDP would fund the deepening these wells to >4 km deep, to reach temperatures >450°C with the basic aim of exploring *supercritical* hydrothermal fluids as a possible energy source. Supercritical fluids have high enthalpy and greatly enhanced rates of mass transfer and chemical reaction.

Drilling the first deep well commenced in 2008 in the Krafla geothermal field within a volcanic caldera in the central active rift zone of NE Iceland. Volcanic eruptions and rifting last occurred there in 1974-85. The IDDP-1 well was drilled and cased to 800 m depth in November 2008 before the winter snows. Drilling resumed in the spring of 2009 and in mid-April had reached 2 km This was followed by more than two months of problems, hole caving, getting stuck, twist offs, cement jobs, side tracks and a failed spot coring attempt. The reason for this caving leading to drilling problems became clear on June 24th at 2104 m depth when rhyolitic magma, with an estimated temperature of 1050 °C, flowed into the drill hole. It was decided not to continue drilling and the well was completed with a cemented production casing and a hanging slotted liner set a few meters above the quenched magma. At the time of writing, a tracer test is underway to check connectivity with wells neighboring wells and surface valves have been installed in preparation for a flow test to evaluate the fluid chemistry, steam production, and potential-power output.

Depending on the result of this flow test of well IDDP-1, future possibilities might include the creation of the world's *hottest Enhanced Geothermal System (EGS),* for example by injecting water into an adjacent well and producing superheated steam from the magma. An advantage of such a strategy would be that any acidic magmatic gases might be neutralized by injecting suitably treated water.

Two new wells, ~4 km deep, will then be drilled at the Hengill and the Reykjanes geothermal fields during 2011-2012, and subsequently deepened into the supercritical zone. In contrast to the fresh water systems at Krafla and Hengill, the Reykjanes geothermal system produces hydrothermally modified seawater on the Reykjanes peninsula, in southern Iceland. This presents an ideal situation to study high-temperature magma-hydrothermal systems analogous to those responsible for the black smokers at submarine divergent plate margins, but at greater depth and temperature than has been possible so far by the ocean drilling program.

The IDDP has engendered considerable international scientific interest and its initial results will be reported in a number of papers at the World Geothermal Congress. The US National Science Foundation and the International Continental Scientific Drilling Program are jointly funding obtaining cores and samples for scientific studies

## 1. INTRODUCTION

The IDDP is a project of an international industry-government consortium working with and international team of scientists from several countries (Friðleifsson et al., 2010). Although the aim of the consortium is to improve the economics of geothermal energy production by producing supercritical geothermal fluids as a possible energy sources, a broad range of techniques will be necessary to investigate the little understood supercritical environment. The consortium therefore welcomed the inclusion of basic scientific studies in the IDDP (Friðleifsson and Albertsson, 2000; Friðleifsson, Albertsson and Elders, 2010).

From the outset the guiding principle was that the incremental costs of drilling and sampling for the science program, and their subsequent study, should be met by the scientific community. Two planning workshops, funded by the ICDP, were held in 2002 and a two year-long feasibility study, funded by Deep Vision, was concluded in 2003 (Friðleifsson et al., 2003). Part I dealt with geosciences and site selection (Fridleifsson et al., 2003), Part II with drilling strategy (Þórhallsson, et al. 2003), and Part III with fluid handling and evaluation (Albertsson et al., 2003). The feasibility study selected three high-temperature geothermal fields, at Reykjanes, Hengill, and Krafla, as sites for deep drilling (Figure 1), all three of which exhibit temperature gradients that are close to the boiling point to depth curve (Figure 2). The IDDP concept is that, instead of drilling conventional geothermal wells that produce a mixture of steam and water, by drilling deeper it should be possible to drill into the supercritical zone (Figure 3).

In late 2003 a member of the consortium offered one of its planned exploratory wells, RN-17, located on the Reykjanes peninsula for deepening by the IDDP (Friðleifsson and Elders, 2005). It was drilled to 3.1 km depth where it was planned to deepen it a further 1.5 km by continuous wireline coring. The 3.1 km deep well was flow tested in November 2005. Unfortunately the RN-17 collapsed and became blocked during this test. In February 2006 the well had to be abandoned after several attempts at reconditioning it had failed.

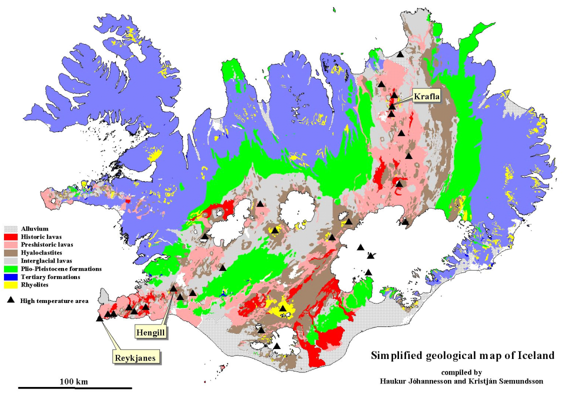


**Figure 1: Simplified geological map of Iceland showing the neovolcanic fissure zones (pink and red) and the locations of the geothermal systems of Reykjanes, Hengill, and Krafla, mentioned in the text.**

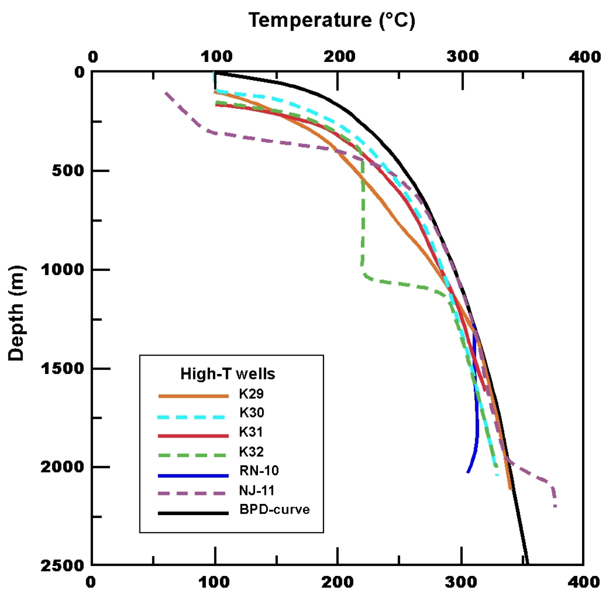


**Figure 2: Temperature gradients in many wells drilled in high-temperature geothermal systems in Iceland follow the boiling point to depth curve (BPD). K = Krafla, RN = Reykjanes, NJ = Nesjavellir (Hengill) (Friðleifsson et al., 2003).**

In June 2006, after considering all of the options available, it was decided to move operations to Krafla, the northernmost of the high-temperature areas shown in Figure 1, as the site for the first deep IDDP borehole.

This well, designated the IDDP-1, is located within a volcanic caldera with higher temperature gradients and more recent volcanic activity than Reykjanes (Figure 2). Because of the difficulty of cooling a deep, small diameter, core hole, the plan was changed to rotary drilling and casing this hole to 3.5 km depth, and then deepening it to 4.5 km into the supercritical zone, and taking a number of spot cores for scientific purposes. Flow testing from only the deepest portion of the well would be attempted. This plan was a compromise between the desire to obtain as much engineering and scientific data as possible and the limitations of safety, technology and budget.

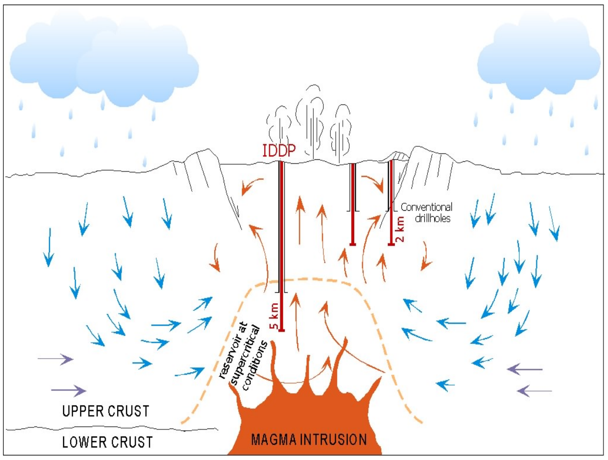


**Figure 3: Schematic model cross section of a high-temperature geothermal system in the neo-volcanic rift zone of Iceland, showing the target of the IDDP.**

## 2. SUPERCRITICAL GEOTHERMAL RESOURCES

Supercritical geothermal fluids in the Earth's crust are of considerable scientific interest and there have been discussions of their potential as sources of high grade energy (Yano and Ishido, 1998; Hashida, et al. 2001**;** Friðleifsson and Elders, 2005; Tester et al., 2006). This is because, in addition to supercritical water having higher enthalpy, large changes in physical properties of water occur near its critical point and the fluid changes from polar to non-polar behavior. Orders of magnitude increases in the ratio of buoyancy forces to viscous forces can lead to extremely high rates of mass and energy transport (Dunn and Hardee, 1981). Similarly, because of major changes in the solubility of minerals above and below the critical state, supercritical phenomena play a major role in high temperature water/rock reaction and the transport of dissolved metals (Norton and Dutrow, 2001).

The critical point (CP) of pure water occurs at 221 bars and 374 °C. Because of the effect of dissolved components the CP for seawater is at ~298 bars and ~ 407 °C (Bischoff and Rosenbauer, 1988). Above the CP in such saline aqueous systems a relatively dense vapor phase containing dissolved salts coexists with a liquid brine phase.

Figure 4 shows the pressure-enthalpy diagram for pure water, showing selected isotherms (Fournier 1999).

The various arrows show different pathways for heated water decompressing as it rises from depths The arrows to the left of the vertical line A-B (A-E and A-L) show possible pathways where upward flow is accompanied by conductive cooling so that supercritical fluid transitions into hot water with, or without, boiling. The path AE is representative of many high-temperature, water-dominated, geothermal reservoirs where typically boiling, induced by decompression, drives thermo-artesian flow in a well bore. The arrow A-B shows a supercritical hydrothermal fluid at A flowing upward and cooling adiabatically to reach the critical point at B where it separates into liquid water and steam at E and D. 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. The target of the IDDP is to form pathways like F-G flow supercritical fluid to the surface in such a way that it transitions directly to superheated steam. Such superheated steam at G contain much higher enthalpy than wet steam at E that typically feeds steam turbines in geothermal plants.

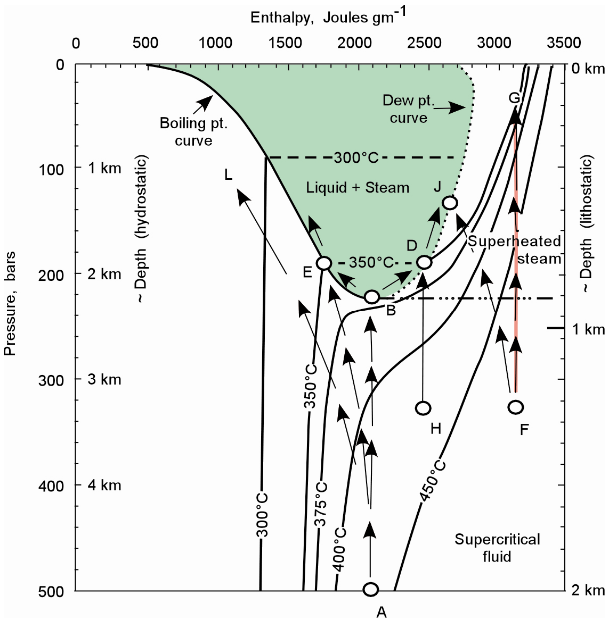


**Figure 4: Pressure enthalpy diagram for pure $H_2O$ with selected isotherms and various cooling paths. Steam and liquid water coexist in the green shaded area, bounded by the boiling point curve to the left and the dew point curve to the right. (Modified from data in Fournier, 1999, Figure 7).**

The depth scales marked at the left and right sides of Figure 4 correspond to pressures in hydrothermal systems – respectively controlled by cold water hydrostatic conditions and by lithostatic load. Because cold water is much denser than superheated steam, if the pressure is controlled by cold water, the critical pressure in a dilute water column would be reached at about 2.3 km depth, corresponding to a pressure of 221 bars. Similarly on the ocean floor the critical pressure should occur at a depth of about 2.9 km, corresponding to the pressure of the critical point of seawater at 298 bars. In most high-temperature hydrothermal systems fluid pressures are hydrostatic. A characteristic of these systems in Iceland is that they are at, or close to, boiling. Thus the maximum pressure and temperature at each depth is determined by the boiling point to depth curve (BPD-curve), and the critical point should be reached at about 3.5 km depth.

## 3. THE IDDP-1 WELL AT KRAFLA

### 3.1 The Krafla Geothermal System

Figure 5 shows the structure of the Krafla caldera (Sæmundsson 1991). The features of importance with respect to drilling the IDDP well are (1) the presence, size and specific location of a magma chamber previously interpreted to exist beneath the Krafla caldera, (2) the pressure temperature conditions within the geothermal field, and (3) the nature of permeability likely at depth at the drill site. The magma chamber in Krafla was inferred from S-wave attenuation during the volcanic eruptions at Krafla in 1975-1984, and interpreted to be at 3–8 km depth below the drill field (Einarsson 1978, Björnsson 1984) and a recent MT-survey has confirmed the existence of low resistivity bodies at these shallow depths within the volcano.

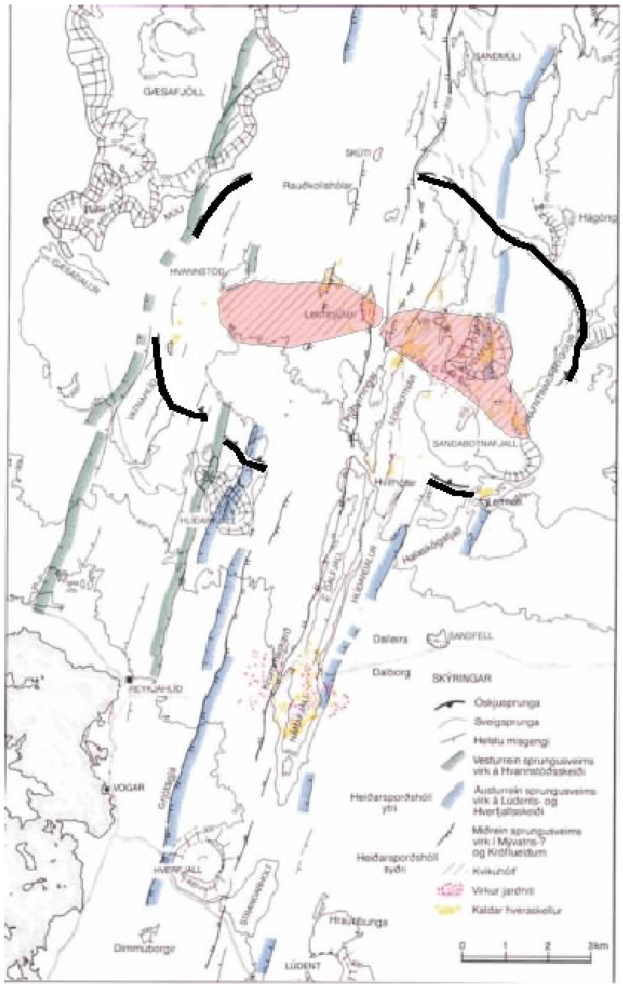

**Figure 5: Simplified structural map of the rift zone in which the Krafla caldera is situated. The heavy black line shows the boundary fault of the caldera and the heavy pink shaded area indicates areas of surface hydrothermal alteration (adapted from Sæmundsson, 1991).**

Temperatures greater than 300°C are common in the production wells with corresponding hydrothermal alteration to epidote-actinolite stage (Guðmundsson and Arnórsson, 2002). Within the two main producing zones at Krafla temperatures of up to 340°C were encountered at depths as shallow as 2.2 km (Figure 6).

The pressure-temperature gradients in producing wells typically follow the BPD curve from about 1100 m downwards. For example, the temperature in the well KG-26 at 2.5 km depth is expected to be 355°C. This suggests that the critical point for pure water should be reached at depths as shallow as about 3.5 km as the produced geothermal waters contains less than 2000 mg/L of total dissolved solids, with some admixture of magmatic gases. The plan was to cement the production casing to ~3.5 km depth in the IDDP well with the expectation that supercritical conditions would be reached soon after drilling out of the 3.5 km deep casing. However, the possibility of reaching temperature conditions higher than that controlled by the BPD-curve at shallower depth, was also considered. For instance, the temperatures below 2200 m depth in well NJ-11 at Nesjavellir in 1985 (Steingrímsson, et al., 1990), clearly surpassed the conditions determined by the BPD-curve, as superheated steam hotter than >380°C was encountered there. Therefore, planning for the IDDP well at Krafla, included dealing with superheated steam at P-T conditions surpassing the BPD-curve, and the possibility of acid magmatic gases.

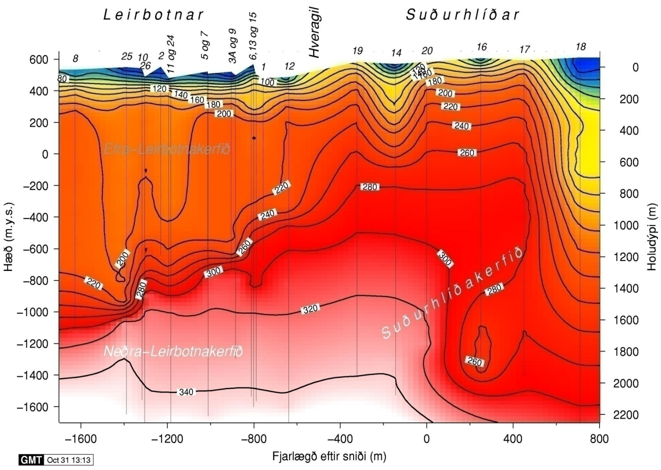


**Figure 6: NW-SE cross section across the producing geothermal fields at Krafla, showing isotherms in °C. The numbered vertical lines are the positions of older drillholes projected into the line of section (Friðleifsson et al., 2003).**

Such acid gases had been encountered in at Krafla in a flow test of the well KJ-36 in December 2008. This well has a surface location about 700 m east of the IDDP well but, unlike the IDDP-1 which will is vertical, KJ-39 is inclined to the NW for a length of 2500 m to intersect fissures associated with an eruption in 1724 AD and a second 2000 year old eruptive fissure 250 m further west. It produced high-pressure, superheated, steam that condensed water droplets which contained HCl at a concentration of 400-900 mg/kg. This observation and its high enthalpy indicate that this steam had followed a pressure-enthalpy path similar to line D-J in Figure 3. Decompressing a high enthalpy saturated, or superheated, vapor as it moved upwards allowed it to intersect the Dew Point Curve causing a small amount of liquid water to begin to condense. As pointed out by Fournier (2007, p. 336), when this occurs in a $H_2O$-NaCl system, neutral $HCl^o$ in the vapor partitions into the newly formed liquid water and dissociates into reactive H+ and Cl-, producing a corrosive solution that initially is undersaturated with respect to the minerals in the wall rock. Experience from other wells indicates that hot saturated and/or superheated steam may be produced from deeper than 2.2 km depth over a wide area in the vicinity of the site of the deep IDDP well that, when condensed, will be acidic.

In November 2008 direct evidence of the presence of magma in the geothermal system was found in the well KJ-39. At a depth of ~ 2.6 km, a temperature of 386 °C was measured within the drill string while circulating drilling fluid. When tripped out the drillhead assembly contained quenched rhyolitic magma (~74% $SiO_2$), containing and relict crystals of fresh basaltic minerals. This magma is possibly formed by anatexis of hydrothermally altered basalt (Mortensen, et al., 2010 B).

### 3.2 Drilling the IDDP-1 Well at Krafla

The operating company at Krafla, Landsvirkjun (the National Power Company) agreed to fund drilling and casing the well to 3.5 km and the IDDP consortium to fund its completion to 4.5 km and subsequent testing. The US National Science Foundation (NSF) and the International Continental Scientific Drilling Program (ICDP) jointly provided funding for coring and sampling the well for scientific studies. It was estimated that the combined NSF and ICDP funds for the IDDP should be sufficient to obtain at least 10-12 drill cores, each 10 m long.

The drilling plan for the IDDP-1 is described in detail by Þórhallsson, et al., 2010. It called for a 32” surface casing to 90 m, a 24 ½” first intermediate casing to 250 m, a 18 5/8” second intermediate casing to 800 m, a 13 3/8” casing to 2400 m, a 9 5/8” casing to 3500 m, and an 7” slotted liner to total depth of 4500 m. Drilling for the intermediate casings began in November 2008 and it was cased to 800 m depth in mid-December. Drilling resumed in late March 2009 with a 16 ½” bit, planning to set the 13 3/8” casing at 2400 m. The expectation was that the target depth of 4500 m would be reached in early July.

There will be several other reports about drilling the IDDP-1 at the World Geothermal Congress in April 2010, so it will be described only briefly here (Ármannsson, 2010; Friðleifsson, et al. 2010; Hólmgeirsson, et al. 2010; Ingason, et al, 2010). Progress was normal until at a depth of 1200 m was reached when the first of multiple problems was encountered. At that depth the drill string became stuck and during attempts to free it, the bottom hole assembly (BHA) twisted off and time was lost fishing. Almost three months of drilling problems, getting stuck, having twist offs, and having to sidetrack three times, then followed. Because of the many problems encountered up to the middle of May, it was decided to set the 13 3/8” anchor casing at 1957 m depth instead of the planned 2400 m.

At 2040 m depth we decided to attempt taking a 10 m long core, but after coring for 3 hours and 2.7 m it was evident that no progress was being made. When the coring assembly was tripped out it was clear that the attempt was a total failure as there was no core in the barrel and the coring bit was completely worn out. In addition to the excessive wear on the core bit, the stabilizers on the core barrel also showed an unusual amount of wear. It is evident that the coring BHA, with its 8” bit, was not stable in the 12 ¼ in hole. A caliper log showed that the stabilizers on the drill string above the core barrel had unfortunately been situated adjacent to zones of caving so that the coring bit was free to move laterally in a partially collapsed hole.

A junk basket run produced a large quantity of cement chips and collapsed rock fill. The rock samples recovered in the junk basket were a complex of surprisingly fresh basalt and granophyre, exhibiting complex interactions with basalt intruding into granophyre and the granophyre intruding into the basalt. After cleaning the hole, attempts were made to stabilize it by cementing the collapsed zones, and drilling was resumed. However problems continued for three weeks in June that led to the third side track being necessary at 1935 m. Then, on June 24th the reason for the more than two months of caving and getting stuck, leading to twist offs, fishing and sidetracks became apparent; the rocks were very hot and therefore thermally stressed. At 2104.4 m depth, the weight-on-bit suddenly declined, while the rate of penetration and the torque shot up. After pulling up the drill string a few meters and maintaining circulation, colorless rhyolitic glass cuttings were returned, followed by abundant, darker, obsidian-like drill cuttings. It became clear magma had flowed into the drill hole. This intrusion of magma within the Krafla caldera presumably is related to eruptions that occurred nearby from 1975-84, and appears to be a sill or dike of unknown extent. The quenched glass is a subalkaline rhyolite with ~ 75% by weight of $SiO_2$ containing < 2 % of $H_2O$ and phenocrysts of magnetite, pigeonite, clinopyroxene, and andesine (personal communication, R. Zerienberg, July 2009). Based on plagioclase – rhyolite glass compositions the water content the geothermometer/hygrometer of Lange et al. (2009) preliminary estimates suggest that the rhyolite magma has a plagioclase liquidus temperature of ~1050 º C.

As indicated above, the IDDP-1 well was sited based on the existing geophysical models and data from nearby wells. Models based on the interpretation of seismic and magnetotelluric data suggested the magma chamber was deeper than 4.5 km at that site. Evidently the resolution of that method was not sufficient to identify the intrusion that the IDDP-1 penetrated. As the intrusion is still molten, if it occurred during the eruptions from 1975-84, it must have a minimum thickness of at least 50-100 m. More detailed geophysical surveys will be necessary to map out the extent of the intrusion as part of estimating its resource potential. It was deemed not feasible to continue drilling deeper in well IDDP-1, given the equipment available. Therefore, the well was completed with a cemented 9 5/8" sacrificial casing inside the anchor casing and a 9 5/8" slotted liner set a few meters above the quenched magma.

Tracer tests are being carried out to check connectivity with wells neighboring well IDDP-1, and surface valves were installed in preparation for a phased program of flow testing beginning at the end of November 2009 to evaluate the fluid chemistry, steam production, and potential-power output. Cold water was continuously injected until mid-August at 25 L/s and then the well was allowed to heat. After 23 days of heating, the zone between 1700 m and 1900 m had reached 320°C but surprisingly the zone from 2000 to 2100 m remained at 50°C due to the effects of the large amount of cold water injection, both during and after drilling.

At the time of writing, the results of thermal recovery and of the initial flow test are not yet known. However depending on the outcome of these tests, future possibilities might include the creation of the world's *hottest Enhanced Geothermal System (EGS)* by injecting water into adjacent wells and producing superheated steam from the magma. An advantage of such a strategy would be that the acidic gases likely to be given off by the magma might be neutralized with injections of suitably treated water.

## 4. INITIAL SCIENTIFIC FINDINGS

The rocks penetrated in the first 800 m of the IDDP-1 well consisted of basaltic flows and hyaloclastites with relatively few dikes. The lithology of the section drilled from 800 to 2005 m consists mainly of three main formations, hyaloclastites from 800- 960m, basaltic lavas from 960 to 1360 m, and primarily basaltic intrusives from 1360 to 2007 m, followed by a composite intrusion of basalt/dolerite and granophyre. Several studies of the drill cuttings and quenched magma from the IDDP-1 are underway and preliminary results will be reported in the coming months.

In preparation for the deep drilling, studies of data and samples from the existing geothermal, wells up to 3 km deep, at both the Reykjanes and Krafla geothermal fields were the undertaken by the IDDP scientific team and some of the results of that work are being reported at this congress. (Freedman, et al., 2010; Marks, et al., 2010; Olsen, et al., 2010; Pope et al., 2010). For example, there were extensive studies of samples recovered from the RN-17 well at Reykjanes. Freedmann et al. (2010) studied zoned epidotes in the trivariant assemblage epidote-prehnite-calcite-quartz-fluid. Using thermodynamic analysis of this assemblage and epidote-prehnite compositions it is possible to calculate $P_{CO2}$ of the hydrothermal fluids in equilibrium at different depths. The data from Reykjanes show how $P_{CO2}$ of the fluids has increased during the evolution of the hydrothermal system likely due to periodic magma injection and degassing during dike emplacement.

Similarly at Reykjanes, Pope et al. (2009, 2010) have used oxygen and hydrogen stable isotopes in hydrothermal minerals, particularly epidote, to resolve the fluid history in these IDDP geothermal systems. The chlorine concentration of modern Reykjanes geothermal fluids indicate that they are hydrothermally modified seawater. However, before the Reykjanes system was penetrated by seawater, it was occupied by dilute glacial melt water. The detailed study of $\delta D$ and $\delta^{18}O$ by Pope et al. (2009) focused on the discrepancy between the modern seawater-like salinity of the Reykjanes fluids and their hydrogen isotopic ratios, which, in contrast, resemble meteoric water ratios. The origin of that discrepancy was constrained by analysis of hydrogen and oxygen isotopes in hydrothermal epidotes from depths of 1 to 3 km. The $\delta D_{fluid}$ calculated to be in equilibrium with these hydrothermal epidotes is lower than that of the modern fluids whereas the $\delta^{18}O$ are within the range observed in the modern fluids. This appears to be the result of diffusional isotopic exchange between seawater and hydrothermal minerals that had previously precipitated from heated dilute, water derived from the Pleistocene glaciers that formerly completely covered the Reykjanes Peninsula.

The disappearance of the thick ice sheet that covered the whole of Iceland during the Pleistocene has left its signature on all of Iceland's long-lived geothermal systems. It has been pointed out that the high permeability within these systems, and the fact that so many of them exhibit thermal gradients close to or even exceeding the BPD curve, could partly be due to the effect of this history (Elders and Friðleifsson, 2009A). Their thermal gradients are a relic of the time when heat transfer occurred under hydrostatic pressures adjusted to an ice cover and their fracture permeability is partly the product of the relaxation of pressure due to removal of the ice.

Marks et al. (2010) discussed one relic of the effect of an ice cover in the hydrothermal mineral assemblages in the RN-17 well at Reykjanes. These show that the system still bears signs of formerly having being covered by an ice sheet and has evolved rapidly since its disappearance. Although the modern thermal gradients follow the BPD curve (Fig. 2) the occurrence of an assemblage of greenschist facies alteration minerals, including prehnite, epidote and garnet, implies that, at some time, temperatures must have reached at least 250 $^oC$ at depths as shallow as 350 m. This means that hydrostatic pressures exceeded the present day BPD curve. Throughout the well hydrothermal alteration is strongly correlated with the nature of the protolith. Calcite bearing hyaloclastites were intensely altered to assemblages of calcic plagioclase, grandite garnet, prehnite, clinopyroxene, and titanite. In contrast, crystalline basalts and intrusives may be only slightly altered to highly altered, with albitization of igneous feldspars and uralitization of the igneous pyroxenes, and the development of hydrothermal anorthite as vein fillings.

Pope et al. (2009, 2010) have also studied the fluid elemental and isotope chemistry of geothermal fluids in the Krafla geothermal field. There the source of these fluids is local, meteoric water as the oxygen isotope compositions of present-day geothermal fluids are not significantly more positive than local meteoric water. This suggests that at Krafla there has either been limited fluid/rock interaction, or that the water to rock ratio is extremely high. Oxygen isotope compositions of hydrothermal minerals exhibit a variability observed spatially and with depth that is a product of complex subsurface hydrology and multiple potential fluid sources, including a significant input of magmatic fluids.

**4.1 Permeability at Depth.**

An important goal of the science program of IDDP is to study permeability changes with depth in the geothermal systems of Iceland. Beneath all three of the proposed IDDP drill sites, the bottom of the seismogenic part of the crust, where 90% of the seismicity occurs, appears to be the transition between brittle and plastic behavior at a depth of between 6 and 7 km below the surface (Friðleifsson and Elders, 2005). Brittle-plastic transitions are strongly dependent on both temperatures and strain rates. According to Fournier (2007, p.325), in basaltic rocks this should occur at about 500-600 $^{o}$C for strain rates of about $10^{-14}$ $s^{-1}$ instead of about at 370-400 $^{o}$C in a rhyolitic system. Non-double couple earthquakes occur in the mid-crust and in the top part of the lower crust in regions of crustal genesis in Iceland, suggesting that hydrous phases may exist in the crust at depths where temperatures exceed 400°C. Based on these seismic data, we expect temperatures at 5 km depth at the proposed IDDP drill sites range from 550 to 650 +/- 100 °C (Friðleifsson and Elders, 2005). It is likely that the base of a hydrothermal cell is controlled by decrease of permeability. Permeability could decrease (1) due to transitions from brittle to plastic behavior, and (2) self-sealing of fractures due to hydrothermal alteration and pressure solution.

Fournier (2007, p. 337-339) suggests that a major factor controlling the decrease of seismicity with depth is a transition from hydrostatic fluid pressure to greater than hydrostatic fluid pressure that marks the limit of downward migration of fluids at hydrostatic pressure. At temperatures > 370 $^{o}$C, increasingly rapid rates of mineral solution and deposition promote very rapid vein filling independent of rock type. Fournier (2007) infers that self-sealing permits fluid pressures in basaltic systems to become greater than hydrostatic (but less than lithostatic) at temperatures above about 370 $^{o}$C, while the brittle to plastic transition occurs much deeper at temperatures above 600 to 700$^{o}$C. Episodic faulting might allow escape of "supercritical" fluids from high-pressure reservoirs into the brittle basalt above. However, such fluid flow is likely to be relatively short-lived because of very rapid vein filling with decreasing pressure. Recharge of ground waters into basaltic rock would most likely occur between dike and sill injections when and where rocks have temporarily cooled to less than "supercritical" temperatures and fluid pressures have decreased to hydrostatic. In any case, seismic evidence indicates that fracturing persists to greater depth and to temperatures greatly exceeding 400$^{o}$C in these high-temperature geothermal systems in Iceland.

Recently new seismic data acquired for the Reykjanes Peninsula suggests that seismicity, observed over a 5 month period in 2005, cuts off at 6 km depth (Geoffery and Dorbath, 2008). This was a detailed passive seismic survey of the Peninsula, more precise than any previous study in the area. These data provide a strong confirmation that abnormally high fluid pressures exist under geothermal systems in SW Iceland. Geoffery and Dorbath (2008) observed a clustering of seismicity beneath geothermal areas and a clear spatial relationship between areas of high seismicity and areas of low $V_P$/Vs ratios, together with a clustering of seismicity beneath geothermal areas. Geoffery and Dorbath (2008) suggest that these earthquakes are linked to high fluid pressures at depth where hydrothermal fluids exist as deep as the base of the brittle crust (Zencher et al., 2006). They further propose that these fluids are probably in the supercritical state with high pressures intermediate between hydrostatic and lithostatic. They suggest that a dual fluid reservoir exists. Down to 3 km depth the fluids are brines at boiling point conditions in a hydrostatic state that are convecting by thermohaline circulation. They infer that, in the deeper reservoir below 3 km, high-enthalpy, high-pressure, supercritical fluid exists. Such fluids dramatically increase the potential for rock fracturing by stress-corrosion micro-cracking (Hashida et al, 2001). Geoffery and Dorbath (2008) speculate further, that during dilatational earthquake activity, denser cold fluids from the upper reservoir would recharge the lower reservoir, leading to separation of a vapor phase that carries heat into the upper reservoir. This process may be involved at slow-spreading mid-ocean ridges allowing seawater to efficiently cool the upper oceanic crust (Geoffery and Dorbath, 2008, p. 5).

**4.2 Implications for Mid-Ocean Ridge Hydrothermal Systems**

Iceland, as only large landmass on the Mid-Atlantic Ridge, is an ideal location to study hydrothermal processes on a divergent plate margin (Elders and Friðleifsson, 2009B). 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 and temperatures, but the maximum temperatures are usually limited to 350-400°C (Kelley, et al. 2002). Nearly all black smoker discharges on mid-ocean rifts are subcritical as many of them occur at depths shallower than the critical pressure of seawater. However the salinity of these high temperature discharges can be either more, or less, saline than seawater by a factor of 2 or more (Some have only 10% of seawater salinity; Bischoff and Rosenbauer 1989; Van Damm, 1995). Examples occur both on the Juan de Fuca Ridge and the East Pacific Rise (Elders and Friðleifsson, 2009B). This is evidence that supercritical phenomena play an important role in the evolution of these fluids and that phase separation of supercritical fluids occurs deeper in the flow systems.

It was not until 2005 and 2006 that submarine hydrothermal vents discharging fluids lying at, or above, the critical point (CP) of seawater were successfully sampled. These occur at 5 $^{o}$S on the Mid-Atlantic Ridge (Koshchinsky et al., 2008). This vent field is characterized by multiple discharges with variable temperatures at water depths of ~3km. One vent discharges reduced salinity fluid at stable temperatures of 407 $^{o}$C and exhibits vigorous vapor phase bubbling, indicating phase separation above the CP. Another vent had a measured temperature of 464 $^{o}$C that falls into the vapor-phase supercritical field for seawater. Koschinsky, et al. (2008) believe that the activity of these supercritical vents was triggered by a seismic episode in 2002, so the supercritical discharge had persisted for at least four years.

The fluids discharged from mid-ocean vents have been modified by reactions with basalt and gabbro, at temperatures of 350-550°C, but extending up to 800°C (Manning and MacLeod, 2000). The interaction of such high-temperature fluids with mafic diabases forms highly Ca-metasomatised epidosites. At the high (> 450°C) temperatures expected in the IDDP boreholes we expect to encounter metamorphic mineral assemblages that record the transition from the greenschist to the amphibolite facies. These zones of intensive reaction are most important for the practical goals of the IDDP. It is predominantly there that mobile fluids are heated and interact chemically with their host, where most of the geologically important heat transport and chemical alteration take place, and where superheated steam should be most easily be produced for power generation (Elders and Friðleifsson, 2009B).

## 5. FUTURE IDDP DRILLING

In the next two or three years IDDP will drill at Hengill and at Reykjanes, with the relevant field operator providing a suitable well, 3.5-4 km deep, for deepening into the supercritical zone by the IDDP, with participation by the scientific community. In addition to exploring for new and enhanced sources of energy, this series of holes in Icelandic geothermal fields, including a return to the seawater system at Reykjanes, will allow a broad array of scientific studies involving water/rock reactions at high temperatures. It will be the first opportunity worldwide to directly investigate hydrothermal processes in a volcanic system in a mid-ocean ridge-like environment (Elders and Friðleifsson, 2009B). If the goal of producing supercritical fluids is successful in Iceland, the same approach could be applied worldwide, wherever suitable high temperature geothermal reservoirs occur, with obvious implications for improving the economics of the geothermal energy industry.

## 6. DISCUSSION

We anticipate that the opportunities presented by the IDDP will lead to major advances in understanding fundamental energy and mass transfer processes of global significance, processes that have implications ranging from plate tectonics, to the formation of oceanic crust and massive sulfide ore-bodies, and to the controls on seawater chemistry. The Icelandic energy industry has invited the scientific community to participate. Thus a major share of the costs of drilling three wells as deep as 5 km will be borne by industry and the scientific program will also benefit from the extensive practical experience of the industrial partners. We should seize such rare opportunities for collaboration between the applied and basic science communities.

While deep drilling and direct sampling of hydrothermal reaction zones is the only way to resolve important scientific questions, the industrial aim for the IDDP is to improve the economics and availability of geothermal energy, an environmentally benign form of alternative energy. If the IDDP approach of using deeper, hotter, supercritical resources is successful, it will make a positive impact on the geothermal industry worldwide, wherever supercritical conditions occur at drillable depth.

The production of high-quality superheated steam by decompressing supercritical fluids has obvious advantages. Drilling deep enough in high-temperature geothermal fields could undoubtedly reach supercritical temperatures and fluid pressures. However it remains to be demonstrated that the economics of doing so is favorable, and that largely depends on the available permeability in the supercritical zones. Today many members the geothermal community are reacting favorably to a recent publication (Tester et al. , 2006) that suggest that the greatest opportunity for future growth of geothermal resources lies in the development of “enhanced geothermal systems (EGS)” where permeability is artificially created by hydraulic stimulation and fluid is supplied through injection wells. This report (available at http://www1.ere.energy.gov/geothermal/future_geothermal. html) suggested that in the USA EGS could provide 100,000 MWe, or more, in 50 years given a program of accelerated development. However, caveats have been raised particularly about the cost and economic viability of such a program (Geothermal Technologies Program, 2008; http://www1.eere.energy.gov/geothermal/pdfs/evaluation_egs_tech_2008.pdf). Tester et al. (2006, Fig. 1.10) point out very much larger power producing potential or “availability” of supercritical water relative to subcritical water. We suggest therefore that in developing EGS, rather than starting "green field" investigations, the place to start is with the highest enthalpy systems, and drilling deep enough to produce the supercritical fluids lying beneath existing high temperature geothermal fields, where the necessary infrastructures are already in place. By doing so one could potentially increase their power outputs by an order of magnitude without increasing their environmental foot prints. We should "enhance" geothermal systems by producing supercritical fluids.

## 7. CONCLUSIONS

While our first attempts to drill into the supercritical environment at Reykjanes and Krafla were both unsuccessful, for different reasons, the prospect of increasing the power output of geothermal fields ten-fold without increasing their environmental foot print remains an attractive prospect. The concept could be applied worldwide, wherever the necessary temperatures and pressures exist at economically drillable depth. The IDDP remains committed to further tests of the idea in Iceland in the next few years. Meanwhile we have the exciting prospect of testing a ~1000 $^{o}$ C Enhanced Geothermal System at only 2100 m depth at Krafla.

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## REFERENCES

Albertsson, A., Bjarnason, J.Ó., T. Gunnarsson, T., Ballzus, C., and Ingason, K.: Part III: Fluid Handling and Evaluation. In: *Iceland Deep Drilling Project, Feasibility Report, (Ed.)* G.Ó. Friðleifsson. Orkustofnun Report OS-2003-007, (2003) 33 pp. (also at http://www.iddp.is).

Ármannsson, H.: IDDP – the Chemistry of the Krafla Geothermal System in Relation to the IDDP Well.

*Proc. World Geothermal Congress*, Bali, Indonesia, April 25-29 (2010) (submitted).

Bischoff J.L. and Rosenbauer, R.J. Liquid-vapor relations in the critical region of the system NaCl-$H_2O$ from 380$^oC$ to 414$^oC$: A refined determination of the critical point of seawater. *Geochimica et Cosmochimica Acta,* **52**, (1988) 2121-2126.

Bischoff, J.L. and R.L. Rosenbauer, R.L. Salinity variations in submarine hydrothermal systems by layered double-diffusive convection. *Jour. Geology* **97**, (1989) 613-623.

Björnsson, A., Dynamics of crustal rifting in NE- Iceland. *Geophysics,* **90**, (1985) 151-162.

Einarsson, P., S-wave shadows in the Krafla caldera, evidence for a magma chamber in the crust. *Bull. Volcanology* **41**, (1978) 1-9.

Elders, W.A., G.Ó. Friðleifsson, G.Ó.: The Iceland Deep Drilling Project (IDDP): Deep Drilling at Krafla to Investigate Supercritical Geothermal Resources. *Trans. Geothermal Resources Council*, (2009A) (In Press).

Elders, W.A., Friðleifsson, G.Ó.: Implications of the Iceland Deep Drilling Project for Improving Understanding of Hydrothermal Processes at Slow-Spreading Mid-Ocean Ridges. *In* Diversity of Hydrothermal Systems on Slow-Spreading Ocean Ridges, Rona, P., C. Devey, J. Dyment, B. Murton, (*Eds.*) *Monograph of the American Geophysical Union* (2009B) (in press).

Dunn, J.C. and Hardee, H.C.: Superconvecting geothermal zones. *J. J. Volcanology, Geothermal Res.***11**, (1981) 189-201.

Fournier, R.O.: Hydrothermal processes related to movement of fluid from plastic into brittle rock in the magmatic-epithermal environment. *Economic Geology,* **94**, (1999) 1193-1211.

Fournier, R.O.: Hydrothermal systems and volcano geochemistry, *in* Durzin, D. (*Ed.*) *Volcano deformation: geodetic monitoring techniques,* Springer-Praxis, Berlin, New York, Chichester UK, Chapter 10, (2007) 323-341.

Freedman, A. J. E., Bird, D. K. , Arnórsson, S., Friðriksson, Þ., Elders, W. A., Friðleifsson, G, Ó., 2009 "Hydrothermal minerals record variations in CO2 partial pressures in the Reykjanes geothermal system, Iceland", ***American Journal of Science***. (2009) (Accepted for Publication, July 2009).

Freedman, A.J.E., Bird, D.K., Arnórsson, S., Friðriksson, Þ., Elders, W.A., Friðleifsson, G. Ó.: Iceland Deep Drilling Project (IDDP): Hydrothermal Minerals Record Variations in CO2 Partial Pressures in the Reykjanes Geothermal System, Iceland. *Proc. World Geothermal Congress,* Bali, Indonesia, April 25-29 (2010) (submitted).

Friðleifsson, G.Ó and Albertsson, A.: Deep Geothermal Drilling at Reykjanes Ridge: Opportunity for an International Collaboration. *Proc. World Geothermal Congress,* Kyushu-Tohoku, Japan, May 28-June 10, (2000) 3701-3706.

Friðleifsson, G.Ó, Albertsson, A. and Elders, W.A.: The Iceland Deep Drilling Project (IDDP) – 10 years later – Still an Opportunity for an International Collaboration. *Proc. World Geothermal Congress,* Bali,, Indonesia, April 25-29 (2010) (submitted).

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

Friðleifsson, G. Ó. and Elders, W.A.: The Feasibility of Utilizing Geothermal Energy from Supercritical Reservoirs in Iceland: A Progress Report of the Iceland Deep Drilling Project. *Transactions of the Geothermal Resources Council,* (2003) 10 p.

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., Pálsson, B., Stefánsson, B., Albertsson, A., Gunnlaugsson, E., Ketilsson, J., Lamarche, R., and Andersen, P.E.: The first IDDP Drill Hole Drilled and Completed in 2009. *Proc. World Geothermal Congress*, Bali, Indonesia, April 25-29 (2010) (submitted).

Geoffroy, L. and Dorbath, C.: Deep downward fluid percolation driven by localized crust dilation. *Geophysical Research Letters,* **35**, L17302, (2008) 1-6.

Geothermal Technologies Program., An Evaluation of Enhanced Geothermal Systems Technology., *U.S. Dept. of Energy* (2008).

Guðmundsson B.Th. and Arnórsson S.: Geochemical monitoring of the Krafla and Namafjall geothermal areas, N-Iceland. *Geothermics* **31**, (2002) 195–243.

Hashida, T., Bignall, G. Tsuchiya, N.T., Takahashi T., and Tanifuji, K.: Fracture Generation and water rock interaction processes in supercritical deep-seated geothermal reservoirs. *Geothermal Resources Council Trans.* **25,** (2001) 225-229.

Hólmgeirsson, S., Guðmundsson, Á., Pálsson, B., Ingason, K., Þórhallsson, S.: Drilling operations of the first deep drilling well (IDDP). *Proc. World Geothermal Congress*, Bali, Indonesia, April 25-29 (2010) (submitted).

Ingason, K., Albertsson, A., Pálsson, B., Ballzus, C., Ármannsson, H., Matthíasson, J., Þórhallsson, S., and Gunnarsson, T.: Iceland Deep Drilling Project (IDDP) - Fluid Handling and Evaluation. *Proc. World Geothermal Congress,* Bali, Indonesia, April 25-29 (2010) (submitted).

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

Koshchinsky A., Garbe-Schonberg, D., S. Sander, S.,K. Schmidt, K., Gennerich, H., and H. Strauss, H.: Hydrothermal venting at pressure-temperature conditions above the critical point of seawater, 5$^o$S on the Mid-Atlantic Ridge. *Geology,* **30** *no.8:* (2008) 615-618.

Lange, R.A., Frey, H.M., and Hector, J., A thermodynamic model for the plagioclase-liquid hygrometer/ thermometer, *Am. Mineral*., **94**: (2009) 494-506.

Marks, N., Schiffman, P., Zierenberg, R., Elders, W.A., Friðleifsson, G.O., and Franzson H.: Isotopic Evidence of Hydrothermal Exchange and Seawater Ingress from Anhydrite in the Reykjanes Geothermal System: Results from IDDP Well Rn-17. *Proc. World Geothermal Congress,* Bali, Indonesia, April 25-29 (2010) (submitted).

Manning, C.E., and C.J. MacLeod, Lower-crustal cracking front at fast-spreading ridges: evidence from the East Pacific Rise and the Oman Ophiolite. *Geol. Soc. Amer. Special Paper* **349 (2000)** 261-272.

Mortensen, A.K., Guðmundsson, Á., Axelsson, G., Ármannsson, H., Björnsson, H., Ágústsson, K., Sæmundsson, K., Ólafsson, M., Karlsdóttir, R., Halldórsdóttir, A., and Hauksson, T.: Krafla geothermal System, Northern Iceland – a Revised Conceptual Model. *Proc. World Geothermal Congress,* Bali, Indonesia, April 25-29 (2010)A (submitted).

Mortensen, A.K., Guðmundsson, Á, Steingrímsson B., Owens, L., Hauksson, T., and Egilsson, Þ.: Geological, Geophysical and Geochemical Conditions Near Siliceous Magma – Revelations from Well KJ-39 in Krafla, Northern Iceland. *Proc. World Geothermal Congress,* Bali, Indonesia, 25-29 April (2010)B (submitted).

Norton, D.L. and Dutrow, B.L.: Complex Behavior of Magma-hydrothermal Processes: Role of Supercritical Fluid. *Geochimica Cosmochimica Acta.* **65,** no. 21, (2001) 4009-4017.

Olsen, N.J., Bird, D. K, Arnórsson, S., Fridriksson, Þ., Fridleifsson, G. Ó., and Elders, W. A.: Iceland Deep Drilling Project (IDDP): Arsenic Distribution and Mobility in Active and Fossil Geothermal Systems in Iceland. *Proc. World Geothermal Congress,* Bali, Indonesia, April 25-29 (2010) (submitted).

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*, **73** (2009) 4468-4488.

Pope, E.C., Bird, D.K., Arnórsson, S., Fridriksson, Þ., Elders, W.A. and Friðleifsson, G.Ó.: The Iceland Deep Drilling Project: Stable Isotope Evidence of Fluid Evolution in Icelandic Geothermal Systems. *Proc. World Geothermal Congress,* Bali, Indonesia, April 25-29 (2010) (submitted).

Skinner, A., Bowers, P., Þórhallsson, S., and Friðleifsson, G.Ó.: Coring at extreme temperatures. Design and Operation of a core barrel for the Iceland Deep drilling Project (IDDP). *Proc. World Geothermal Congress,* Bali, Indonesia, April 25-29, (2010)B (submitted).

Sæmundsson, K.: Jarðfræði Kröflukerfisins (The geology of the Krafla system- *in Icelandic*) *(In)* Garðarsson A. and Einarsson, Á. (*Eds*) *Náttúrra Mývatns,* HIN, (1991) 24-95.

Steingrímsson, B., Guðmundsson, Á., Franzson, H. and Gunnlaugsson, E.: Evidence of a supercritical fluid at depth in the Nesjavellir field. *Proc. Fifteenth Workshop on Geothermal Reservoir Engineering Stanford University*, Stanford California, January 23-25, 1990 SGP-TR-130, (1990) 81-88.

Tester, J.W. et al.: The Future of Geothermal Energy: Impact of Enhanced Geothermal Energy (EGS) on the United States in the 21st Century. MIT Panel Report to the DOE, (2006) 9 Chapters.

Þórhallson, S., Matthíasson, M., Gíslason, Þ., Ingason, K., Pálsson, B., and Friðleifsson, G.Ó.: Part II: Drilling Technology, 75 p. & appendix (45 p). (*In): Iceland Deep Drilling Project, Feasibility Report,* (Ed). G.Ó. Friðleifsson. Iceland National Energy Authority, Orkustofnun Report OS-2003-007 (2003). (also at http://www.iddp.is).

Þórhallsson, S., Pálsson, B, Hólmgeirsson, S., Ingason, K. and Bóasson, H.: Well design and drilling program for the Iceland Deep Drilling Project (IDDP). *Proc. World Geothermal Congress,* Bali, Indonesia, April 25-29 (2010) (submitted).

Van Damm, K.: Controls on the chemistry and temporal variability of seafloor hydrothermal fluids. *Amer. Geophys. Union Geophysical Monograph* **91**, (1995) 222-247.

Yano Y., and Ishido, T.: Numerical investigation of production behavior of deep geothermal reservoirs at super-critical conditions. *Geothermics,* **27**, No. 5/6, (1998) 705-721.

Zechner, F., M. Bonafede and R. Stefansson, Near lithostatic pore pressures at seismogenic depths: a thermo-poro-elastic model. *Geophys. J. Int.* **166** (2006) 1318-1334.