The Iceland deep drilling project: Its global significance

Wilfred A. Elders [1], Gudmundur O. Fridleifsson [2], and Seiji Saito [3]
[1]Institute of Geophysics & Planetary Physics, University of California, Riverside, CA 92521-0423, U.S.A.
Email: Wilfred.Elders@ucr.edu
[2] Orkustofnun, Geoscience Division, Grensasvegur 9, IS-108, Reykjavik, Iceland.
[3] Dept. of Geoscience & Technology, Graduate School of Engineering, Tohoku University, Aramaki-Aza-Aoba 01, Sendai, 980-8579, Japan.

Abstract

The Iceland Deep Drilling Project (IDDP) is a long-term program to improve the economics of geothermal energy by producing **supercritical** hydrous fluids from drillable depths. Supercritical fluids have higher enthalpy than steam produced from two-phase systems. Large changes in physical properties near the critical point can lead to extremely high flow rates. Studying supercritical fluids will require drilling wells and sampling fluids and rocks to depths of 3.5 to 5 km and at temperatures of 450-600°C. Although drilling such deep wells is expensive, the power outputs from supercritical wells should be considerably enhanced. Iceland is a very favorable environment for this study. It is the largest landmass straddling a mid-ocean ridge, where active rifting provides the permeability and volcanism provides the heat sources for a major geothermal industry. Very high heat flows within these rifts indicate that supercritical temperatures exist at drillable depths. Seismic activity continues to below 5 km in these high temperature geothermal fields, indicating that even at supercritical temperatures, the rocks are brittle and therefore permeable. Similarly because of the high rain and snowfall, most of Iceland's geothermal systems produce very dilute fluids. If the IDDP is an economic success this same approach could be applied in other high-temperature volcanic geothermal systems elsewhere, an important step in enhancing the geothermal industry worldwide. Given Iceland's unique position as the largest landmass astride the Mid-Atlantic Ridge, the wide-ranging scientific and engineering program that is an integral part of the IDDP will be of global significance. As well investigating supercritical phenomena, drilling in this environment can address a wide range of world-class scientific questions, such as the formation of ophiolites, hydrothermal ores, and black smokers on mid-ocean ridges.

Keywords: *Supercritical fluids, geothermal energy, scientific drilling, Mid-Atlantic Ridge.*

1 Introduction

This paper, one of five at this conference dealing with the IDDP, concerns the significance of the project from an international perspective. Over the next several years the IDDP plans to drill a series of boreholes to penetrate into supercritical fluids believed to be present beneath three currently exploited geothermal systems in Iceland (Figure 1). This requires drilling to depths greater than 4 to 5 km, and sampling hydrothermal fluids at temperatures of 400 to 600°C. The IDDP is an outgrowth of "Deep Vision", a program being carried out in Iceland by a consortium of three leading Icelandic energy companies and Orkustofnun (a government agency and consulting company). There is a rising demand in Iceland for electricity for energy intensive industries such as aluminium smelting. Deep Vision aims to enhance geothermal economics by harnessing supercritical hydrothermal fluids.

Iceland is a particularly favorable location for research on supercritical fluids as repeated seismicity and volcanic activity in the rift environments create high permeability and high temperatures at drillable depths. These circumstances are the product of the special geological environment of Iceland, a coincidence of a mantle plume with the divergent plate boundary of the Mid-Atlantic Ridge (Figure 1).

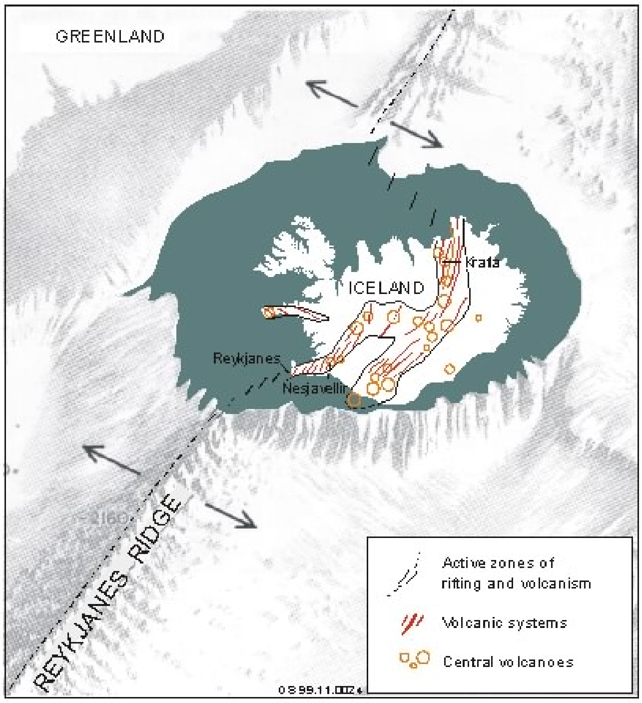

Figure 1: Iceland and its zones of active rifting and volcanism. The locations of three drill sites being considered for the IDDP (Reykjanes, Nesjavellir, and Krafla) are shown.

1.1 Progress to date

Deep Vision was established in the spring of 2000 and in June of that year at the World Geothermal Congress in Japan the idea was laid before the geothermal community with an invitation for international participation (Fridleifsson and Albertson, 2000). Phase I of the IDDP, a feasibility study, began in March 2001. This had three working groups whose assignments were: (1) *geosciences* – to define drilling targets and prioritize candidate sites for drilling, (2) *drilling technique* – to determine the optimum strategy for drilling supercritical wells with regards to safety and costs, and (3) *fluid handling and evaluation* – to evaluate the technical aspects of producing, sampling, and utilizing superheated fluid. At the time this paper was being written (February 2003), the Final Report of this Feasibility Study was being reviewed by Deep Vision (Albertsson, et al., 2003; Fridleifsson, et al., 2003: and Thórhallsson, et al., 2003; these reports are available at http://www.os.is/iddp/). The details of the findings of these reports are discussed in the accompanying papers at this conference about the IDDP. Assuming a favorable response by Deep Vision, detailed planning and funding for drilling and science will commence in 2003. Deep Vision has already had discussions with some potential international industrial partners. If suitable partnerships and funding are arranged in timely fashion, we anticipate that drilling could begin in 2004 or early 2005.

Deep Vision is also interested in integrating scientific investigations into the engineering aims of the IDDP to the mutual advantage of both. With financial support from the International Continental Scientific Drilling Program (ICDP), a Science

Applications Group of Advisors (SAGA) with both Icelandic and international membership, was formed in June 2001 to advise the three Principal Investigators about the science program (the authors of this report). SAGA held an international workshop in March 2002 to define the anticipated conditions in the drilling targets and recommend the best technical approaches for drilling, sampling, and measurement. A second international workshop, held in October 2002, reviewed approximately 40 separate proposals submitted by the international scientific community to provide a framework for a comprehensive science program.

2 Supercritical conditions

While the physics and chemistry of supercritical geothermal fluids in the Earth's crust are of great interest, 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 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. Similarly, because of major changes in the solubility of minerals above and below the critical state, supercritical phenomena can play a major role in high temperature water/rock reaction and the transport of dissolved metals. Hitherto, study of the supercritical phenomena has been restricted to either small-scale laboratory experiments or to investigations of "fossil" supercritical systems exposed in mines and outcrops. The IDDP will drill deep enough into already known geothermal reservoirs in Iceland to reach supercritical conditions believed to exist at depth.

At temperatures and pressures above the critical point, which occurs for pure water at 221.2 bars and 374.15°C (but higher in waters with dissolved components), only a single phase, supercritical fluid exists. Figure 2 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 Deep Vision 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 the diagram correspond to pressures in geothermal reservoirs – respectively controlled by cold water-hydrostatic conditions and by lithostatic load. Cold water is much denser than superheated steam. Thus if the pressure is controlled by cold water, such as on the ocean floor, the critical pressure in a dilute water column would be reached at about 2.3 km depth. That is the reason why 400-600°C hot hydrous fluids can be expelled directly into the oceans in the black smokers on mid-ocean rifts 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 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 2). 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 high-temperature hydrothermal systems. 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, hole 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.

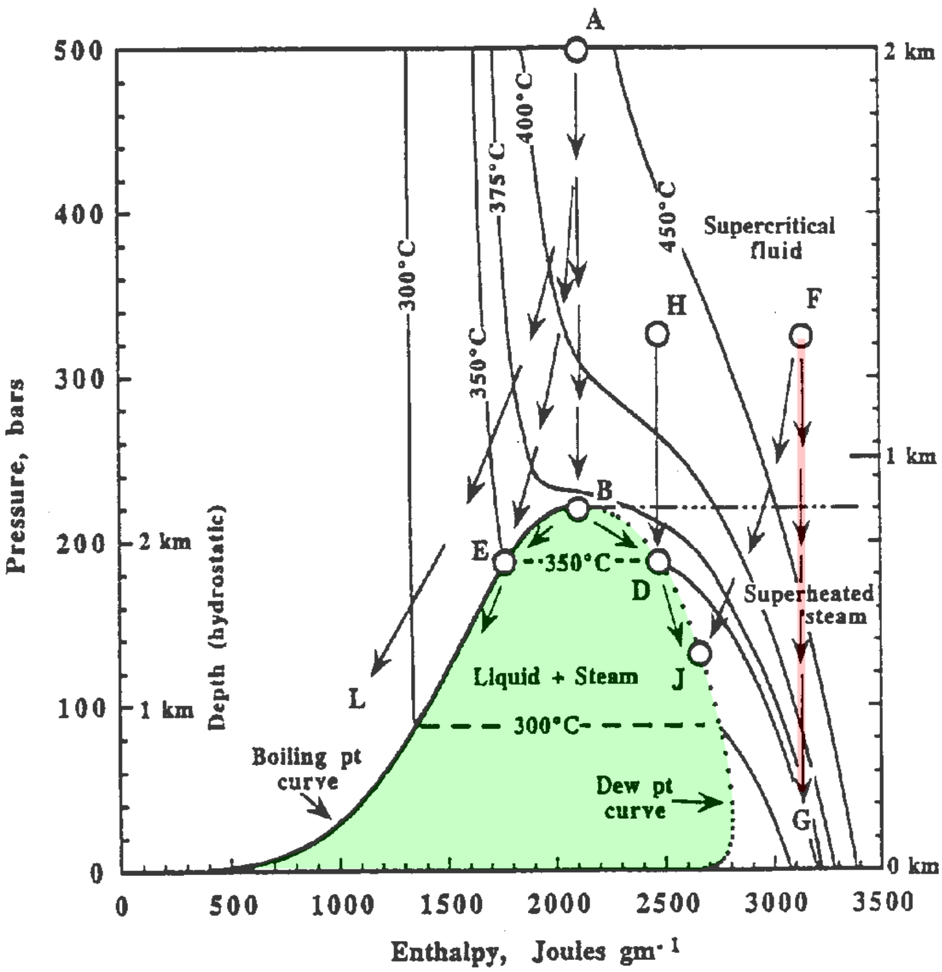

Figure 2: Pressure enthalpy diagram for pure H_2O with selected isotherms. The conditions under which steam and water coexist is shown by the shaded area, bounded by the boiling point curve to the left and the dew point curve to the right. The arrows show various different possible cooling paths (Fournier, 1999).

2.1 The special circumstances in Iceland

Iceland is the largest landmass straddling a mid-ocean ridge, a tectonic setting that results in the active rifting and volcanism that provides the heat source for the well-established Icelandic geothermal industry. In Iceland there is extensive experience and knowledge of how to harness high yield, high temperature geothermal fields in active tensional regimes. Very high heat flows within this active tensional regime indicate that supercritical temperatures should exist at drillable depths in several places in Iceland. Temperatures greater than 300°C are commonly encountered in wells drilled to depths of only 2 km in the three candidate high-temperature geothermal fields. The existence of permeable regions in brittle basaltic rock at supercritical temperatures at greater depths in these geothermal fields can be inferred from the distribution of hypocentral depths of seismic activity that continues to below 5 km depth.

Each of the three sites selected for consideration by the IDDP 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 probably is an active sheeted dike swarm. Recently a 2500 m deep well drilled in the Reykjanes field penetrated permeable formations, with fluid convection and temperatures well above 300°C. Fluids produced by 2 km deep geothermal wells in this system are evolved seawater. At Nesjavellir, the Hengill central volcano is the high temperature heat source for a geothermal reservoir in a graben that has temperatures of up to 400°C at 2.2 km, and is recharged by meteoric water. The Krafla high-temperature geothermal field is developed above a magma chamber in a mature, active, volcanic caldera. It produces evolved meteoric water with some addition of volcanic gases. Each of these sites is an attractive alternative to reach supercritical conditions. The Geosciences Working Group suggested that the order of priority for the first drill site of the IDDP is 1) Nesjavellir, 2) Krafla and 3) Reykjanes (Fridleifsson et al., 2003).

2.2 Broader scientific benefits of the IDDP

In addition to its economic goals, the IDDP will permit scientific study of a broad range of important issues, including investigation of the development of a large igneous province, the magmatic and fluid circulation character of the Mid-Atlantic Ridge (on land), and investigations and sampling of fluids at supercritical conditions, aspects of high-temperature hydrothermal systems that have rarely been available for direct observation. In addition, the IDDP will require use of techniques for high-temperature drilling, well completion, logging, and sampling, techniques that will have potential for widespread applications in drilling into both oceanic and continental high-temperature hydrothermal systems. This prospect opens up the opportunity for a very comprehensive scientific program investigating the anatomy of a mid-ocean rift zone, by tying together land–based and ocean-based deep borehole studies with complementary geological and geophysical and seismic imaging studies, putting the drilling activities into a broad regional geologic context.

2.3 Economic benefits of the IDDP

In 2000 Iceland ranked eighth in the world in terms of electrical capacity from geothermal resources and in the decade 1990-2000 the installed electrical generating capacity from geothermal resources in Iceland increased by a factor of four (Bulletin Geothermal Resource Council, 2003). Thus Iceland, with only 280,000 inhabitants, is the world leader in terms of renewable energy use per capita. This is even more evident when direct use of geothermal resources is also considered. 87 % of the population nationally, and 99.8% of the inhabitants of the capital city Reykjavik, live in dwellings connected to a district heating system. Thus geothermal energy plays a very important role in the quality of life in Iceland. The total energy use for electricity in Iceland is 8000 GWh/a and of this more than 5000 GWh/a is used in energy intensive industries such as aluminium smelting. Given the lack of hydrocarbon resources in Iceland the alternatives to meet this growing demand are more hydroelectricity or further development of the large geothermal resource base present in Iceland.

An important component of the cost of electricity from geothermal resources in Iceland is the expense of drilling the necessary high-temperature production wells that typically cost about US$ 2.5 million each. There are three obvious approaches to improving the economics of the geothermal industry: (1) To reduce the cost of drilling and completing geothermal production wells, (2) To cascade the usage of thermal energy by using the effluent water for domestic heating and as a heat source for industrial processes, and (3) To reduce the number of wells needed by increasing the power output of each well, by producing supercritical fluids. However, drilling deep enough to produce supercritical fluids is expensive. Thórhallsson, et al., (2003) estimate that a well with 9 5/8” casing to 3,500 m, and a slotted liner to total depth of 5,000 m, and with 1500 m of core, would cost US$ 14 to15 million. On the other hand, preliminary modeling studies, by Albertsson, et al., (2003) indicate that, under favorable conditions, a 5000 m deep well producing from a supercritical geothermal reservoir at temperatures significantly greater than 450^{o}C could yield sufficient high-enthalpy steam to generate 40-50 MWe, an order of magnitude greater electrical power production than from a well 2 km deep producing from a 300^{o}C reservoir. Thus the IDDP aims to make large increases in power output per well, an approach that, if successful, could be used in high-temperature geothermal systems in volcanic terrains worldwide.

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