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The Iceland Deep Drilling Project

A New Era in Geothermal Development?

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Abstract

The Iceland Deep Drilling Project (IDDP) announced in September 2007 that an international industrial consortium had just signed a new contract to collaborate in 5 km deep exploratory drilling in Iceland. The consortium collaborating to fund this investigation of supercritical geothermal energy consists of three leading Icelandic power companies, Hitaveita Sudurnesja Ltd., Landsvirkjun, Orkuveita Reykjavikur, together with Orkustofnun (the National Energy Authority) and Alcoa Inc. (an international aluminum company). The three power companies financed a pre-feasibility study for the project that was completed in 2003 (Fridleifsson, 2003). Each of the three power companies is committed to drill, at their own cost, a 3.5-4.0 km deep well in a geothermal field that they operate (at Krafla, Hengill and Reykjanes), see Fig. 1 & 2. The design of these wells will permit them to be deepened to 4.5-5.0 km by the IDDP, funded by the consortium with additional funds from international scientific agencies (NFS and ICDP). The first deep IDDP well will be drilled in the latter part of 2008 in the Krafla geothermal field near the northern end of the central rift zone of Iceland, within a caldera that was volcanically active 1975-1984. Two new wells, ca. 4 km deep, will then be drilled at the Hengill and the Reykjanes geothermal fields during 2009-2010, and subsequently deepened. 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, where the Mid-Atlantic Ridge comes on land in southern Iceland. Processes at depth at Reykjanes should be similar to those responsible for black smokers on ocean spreading centers.

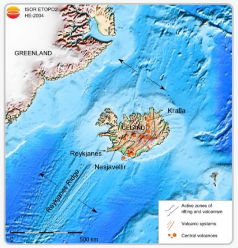


Figure 1: The location of Iceland on the Mid-Atlantic Ridge at the center of a large igneous province. The red dots show locations of Holocene volcanoes. Deep drilling is proposed at each of the geothermal fields at Reykjanes, Nesjavellir (Hengill) and Krafla.

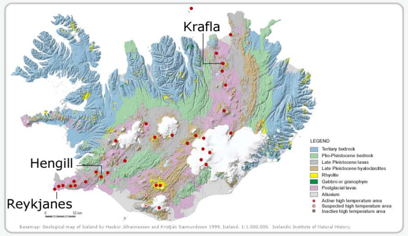


Figure 2: A geological map of Iceland showing the location of the three high-temperature hydrothermal systems being considered for deep boreholes by the IDDP.

Scientific Interest

The IDDP has engendered considerable international scientific interest. The US National Science Foundation (NSF) and the International Continental Scientific Drilling Program (ICDP) will jointly fund the coring and sampling for studying the data and samples that will be recovered by deep drilling research is underway on samples from existing wells in the target geothermal fields, and on exposed "fossil" geothermal systems and active mid-ocean ridge systems that have conditions believed to be similar to those that will be encountered in deep drilling by the IDDP.

The Main Objective of the IDDP

Is to investigate whether it is economically feasible to produce energy from geothermal systems at supercritical conditions. This will require drilling to depths of 4 to 5 km in order to reach temperatures of 400-600°C. Today, geothermal wells in Iceland typically range up to 2.5 km in depth and produce steam at about 300°C, or less, at a rate sufficient to generate about 3-10 MWe (of electricity). It is estimated that producing steam from a well penetrating a reservoir with temperatures >450°C, and at a rate of 0.67 m^3/s, could generate 40-50 MWe (Fridleifsson and Elders, 2005). If IDDP's test of this concept proves successful, it could lead to major improvements in the development of high-temperature geothermal resources worldwide.

The Krafla Drill Site

The Krafla high-temperature geothermal system is located within the Krafla volcanic caldera where a 60 MWe power plant is currently operating (Fig. 3 & 4).
The geology is dominated by an active central volcano and an active cross cutting fissure swarm. The volcanic activity is episodic, occurring at 250-1000 year intervals, and each episode apparently lasts for 10-20 years, the most recent eruptive episode lasted from 1976 until 1984 (Björnsson, 1985).
The features of greatest importance with respect to drilling the ICDP deep well are:

1. The presence, location and size of the magma chamber believed to exist beneath the caldera on the basis of seismic and magnetotelluric studies (Fig. 6).
2. The pressure/temperature conditions at depth.
3. The existence and nature of permeability at depth (Fig. 5).

The magma chamber believed to be the heat source for the system was initially inferred from S-wave attenuation at 3-7 km depth during the 1975-84 eruptions (Einarsson, 1978). Figure 5 is a NW-SE cross section showing the temperature distribution at Krafla within the two main production bore fields at Krafla. The P-T gradients in wells typically follow the boiling point to depth curve. For example, in the well KG-26 in the Leirbotnar field near the west end of the cross section, the temperature at 2500 m depth is about 355°C (Fridleifsson, et al., 2006). This suggests that in the main production zone the critical point for pure water would be reached at ~3.5 km depth. As the produced geothermal fluids at Krafla contain only about 1000-2000 mg/kg of total dissolved solids, if conditions are similar in the IDDP well, it is possible that supercritical conditions could be reached soon after drilling below the 3.5 km deep casing, assuming hydrostatic pressure condition with increasing depth. The proposed location of the drillhole is near the margin of the inferred magma chamber. The aim is not to intersect the magma chamber directly, where permeability could be low or absent, but rather to intersect the permeable heat exchange system at its margins.

Figure 3: A view to the Krafla Central Volcano. The 60 MWe geothermal power plant is seen in the foreground. One of the potential IDDP drillsites is shown by a red circle.

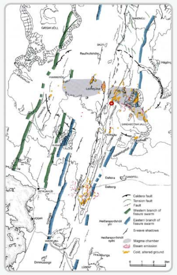


Figure 4: A simplified structural map (from Saemundsson 1991) showing the presently active fissure swarm, for the last ~3000 years, and also more than 8000 years ago (outlined in blue), and a fissure swarm further west, active during mid-Holocene ~5.000 years ago (outlined in green).
1- The caldera fracture (solid black dash),2- chief faults and fractures (lighter dashes), 3- center of Mývatn and Krafla fires (double marked dash), 4-outlines of the magma chamber (inclined hatch), 5-active fumaroles (red symbols), 6-hydrothermal surface manifestations (yellow symbols).

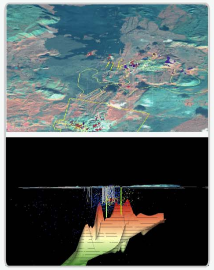
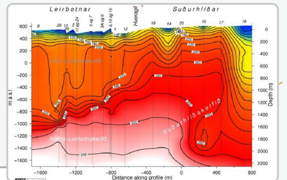
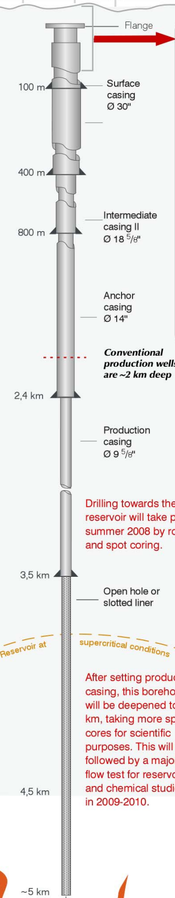


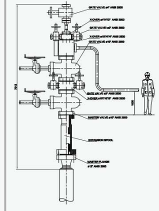
Figure 6 A: Oblique airphoto showing the recent lava flows and the outlines of the geothermal field.
Figure 6B: Model of the low resistivity body underlying Krafla and locations of hypocenters and existing geothermal wells. The two green lines show proposed locations considered for the IDDP well.

Figure 5: NW-SE cross section showing the temperature distribution at Krafla within the two main production drill fields Leirbotnar and Sudurhlidar. The proposed IDDP drillhole is located south of well 26 in the Leirbotnar field on the west side in the diagram. Temperature at 2400 m depth in the IDDP well is expected to be ~350°C.



Well Head





Flowing well:
T= 480°C and P= 195 bar
Closed well:
T= 400°C and P= 220 bar
(T= 20°C and P= 267 bar)

Drilling towards the supercritical reservoir will take place in summer 2008 by rotary drilling and spot coring.

After setting production casing, this borehole will be deepened to 4.5 km, taking more spot cores for scientific purposes. This will be followed by a major flow test for reservoir and chemical studies in 2009-2010.

Science Program

The objective of the consortium funding the IDDP is economic. In Iceland a typical geothermal well, 2 to 3 km deep, produces steam at a rate sufficient to generate 3 -10 MWe of electricity. A feasibility study funded by the IDDP indicates that, with the same volumetric flow rate, a well producing superheated steam derived from supercritical fluid would have an order of magnitude higher power output relative to one producing subcritical fluid (Fridleifsson, 2003). However from the outset the consortium, recognizing that a broad range of scientific studies would be necessary to better understand the poorly know supercritical environment, welcomed the inclusion of basic scientific studies in the IDDP and invited participation from the international scientific community (Fridleifsson and Albertsson, 2000). The guiding principle was that the incremental costs of drilling and sampling for the science program, and subsequent scientific studies, should as far as possible be funded by the scientific community. Consequently we sought significant funding from the ICDP and the US National Science Foundation (NSF) and these efforts have been successful.
The main questions to be addressed include:

A. Do natural supercritical fluids exist at economically drillable depths and do they have economic potential?
B. What are the physical-chemical properties of natural supercritical fluids?
C. How do supercritical fluids couple hydrothermal systems with magmatic heat sources?
D. How do supercritical fluids affect chemical and mineral alteration, fracture propagation, permeability, and fluid flow at the magma-hydrothermal interface?

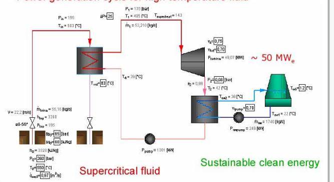
In preparation for these investigations, studies of rock and fluid samples from existing wells at Reykjanes and Krafla, are already underway and are reported in accompanying posters at this meeting.
In the coming decade the IDDP will drill a series of deep holes in Icelandic geothermal fields, including a return to the seawater system at Reykjanes. In addition to exploring for new abundant sources of high-grade energy, this project will provide the first opportunity worldwide to investigate the coupling of hydrothermal and magmatic processes in volcanic systems on a mid-ocean ridge. This will enable a broad array of scientific studies involving water-rock reactions at high temperatures. Active processes in such deep hydrothermal reaction zones that control fluid compositions on mid-ocean ridges have never before been available for such comprehensive direct sampling and study. Such environments play an extremely important role in heat transfer, hydrothermal alteration and ore genesis. 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 (IODP). At the same time, investigation of such high enthalpy geothermal resources could usher in a new era in geothermal development worldwide.

Electric Power Generation

This comparison is based on the same volumetric flow rate of inflowing steam. Energy output may increase by an order of magnitude by using supercritical fluid.

	Conventional dry-stream well	IDDP well
Downhole temperature	235°C	430 - 550°C
Downhole pressure	30 bar	230 - 260 bar
Volumetric rate of inflow	0.67 m^3/s	0.67 m^3/s
Electric power output	~ 5 MW_e	~ 50 MW_e

Power generation cycle for high-temperature fluid



The IDDP feasibility study assumed a heat exchange system would be needed for electric power generation.

Acknowledgments

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Background of the IDDP 2000 - 2007

The major energy companies of Iceland formed a consortium to improve the economics and availability of geothermal resources by investigating the deeper levels of hydrothermal systems. Drilling the necessary deep wells presents both technical challenges and opportunities for important scientific studies. The IDDP therefore welcomed participation by the international scientific community.

Participants from 12 different countries attended two IDDP workshops funded by the International Continental Scientific Drilling Program (ICDP); the first of these discussed the optimal scientific drilling strategy, and the second discussed the science program based on more than 50 scientific proposals from different investigators.

As a first step towards achieving its goals, rather than drilling a new wide-diameter well from the surface to the total depth, the IDDP proposed to deepen an industry geothermal well being drilled by Hitaveita Sudurnesja, situated in a geothermal field on the Reykjanes Peninsula. This well would be ideally situated for scientific studies as the Mid-Atlantic Ridge emerges from the ocean at the southwest tip of Iceland (Figure 1). Thus the Reykjanes well would permit scientific investigations both of potentially economic high-temperature hydrothermal phenomena and of mid-ocean ridge processes similar to those that feed black smokers.

The well was drilled to a depth of 3.1 km. The rocks penetrated consisted of Holocene tholeiites, hyaloclastites, marine sediments, pillow basalts, and relatively coarse-grained diabase dikes. At that time it was planned that the IDDP would rotary drill and spot core this well to 4.0 km depth in 2006, and then, in 2007, to deepen the borehole from 4.0 km to 5.0 km, using continuous wireline coring.

The 3.1 km deep well became blocked during a flow test.

Subsequent attempts to recondition the well failed, and the well had to be abandoned.

After considering all the options available, it was decided that operations would move to Krafla in NE Iceland, one of the central volcanoes shown in Figure 2. Landsvirkjun, the operator of the Krafla geothermal field, agreed to drill a 3.5 km deep well and make it available to the IDDP for deepening into the supercritical zone. The hydrothermal system of Krafla is in a volcanic caldera with higher temperature gradients and more recent volcanic activity than at Reykjanes.

Increased interest in the IDDP on the part of industry. Alcoa, Inc., an international aluminum company, joined the consortium as an equal financial partner. Orkuveita Reykjavikur and Hitaveita Sudurnesja each made a commitment to drill a 3.5 km deep well in their geothermal fields at Hengill and Reykjanes, respectively, and make then available for deepening, as contributions to the IDDP.

A workshop reviewed the current situation, reconsidered the plans in view of new circumstances. However because deep drilling plans are furthest along at Krafla, it was decided to focus on that field first.

The partners in the IDDP consortium signed a new contract to collaborate in deep drilling in Iceland.

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