DRILLING FOR DEEP GEOTHERMAL RESOURCES IN ICELAND

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Keywords: deep drilling, supercritical, Iceland

SUMMARY - The Iceland Deep Drilling Project (IDDP) will drill to depths of 4 to 5 km and temperatures of 400–600° C in each of three different high-temperature geothermal fields in Iceland. The aim is to investigate the feasibility of producing *supercritical* geothermal energy, and achieve large increases in the power output of these fields, without increasing their environmental footprints. The first deep well is in the Krafla geothermal field, within a volcanic caldera in NE Iceland. This well will be drilled to 800 m depth in September 2008 before the winter snows. In the spring of 2009 it will be drilled and cased to 3.5 km depth and deepened to 4.5 km by July. If a flow test is successful, a pilot power plant should follow in 2010. Two new ~4 km deep wells will be drilled in SW Iceland at the Hengill and the Reykjanes geothermal fields during 2009-2011, and subsequently deepened to supercritical conditions. If the economic feasibility of supercritical geothermal resources in Iceland is demonstrated, major improvements in the development of high-temperature geothermal resources could result worldwide. For example, the same approach could be used in the Taupo Volcanic Zone.

1. THE GEOLOGICAL SETTING OF THE GEOTHERMAL RESOURCES IN ICELAND

Iceland is the largest landmass straddling a divergent plate boundary, the slow-spreading Mid-Atlantic Ridge. The surface expression of this plate boundary on land manifests itself in narrow central rift zones, 20 to 50 km wide, with active rifting and frequent volcanic eruptions (Fig. 1). Seismicity in Iceland occurs throughout the neovolcanic zone but is mainly concentrated in the South Iceland Seismic Zone (SISZ) and the Tjörnes Fracture Zone (TFZ), that together connect the offset section of the spreading rift in Iceland to the Reykjanes (to the south) and Kolbeinsey Ridges (to the north) (Sigmundsson & Sæmundsson, 2008). There are numerous low- and high-temperature hydrothermal systems in Iceland and these are the basis of a geothermal industry that supplies space heating to 87% of its buildings and generates about a third of it electric power. The high-temperature systems (>180 ^{o}C) are restricted to the neovolcanic zones of Upper Pleistocene and Holocene age (< 0.8 Myr) rifting and volcanism, where more than twenty-four volcanoes have erupted in post-glacial times, with about 20-25 eruptions each century (Figure 1). These hydrothermal systems,

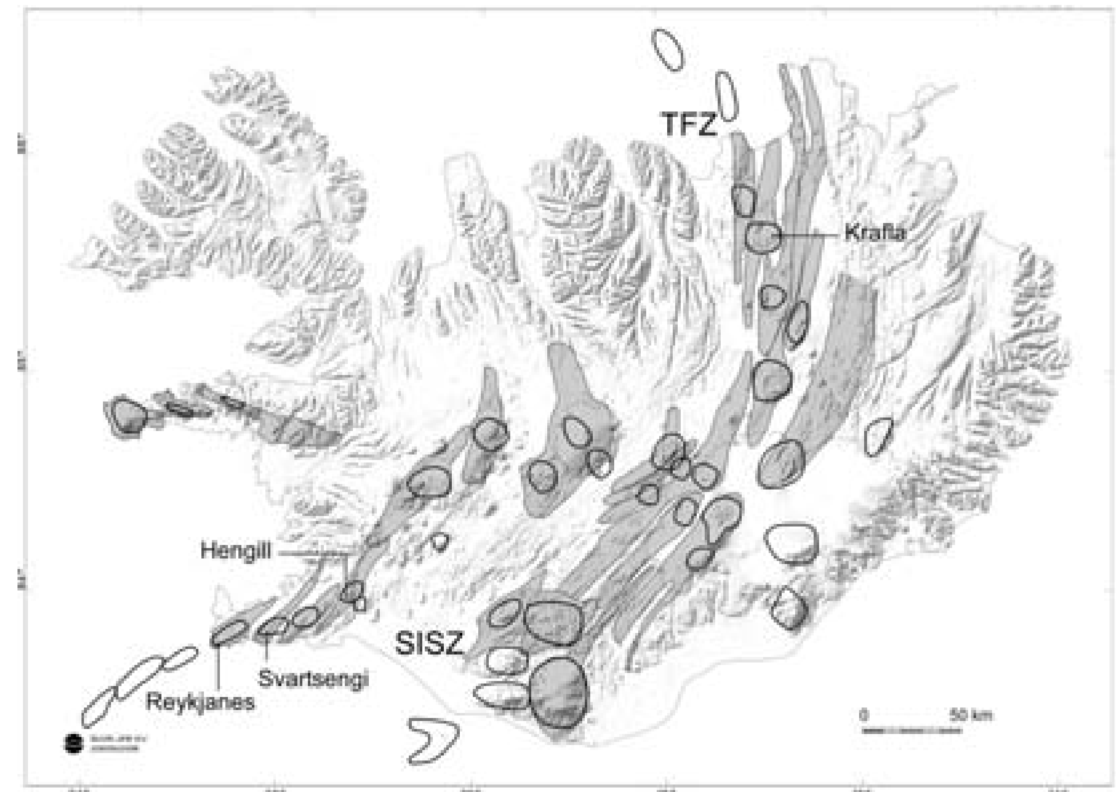

Figure 2: Shaded relief map of Iceland showing the neovolcanic systems of fissure swarms and central volcanoes and the locations of the hydrothermal systems of Reykjanes, Svartsengi, Hengill and Krafla, mentioned in the text. SISZ is the South Iceland Seismic Zone, and TFZ is the Tjörnes Fracture Zone. (Modified from Sigmundsson & Sæmundsson, 2008).

with the exception of Svartsengi and Reykjanes, differ from mid-ocean ridge hydrothermal systems in that they contain hydrothermally modified meteoric water rather than modified seawater.

The current installed geothermal electrical generating capacity in Iceland is 480 MWe, but it is expanding rapidly to supply planned new aluminium smelters and is expected to grow to 1500 MWe in the near future (Lund et al., 2008). This expansion will utilize high-temperature geothermal resources from conventional depths (<3km). However, looking to the future, an industrial consortium is funding exploration of deeper resources to make large increases in the output of existing geothermal fields without increasing their environmental footprint. The emphasis of this deep drilling program is on the supercritical regime (Friðleifsson & Elders, 2005).

2. SUPERCRITICAL GEOTHERMAL RESOURCES

At temperatures and pressures above the critical point of a liquid and its vapor, only a single phase supercritical fluid exists. The critical point of pure water occurs at 221 bars and 374 °C, (higher in waters with dissolved components). For example, the critical point for seawater is at ~ 300 bars and ~411 °C (Bischoff & Rosenbauer, 1984). Figure 2 shows the pressure-enthalpy diagram for pure water, showing selected isotherms (Fournier, 1999).

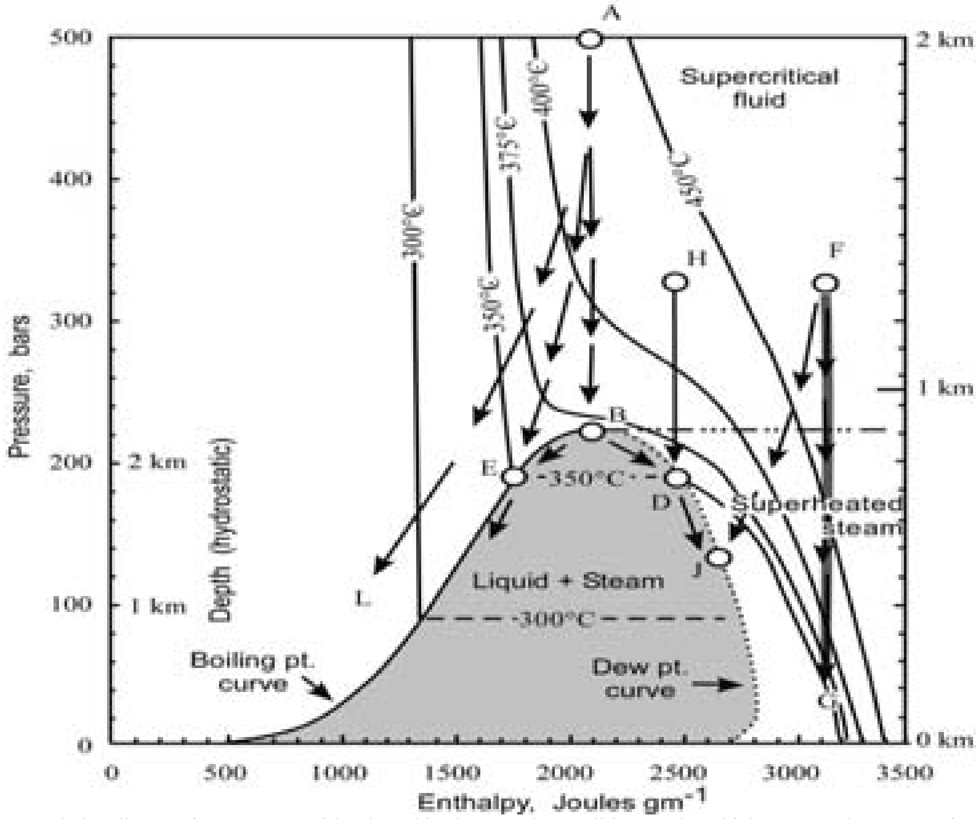

Figure 2: Pressure enthalpy diagram for pure H_2O with selected isotherms. The conditions under which steam and water coexist is shown by the shaded area, bounded by the boiling point curve to the left and the dew point curve to the right. The arrows show various different possible cooling paths; see text (from 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 that could occur in vapour-dominated geothermal reservoir. Steam turbines in geothermal plants generate electricity by condensing the steam separated from the two phase system that, depending upon the enthalpy and pressure at which steam separation occurs, is often only 20-30% of the total mass flow.

The depth scales marked at the left and right sides of Figure 5 correspond to pressures in hydrothermal systems, controlled respectively by cold hydrostatic conditions and by lithostatic load. If a hydrostatic hydrothermal system is boiling from the surface down, the maximum pressure and temperature at each depth is determined by the boiling point to depth curve (BPD-curve), and the critical point for dilute fluids 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 hydrothermal systems couple with their heat sources.

3. POTENTIAL APPLICATIONS

Not only does supercritical water have higher enthalpy than steam produced from boiling water, but another important factor is that large changes in physical properties of water occur near its critical point. Orders of magnitude increases in the mobility, i.e. ratio of fluid density to viscosity, allow 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 play a major role in high temperature water/rock reaction and the transport of dissolved metals (Norton & Dutrow, 2001).

The concept behind the Iceland Deep Drilling Program is to produce supercritical fluid to the surface in such a way that it transitions directly to superheated steam along a path like F-G in Fig. 2. Modeling carried out as part of a feasibility study by IDDP, completed in 2003, (available at http://www.iddp.is), indicates that, relative to the output from conventional geothermal wells 2.5 km deep, a large increase in power output per well is likely if fluid is produced from a reservoir hotter than 450°C (Albertsson et al., 2003). A typical geothermal well in Iceland, 2.5 km deep, yields fluids in the range of 200-320°C, an output sufficient to generate to 5-15 MWe of electric power, depending on P-T conditions and the flow rate. An IDDP well tapping a supercritical reservoir with temperatures of 430–550°C and pressures of 23–30 MPa may be expected to yield 40-50 MWe, at the same volumetric inflow rate. Thus an IDDP well could yield up to a tenfold improvement in power output relative to a typical conventional well. To produce supercritical fluids requires drilling deeper than 4 km to reach temperatures >450°C. The feasibility study identified three locations where supercritical fluids were likely to exist at drillable depths in the geothermal fields at Reykjanes, Hengill, and Krafla (Figure 1).

4. THE KRAFLA GEOTHERMAL FIELD

In the first effort to implement this program in 2005 it was planned to deepen a 3.2 km deep in the Reykjanes geothermal field (Friðleifsson & Elders, 2005). However technical considerations made this well an unsuitable candiate for deepening and so attention moved to the Krafla geothermal field, within a volcanic caldera in the active rift zone of NE Iceland, where temperatures >300 ^{o}C are encountered at ~2 km depth over a wide area. During 1975-1984, a rifting episode occurred at the Krafla volcano, involving 9 volcanic eruptions and some 15 subsidence and uplift events. The volcanic activity adversely affected parts of the Krafla geothermal field, as acid gases made steam from some of the existing wells unsuitable for power generation for several years. However, a large magma chamber at 3-7 km depth was detected by S-wave attenuation within the center of the caldera, believed to be the heat source of the active geothermal system. A recent MT-survey has confirmed the existence of low resistivity bodies at these shallow depths within the volcano. The selection of the first drill site for the IDDP well is based on detailed geological mapping accompanied by a wealth of geological, geophysical and geochemical data, and by extensive exploratory and production drilling since 1971 (Friðleifsson, 2003).

The lengthy process of funding and contracting for the deep well at Krafla is now completed and preparation of the first IDDP well commenced in June 2008. The IDDP well will be drilled and cased to 800m depth in September before the winter snows. Beginning in the spring of 2009 this well will be drilled and cased to 3.5 km depth and deepened to 4.5 km. Several spot cores for scientific studies will be collected between 2.4 km and the total depth, which should be reached in July 2009. After the well heats, it will be flow tested and, if successful, a pilot plant for power production should follow in 2010. Two new 4 km deep wells will be drilled at the

Hengill and the Reykjanes geothermal fields during 2009-2011, and subsequently deepened to supercritical temperatures and pressures. In contrast to the fresh water systems at Krafla and Hengill, the Reykjanes geothermal system produces hydrothermally modified seawater. Processes at depth on the Reykjanes Peninsula in southern Iceland, where the Mid-Atlantic Ridge comes on land, should be somewhat similar to those responsible for black smokers on oceanic rift systems.

5. CONCLUSIONS

The IDDP has engendered considerable international scientific interest, and fortunately, from the outset, the IDDP consortium was receptive to including scientific studies in the project, provided that any additional costs thus incurred were met by the scientific community. The authors have secured funding from the International Continental Scientific Drilling Program and from the US National Science Foundation to jointly fund coring and sampling for scientific studies in the first well at Krafla. Together they are coordinating an international team of investigators that will study these materials, and research is underway on samples from existing wells in the targeted geothermal fields.

We anticipate that the opportunities presented by the IDDP will lead to a major advance 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. 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. This is particularly true of the “Pacific Rim of Fire”, of which Taupo Volcanic Zone is an important part.

6. ACKNOWLEDGEMENTS

We thank the international industry-government consortium, consisting of three leading Icelandic power companies, Hitaveita Sudurnesja Ltd., Landsvirkjun Ltd, and Orkuveita Reykjavikur Ltd, together with Orkustofnun (the National Energy Authority), Alcoa Inc. (an international aluminium company) and StatoilHydro ASA (an international oil company based in Norway), for the opportunity to participate in the IDDP. Financial support from the International Continental Scientific Drilling Program to Friðleifsson and Elders, and from the US National Science Foundation grant No EAR-0507625 to Elders, has made the downhole sampling and research program of the IDDP possible.

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