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The Iceland Deep Drilling Project – Scientific Opportunities

Wilfred A. Elders* and Gudmundur O. Fridleifsson**

*Dept. of Earth Sciences, University of California, Riverside, CA 92521, USA

**ISOR (Iceland GeoSurvey), Grensasvegur 9, IS 108 Reykjavik, Iceland.

wilfred.elders@ucr.edu, gof@isor.is

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ABSTRACT

The major energy companies of Iceland initiated the Iceland Deep Drilling Project (IDDP) to investigate the deeper levels of hydrothermal systems and determine if utilizing supercritical fluids could increase power production from such wells by a factor of 5-10 relative to that from conventional geothermal wells. The primary objective of IDDP is to find >450°C supercritical geothermal fluids at drillable depths, and to study their physical and chemical nature and energy potential. Over the next decade this will require drilling a series of wells 4–5km deep. Such deep, hot wells present both technical challenges and opportunities for important scientific studies.

Early in 2005 an Icelandic energy company will drill and flow test a 2.7 km deep well on the Reykjanes Peninsula at the southwest tip of Iceland, where the Mid-Atlantic Ridge emerges from the ocean. In 2006 the IDDP plans to deepen this well to 4.0 km, obtain several spot cores, and then carry out a second flow test at that depth, where temperatures approaching 400°C are possible. After evaluating the technical and scientific results from this depth, and the funding situation, a third phase of drilling with continuous coring is planned to reach 5 km depth, where a third flow test would be scheduled.

The IDDP borehole at Reykjanes will allow sampling fluids from 2.7 km, 4.0 km and 5.0 km, and produce more than 1.0 km of core from a high-temperature hydrothermal system located in an ophiolite-like environment that is actively forming today. This will be a very important contribution to global science and have clear connections to the studies of mid-ocean ridges by the Integrated Ocean Drilling Program. At the same time, we will gain a great deal of information about the deeper levels of a hydrothermal system and investigate an unconventional, very high-enthalpy geothermal resource.

From a scientific perspective this plan is very appealing. The geological setting of the Reykjanes well is a superb location for scientific investigations of both high-temperature hydrothermal phenomena and mid-ocean ridge processes. The IDDP drilling will address a wide range of world-class scientific questions, such as the formation of hydrothermal ores, and black smokers on mid-ocean ridges, and the coupling of hydrothermal systems with their magmatic heat sources. The IDDP therefore welcomes participation by the international scientific community and has planned a very comprehensive program of research with collaborating scientists from a dozen different countries. However we are still open to consideration of additional research activities.

INTRODUCTION

Over the next several years the Iceland Deep Drilling Project, IDDP, expects to drill and test a series of boreholes that will penetrate supercritical zones believed to be present beneath three currently exploited geothermal systems in Iceland, at Krafla, Hengill (Nesjavellir) and Reykjanes (Figure 1). This will require drilling to depths greater than 4 to 5 km, in order to produce hydrothermal fluids at temperatures of 450 to 600°C.

The IDDP was launched in 2000 by Deep Vision, a consortium of Icelandic energy companies (Hitaveita Sudurnesja Ltd., Landsvirkjun, Orkuveita Reykjavikur and Orkustofnun) (Fridleifsson and Albertsson, 2000). The principal aim is to enhance the economics of high temperature geothermal resources. A two-year long feasibility study was completed in 2003, dealing with geosciences and site selection (Fridleifsson et al., 2003), drilling techniques (Thorhallsson et al., 2003), and fluid handling and evaluation (Albertsson et al., 2003). These reports are available on the IDDP website at http://www.iddp.is/. In November 2003, based on the findings of this report, Deep Vision decided to proceed to the operational stage and to seek international partners.

From the outset Deep Vision has been receptive to including scientific studies in the IDDP. An international advisory group, SAGA, that has assisted Deep Vision with science and engineering planning of the IDDP, was established in 2001, with financial support from the International Continental Scientific Drilling Program (ICDP). SAGA discussed the drilling and scientific issues associated with the IDDP at two international workshops held in 2002. Altogether some 160 participants from 12 nations participated in the workshops. The recommendations of these workshops to IDDP are described in SAGA reports which are also available on the IDDP website. They are summarized and updated in two papers about the IDDP in press in a special issue of the Geothermics (Fridleifsson and Elders, 2004; Thorhallsson et al. 2004).

Modelling described in the feasibility report indicates that, relative to the output from conventional geothermal wells 2.5 km deep, a ten-fold increase in power output per well is likely if fluid is produced from reservoir hotter than 450°C. This is because supercritical fluids have very low viscosity and density, so that extremely high flow rates should be possible from such wells. A typical geothermal well in Iceland yields a power output equivalent to approximately 5 MW of electric power. An IDDP well tapping a supercritical reservoir with temperatures of 430 – 550°C and pressures of 23 – 26 MPa may be expected to yield 50 MW of electric power given the same volumetric inflow rate. However to reach these conditions requires drilling deeper than 4 km.

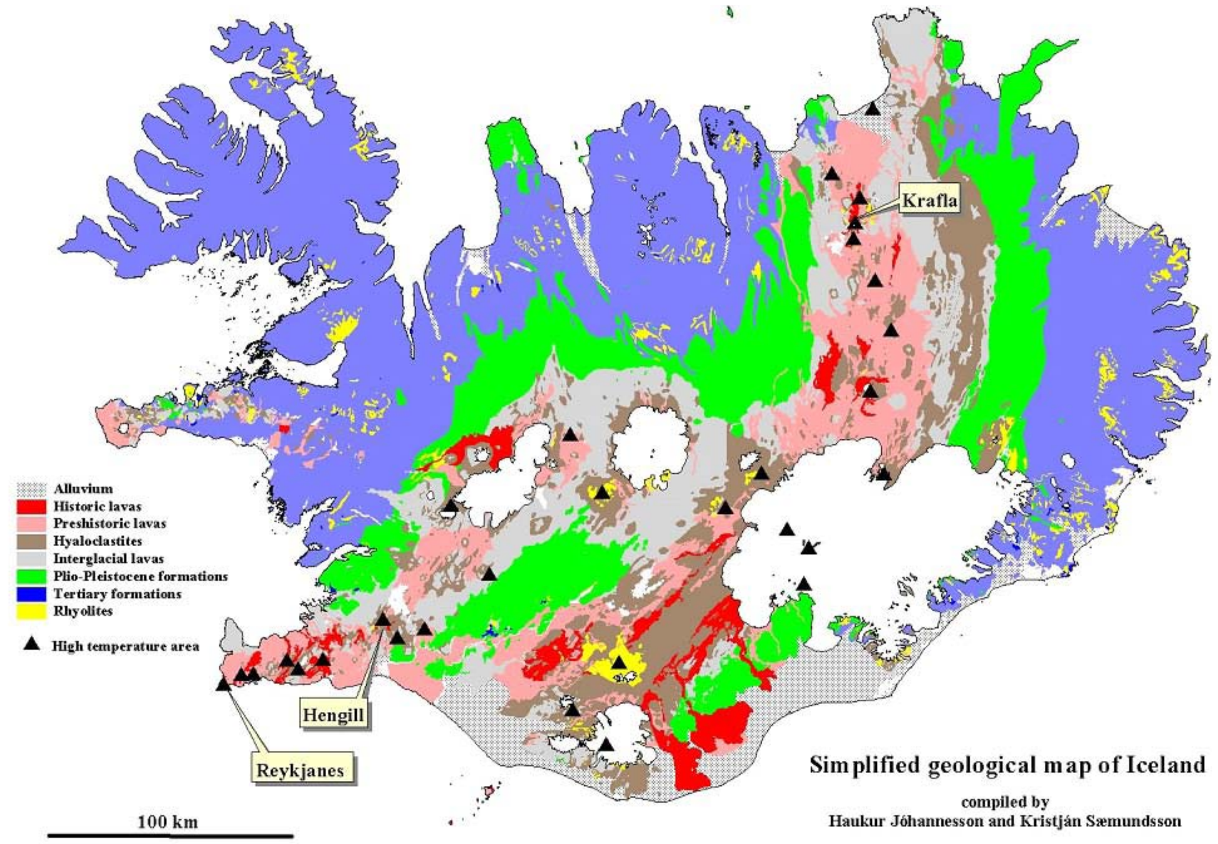


Figure 1: The geological setting of the high-temperature geothermal fields of Reykjanes, Hengill (Nesjavellir), and Krafla, being considered for deep drilling by IDDP.

The feasibility study also concluded that an IDDP well 5 km deep could be drilled using available technology but such a deep production well would cost 8-9 million USD and a full-scale exploratory IDDP well, with extensive coring required by the science program could cost 14.4-15.5 million USD. Drilling deeper wells to test such an unconventional geothermal resource would also allow testing of injecting cold water into fractured rock to sweep heat from a very hot reservoir. Experiments in permeability enhancement could also be conducted.

In December 2003 a member of the Deep Vision consortium, Hitaveita Sudurnesja Ltd (HS), offered to allow IDDP to deepen one of their planned 2.7 km deep exploratory/production wells for scientific studies. It is located on the Reykjanes peninsula, where the Mid-Atlantic Ridges emerges from the ocean and so is ideally located for scientific studies of supercritical phenomena and the coupling of hydrothermal and magmatic systems on mid-ocean ridges (Figures 1 & 2). We plan a comprehensive scientific program, involving investigators from more than 12 different countries, to take advantage of this unparalleled research opportunity.

2. MAIN SCIENTIFIC TARGETS

Although the aim of the industrial consortium is to investigate deep geothermal resources, the site at Reykjanes offers an unusually attractive target for scientific drilling. The active rifting and volcanism in Iceland is usually regarded as being due to its location at the coincidence of the spreading centers of the Mid-Atlantic Ridge and a mantle plume (Conrad, et al., 2004). Iceland is the largest landmass straddling a mid-ocean ridge and lies at the center of an actively forming Large Igneous Province stretching from Greenland to Scotland (Figure 2). Typically rocks near the surface in Reykjanes are hyaloclastites and basalt flows, which overlie sheeted dike swarms. These undoubtedly pass downwards into mafic intrusives gabbros, which in turn should be underlain by ultramafic rocks typical of the upper mantle (Figure 3A and B). With few exceptions, such as the Oman Ophiolite, ocean crust is not usually available to study at outcrop. However the Reykjanes site offers the advantage of permitting drilling into an ophiolite sequence on land, and to directly study *active* formation of ocean crust.

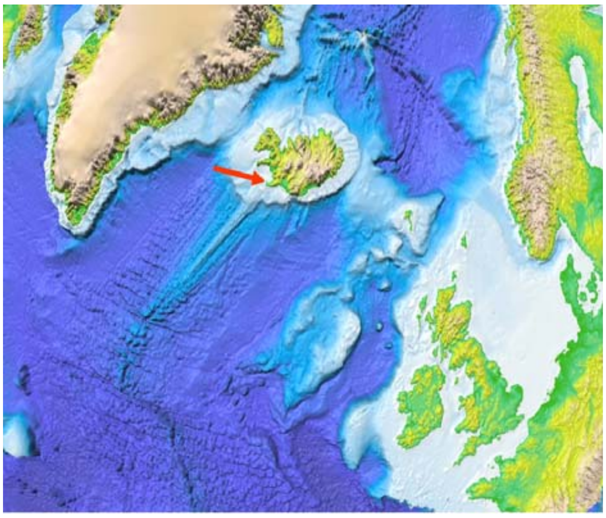
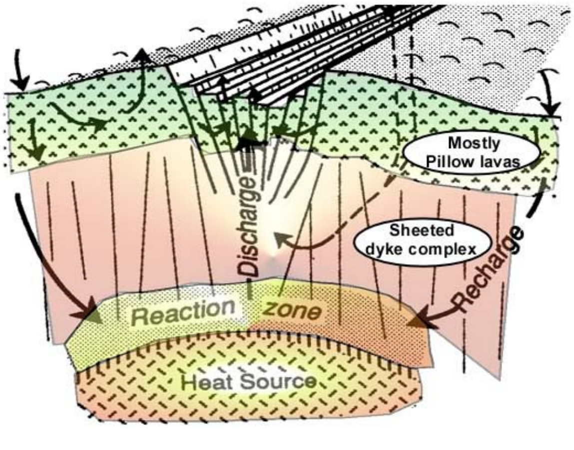


Figure 2: The arrow shows the location of Reykjanes Peninsula on the Mid-Atlantic Ridge at the South West tip of Iceland



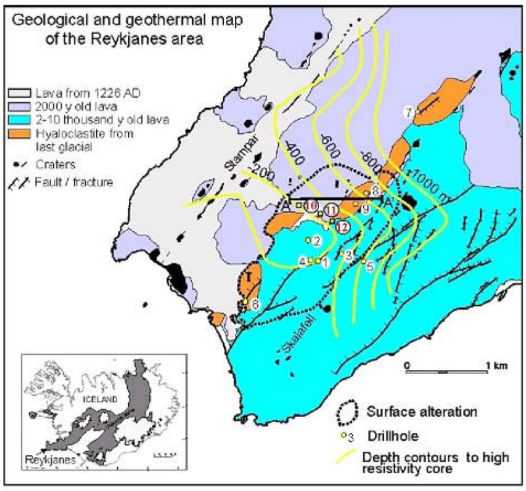


Figure 3A: LEFT: A schematic diagram of the crust in the central rift zones of Iceland showing a hydrothermal system heated by intrusions. Heat sources are thought to be commonly at 5 –10 km depth.

Figure 3B. RIGHT: Geological map of the Reykjanes Peninsula showing the locations of existing geothermal wells and candidate sites for the first IDDP well (Fridleifsson, et al., 2003).

Mid-ocean ridges are a major feature of planet earth and are one of the major targets for study by the Integrated Ocean Drilling Program (see “InterRidge – the Next Decade”, and “Ridge 2000 Science Plan”. However, although it is on land, the drill site offered to the IDDP is also ideally situated for a broad array of scientific studies involving reactions between basalt and seawater at high temperatures, reaching supercritical conditions where exceptionally high solubility and mass and energy transfer occur. The flux of seawater through mid-ocean rift hydrothermal systems is the major control of the chemistry of the oceans. However these processes are difficult to study by direct observation. Ocean drilling has penetrated only a few hundred meters into high-temperature marine hydrothermal systems (Kelley, Baross and Delaney, 2002). Furthermore ODP-type riser-less drilling does not allow fluid sampling. In contrast, the proposed drilling in collaboration with industry in Iceland will reach depths of 5.0 km and produce abundant fluid samples from three different depth levels.

As currently envisaged, the IDDP borehole is designed to reach 2.7, 4.0, and 5.0 km in successive stages. Depending on the fluid pressure, the drilled interval between 2.7 and 4.0 km should approach geochemical and pressure-temperature conditions similar to those of black smokers on oceanic spreading centers. The second phase of drilling and coring was designed to penetrate into supercritical fluids which couple black smoker hydrothermal systems with their volcanic heat sources. These environments have never been available for comprehensive direct study and sampling. Deep drilling will create a deep observatory to study the temporal behavior of this complex system.

2.1 Supercritical Phenomena

Currently high-temperature geothermal wells in the worldwide geothermal industry produce a two-phase mixture of water and steam at temperatures typically in the range of 200-320°C. The aim of Deep Vision is to improve the economics of geothermal resources by producing supercritical hydrothermal fluids. As indicated above, our modeling suggests that wells producing high enthalpy supercritical fluids should have much higher flow rates, and hence power outputs, than are currently being utilized by the international geothermal industry. The goal of the IDDP is to drill deep enough into already known geothermal reservoirs in Iceland to reach supercritical conditions and enhance the power outputs per well.

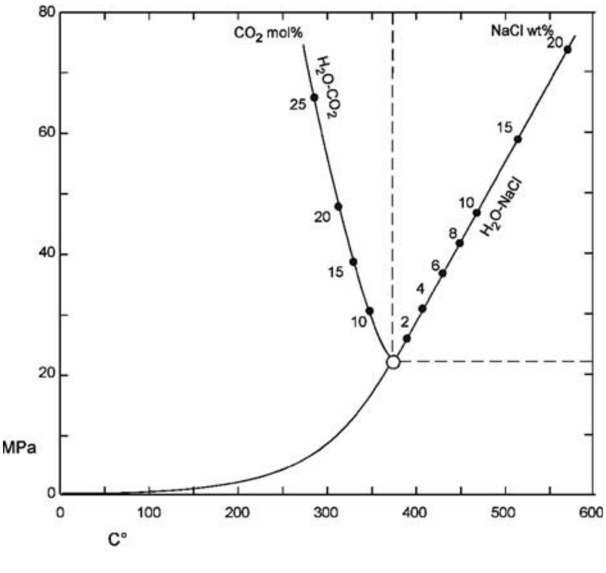


Figure 4: The effects of dissolved NaCl and CO_2 on the critical point of water

Figure 4 shows how the boiling point of pure water is elevated by increasing pressure until the critical point (CP) is reached at a temperature of 374.15^o C and a pressure of 22.21 MPa. Ascending the boiling point curve towards the CP, the density of water decreases whereas the density of steam increases until at the CP their densities are equal and only a single phase, supercritical fluid, exists. As shown in the Figure, the effect of dissolved salt is to elevate the pressure and temperature of the CP, whereas the effect of a dissolved gas, such as CO_2 is to lower its temperature (Bischoff and Rosenbauer, 1984).

Supercritical phenomena are very important in nature, but the physics and chemistry of supercritical geothermal fluids in the Earth's crust are poorly known, and there have not yet been any attempts to put natural supercritical fluids to practical use. Superheated steam produced from a fluid initially in the supercritical state will have a higher enthalpy than steam produced from an initially two-phase system. However large changes in physical properties of fluids occur near the critical point. Orders of magnitude increases in the ratio of buoyancy forces to viscous forces occur that can lead to very high rates of mass and energy transport (Norton and Dutrow, 2001). 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 (Fournier, 1999). Hitherto, study of such supercritical phenomena has been restricted to either small-scale laboratory experiments or to investigations of "fossil" supercritical systems exposed in mines and outcrops. Furthermore mathematical modeling of the physics and chemistry of supercritical fluids is hampered by a lack of a reliable thermodynamic database over the range of temperatures and pressures of the supercritical state, particularly for saline fluid compositions.

Thus a major aim of the science program of the IDDP is to investigate an active subcritical to supercritical transition and determine pressures, temperatures, and fluid compositions and gain insight into the physics and chemistry of the supercritical state in nature. Samples from the IDDP well will give us a first-hand look at these active processes and allow us to study the fracture history and permeability. Because the thermodynamics of supercritical solutes is poorly known (Fournier, 1999), at the transition from sub- to supercritical conditions at the magma-hydrothermal interface, the paired samples of fluids and minerals from the IDDP borehole will be extremely valuable for testing and improving our numerical models of fluid-rock reactions that control the compositions of both fluids and minerals under supercritical conditions.

The depths at which supercritical conditions are reached depend on temperature and pressure gradients that may be controlled by cold or hot water hydrostatic conditions or, deeper in the system, by lithostatic load, depending on the permeability. 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/depth curve, and the critical point for pure water would be reached at about 3.5 km depth. For saline systems the critical point occurs at higher pressures and temperatures, and therefore at greater depth. At the site of the proposed for the IDDP, in the Reykjanes geothermal system, the fluid concerned is modified seawater, so the critical temperature will be elevated to about 410°C (Bischoff and Rosenbauer, 1984). Based on data from existing wells on the Reykjanes Peninsula, we anticipate temperatures in the range of >320°C at 2.5 km and above 400°C at 4.0 km, so that reaching supercritical temperatures in modified seawater will require drilling deeper.

2.2 Permeability Effects.

As pointed out by Fournier (1999), athough the hydrostatic boiling point-depth curve controls the maximum P-T in many high-temperature geothermal systems, exceptions are common, depending on the permeabilty and how the hydrothermal system couples with its magmatic heat source (Figure 5). The line A-B in the figure represents an adiabatic gradient in an ascending plume of subcritical hot water that intersects the boiling point/depth curve and boils as pressure declines. The fundamental control over pressure in the Reykjanes hydrothermal system could be the hydrostatic gradient in the cold seawater that surrounds the peninsula. The higher the gradient of fluid pressure, the shallower the depth at which supercritical temperatures and pressures will be encountered. On the other hand, water-rock reaction and self-sealing might permit strong horizontal gradients of pressure in the system, and lower fluid pressures cause the critical point to be deeper.

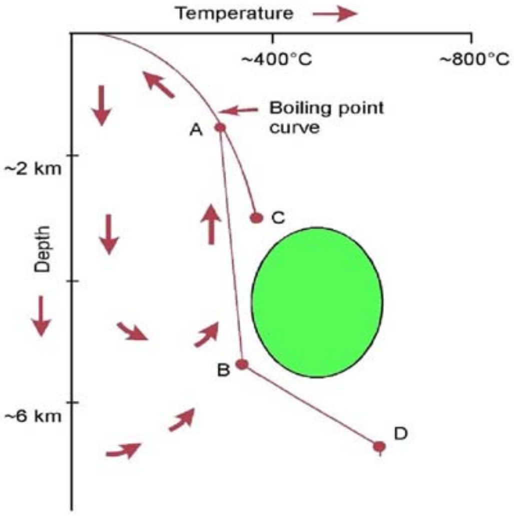


Figure 5: Conceptual model of temperature-depth relations in a convecting hydrothermal cell. Adiabatic gradient A-B; critical point C; and conductive gradient B-D, below the brittle-ductile transition. The ellipse represents the target region for the IDDP.

2.3 Supercritical Conditions in Iceland

Supercritical conditions have been encountered while drilling in a small number of geothermal fields worldwide, as far apart as Larderello, Italy, and Kakkonda, Japan but they have presented problems for commercial exploitation. These problems include low permeability, hole instability due to thermal creep, and the presence of acid volcanic gases.

The IDDP feasibility study concluded that three existing geothermal fields, Krafla, Nesjavellir, and Reykjanes, were prime candidates in Iceland for the IDDP to drill for supercritical conditions (Figure 1). All three of these sites have high temperatures and permeabilities and frequent seismicity. At each site the maxima in hypocentral depths is located at 5–6 km, suggesting that permeability persists at least to those depths, and that the brittle ductile transition occurs at 6-7 km (Figure 6).

After a careful evaluation of the Feasibility Study, the industrial consortium decided in November 2003 to proceed to plan the drilling of the first deep exploratory well. Early in 2004 a member of the consortium began drilling six 2.5 km deep wells in an existing geothermal field on the Reykjanes Peninsula, and offered to make one of them available for IDDP to deepen (Figure 3B). Drilling and casing this 2.5 km deep borehole will cost the company approximately 3 million USD. The science team strongly endorsed this site on the Reykjanes peninsula, the landward extension of the Mid-Atlantic Ridge, as being an unparalleled opportunity for scientific research.

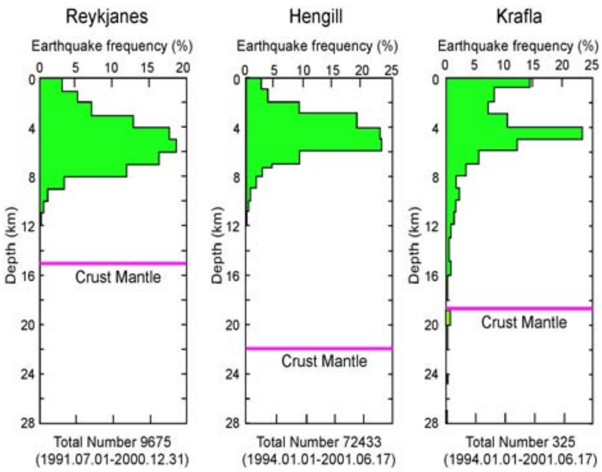


Figure 6: Earthquake frequency with depth beneath three developed geothermal fields in Iceland, at Reykjanes, Nesjavellir (within Hengill volcano) and Krafla. For locations see Figure 1 (Fridleifsson, et al., 2003)..

The data from the permanent network of seismometers covering the Reykjanes region, and the seismic studies that will be done as part of the IDDP, will allow us to relate seismicity to the fracturing and hydrothermal processes observed in the borehole. In the same way that deep drilling will allow us to investigate possible transitions to supercritical conditions, by drilling into the seismogenic zone beneath Reykjanes, we can investigate the relationships between temperatures, fluid pressures, fracturing and seismicity, and possibly creep due to transitions to ductile behavior.

2.2 The Mid-ocean Ridge Hydrothermal Environment.

An important goal of the science program of IDDP is gaining information on how deep hydrothermal cells penetrate in a mid-ocean ridge environment. Conventional wisdom suggests that the base of a hydrothermal cell is controlled by decrease of permeability due to transitions from brittle to ductile behavior with increasing temperatures (Fournier, 1999). Thus the line B-D in Figure 5 is drawn as a conductive thermal gradient in a ductile zone near a magmatic heat source. However we do not know the depth of the permeability change shown at point B. Many black smokers on ocean spreading centers, and hydrothermal systems on land seem to have an upper temperature limit of $<400^{o}$C and this might imply that permeability effectively ceases at that temperature. On the other hand, this limit might be controlled by transitions from supercritical to subcritical behavior, as seismic evidence indicates that fracturing persists to greater depth and to temperatures exceeding 400^{o}C. Figure 6 shows that for almost 10,000 earthquakes in a nine-year period at Reykjanes the greatest frequency in depth of hypocenters occurred at slightly more than 5 km and that frequent seismicity persisted to 8 km. In the laboratory the brittle-ductile transition in basalt occurs at about 600^{o}C so this is the likely temperature at 8 km. However, the temperature of this transition is strain rate dependent. The active rifting at Reykjanes should result a high strain rate, permitting short-lived episodes of fracture failure at even higher temperatures. Thus the temperature at 8 km could be $>600\ ^{o}$C.

3. BENEFITS TO INTERNATIONAL SCIENCE.

A prime scientific objective is to investigate the circulation of fluids, at or near supercritical conditions (around 410^{o} C) and their physical and chemical variations, within oceanic-type crust at an active spreading center. This will greatly enhance our understanding of the fundamental way in which the Earth loses heat through volcanism and hydrothermal circulation at the mid-ocean ridges. The implications of this process range from plate tectonics, to the controls on oceanic chemistry and even the origin of life (Kelly et al., 2002). The international science community has made investigation of hydrothermal systems at mid-ocean ridges a high priority as demonstrated through funding of programs like RIDGE and InterRidge, and extensive scientific drilling conducted by the Ocean Drilling Program (ODP). One of the least understood, least accessible, but most crucial, aspects of lithosphere-hydrosphere interaction is the transition from subcritical to supercritical conditions in the hydrothermal environments near mid-ocean ridge magma chambers.

This high-priority research target has hitherto been beyond the technical capabilities of the ODP, but can be best addressed by scientific drilling on land in the Reykjanes magma-hydrothermal system. Indeed the Reykjanes Peninsula should be regarded as a *Mission Specific Platform* for the new Integrated Ocean Drilling Program (IODP) to study ocean ridge hydrothermal systems. The proposed deep drilling represents a unique opportunity for the international research communities to make a giant leap forward in understanding one of the most fundamental energy and mass transfer process between the interior of the earth and the oceans.

3.1 The Need for Drill Cores

A major aim of the science program of the IDDP is to investigate the transition from subcritical to supercritical conditions in an active hydrothermal system and determine pressures, temperatures, and fluid compositions to and insight into the physics and chemistry of the supercritical state in nature. We do not know how oceanic and hydrothermal and magmatic systems couple together. Studies of exposed “fossil” ocean-ridge systems indicate that supercritical seawater-derived fluids remarkably have pervaded every cubic centimeter of their basaltic host rocks. We do not know if this occurs by diffusion from spaced-out fractures, or by microfracturing and fluid advection on a sub-millimeter scale. To investigate the systematics of magma-hydrothermal processes near critical conditions a major requirement is to obtain as much core as possible. Study of the coupling of the chemical and mineral alteration, fracture propagation, pressure solution, and fluid flow will be based on analysis of data on mineral chemistry, isotopes, geothermometry, and fracture geometry. More than half the science projects proposed to the IDDP would be impossible or severely compromised without drill core. Approximately 60 science projects that have been proposed to participate, in the IDDP by scientists from USA, Canada, Iceland, Germany, France, Italy, Russia, New Zealand and Japan

Today, the usual practice in Iceland is to use downhole motors, for their high penetration rate while rotary drilling, and this produces very fine-grained drill cuttings. Unraveling the nature and chronology of fracture failure and vein in-filling and detection of time serial fracture events and determination of constituitive rock properties requires core. Measurements of mechanical and thermal properties of core as a function of temperature are necessary to quantify processes related to brittle-ductile behavior. The permeability and thermal diffusivity of fractured and intact, fresh and altered, basalt comprise essential baseline information for fluid circulation models.

As the scientific studies require that as much drill core as possible, especially from the deeper part of the borehole in the supercritical zone, we plan to use the DOSECC Hybrid Coring System (DHCS) for coring that part of the well. The DHCS uses a small diameter mining type core barrel, with a hole diameter 3 7/8 inches. However coring is slower and therefore more expensive than conventional drilling. Given the uncertainties of the budget at the time of the preparation of this paper, drilling and coring plans are still under active discussion, so that the current drilling plan will doubtless be modified and improved as the project develops. The current drilling plan would yield fluid samples from flow tests at depths 2.7, 4.0 and 5.0 km depths; pressure, temperature and flow-meter logs over the whole drilled intervals; drill cuttings down to 4.0 km depth, including several spot cores from 2.7-4.0 km depth, and continuous drill cores from 4.0 to 5.0 km depth. This plan is technically challenging and therefore expensive. Few boreholes in the world have ever been drilled at temperatures of greater than 400^{o}C.

In distributing subsets of cores, cuttings, fluid samples and borehole data to interested scientists we envisage following a protocol similar to that used by the Ocean Drilling Program. For a limited time such distribution would be limited to the IDDP science team. The moratorium on distribution would then be lifted and the materials will be made available to scientists worldwide. We expect that the cores and other samples and data will be archived in the sample repository of the Natural History Museum of Iceland but we will seek the advice and approval of the funding agencies on this issue.

4. CONCLUSIONS

The aim of the Iceland Deep Drilling Project is to increase the availability and improve the economics of an environmentally benign form of alternative energy, an issue of great importance to society. If successful it will make a positive impact on the geothermal industry worldwide, wherever high-temperature geothermal resources exist. For the geothermal research community the IDDP has the potential to improve the economics and availability of alternative energy wherever high-temperature geothermal resources occur, for example in Italy, Greece, Turkey, Japan, Indonesia, the Philippines, Kamchatchka, New Zealand, in western North America, and in Central America. For example, within the European Union, supercritical sources may exist within Italy, Turkey, Greece, Spain (Canary Islands), Portugal (The Azores), and French Guadeloupe. The EU has emphasized the need for increased use of renewable energy, and has proposed a target of 15% of energy used should be renewable energy by 2010. If this proposed target is to be achieved, very innovative research and development will be needed to fully develop all available sustainable energy resources in Europe. We propose that the EU should develop a focused program development of “Unconventional Geothermal Resources”, including geothermal reservoirs at supercritical conditions.

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