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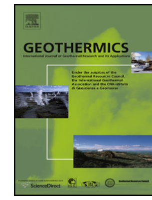

The concept of the Iceland deep drilling project

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ABSTRACT

Calculations discussed in the Iceland Deep Drilling Project feasibility study in 2003 indicated that, for same volumetric flow rate of steam, a geothermal well producing from natural supercritical fluid would have the potential to generate power outputs an order of magnitude greater than from conventional high-temperature wells (240–340 °C). To reach supercritical hydrous fluid conditions in natural geothermal systems requires deep drilling to a minimum depth of some 3.5–5 km were temperature conditions can be expected to range between 400 and 600 °C in reasonably active high-temperature fields. Three geothermal fields in Iceland, Reykjanes, Hengill and Krafla, were selected as suitable locations for deep drilling to test this concept in search of natural supercritical geothermal fluid systems.

1. Introduction

The Iceland Deep Drilling Project (IDDP), is a long term program by an industry-government consortium aimed at investigating unconventional, very high-temperature, geothermal systems. Its aims are to improve the economics of geothermal resources, minimize the environmental impact of harnessing geothermal reservoirs, evaluate the volume of deep accessible geothermal resources, examine extraction of valuable minerals and metals, and support sustainable energy development in society.

The IDDP was established in the year 2000 by a consortium of three Icelandic energy companies, Hitaveita Suðurnesja (now HS Orka hf) (HS), Landsvirkjun (LV) and Orkuveita Reykjavíkur (OR), and Orkustofnun (OS) (the National Energy Authority of Iceland). Also in the year 2000 the basis for the IDDP concept of drilling for geothermal resources at supercritical condition (>374 °C and >221 bars for pure water, increasing with increased salinity) was explained further at the World Geothermal Congress 2000 in Japan (Friðleifsson and Albertsson, 2000).

Supercritical water has much higher enthalpy and lower viscosity than a two phase mixture of steam and water at subcritical temperatures and pressures (Dunn and Hardee, 1981; Hashida et al., 2001; Fournier, 1999). Modeling (Albertsson et al., 2003) indicated that a well producing supercritical water could have an order of magnitude higher power output than a conventional high-temperature geothermal well, given the same volumetric flow rate of steam.

From the beginning, the IDDP consortium welcomed the inclusion of basic scientific studies in the IDDP (Friðleifsson and Albertsson, 2000; Elders et al., 2001; Friðleifsson and Elders, 2005). As a guiding principle, the consortium expressed their opinion that incremental costs of drilling and sampling for the science program, and their subsequent study, should primarily be met by the scientific community, to the mutual benefit of both, whereas the basic costs of drilling should primarily be met by the IDDP consortium. In 2005, HS offered the 3085 m deep well RN-17 at Reykjanes as a well of opportunity to IDDP to deepen into the supercritical zone. Unfortunately that well was lost during a flow test later the same year, before IDDP could take it over for deepening to the proposed 4–5 km depth (SAGA Report 2006 at http://www.iddp.is). In June 2006, a decision was made to move the IDDP operations to Krafla in NE-Iceland (Fig. 1). Funding for deepening that well had already been secured by the Icelandic consortium and in 2005 funds for scientific coring had been awarded from both the ICDP (International Scientific Continental Drilling Program) and the NSF (United States National Science Foundation).

In 2007, Alcoa Inc. (Alcoa), an international aluminum company, joined the IDDP consortium, followed in 2008 by Statoil, an international oil and gas company. In 2007 each of the three Icelandic power companies had announced their commitment to drill, at their own cost, a 3.5–4.0 km deep fully cased well, in each of the three - geothermal fields, Krafla, Hengill and Reykjanes. These wells were to be designed to be suitable for deepening to 4.5–5.0 km depth. The deepening of one of these wells as a joint IDDP consortium project would then be funded by the IDDP energy consortium, with additional funds from ICDP and NSF to cover spot coring costs and part of the subsequent laboratory studies. Additional funding would still be needed for the petrophysical, geophysical and many other scientific and engineering studies associated to each of the

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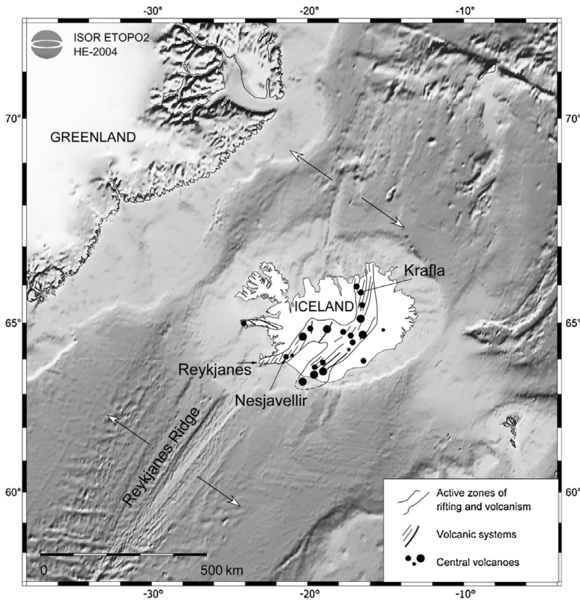

Fig. 1. The location of Iceland on the Mid-Atlantic Ridge. The arrows show the spreading directions (spreading rate ~2 cm/year) on the mid-ocean ridge crossing Iceland, which rises above sea-level due to an underlying hot spot or mantle plume. Due the plume numerous evolved central volcanoes (~100) developed within the active rift zones in Iceland since late Miocene. The three active high-temperature hydrothermal systems where the IDDP will carry out 4.5–5 km deep drilling, at Reykjanes, Hengill, and Krafla, are located within the presently active rift zone.

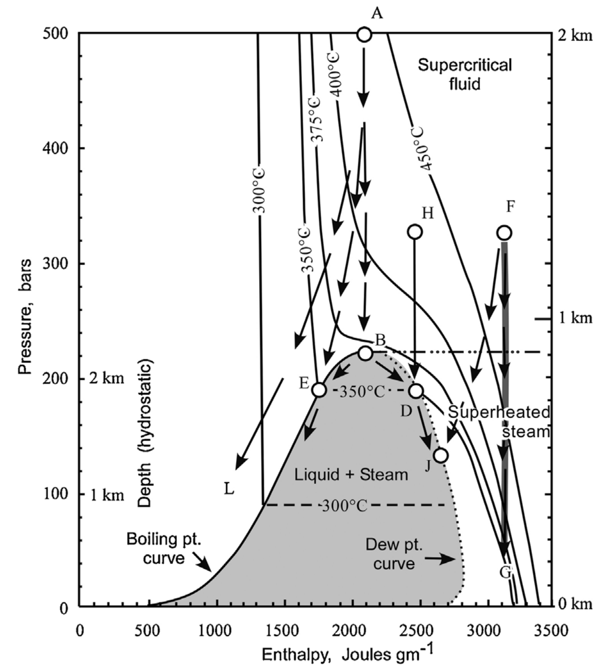

Fig. 2. Pressure-enthalpy diagram for pure H_2O with selected isotherms. The shaded area showing the conditions under which steam and liquid water co-exist is bounded on the left by the boiling point curve and to the right by the dew point curve. The arrows show various different cooling paths of ascending fluids; see text (compiled from data in Barton and Toulmin (1961), Fournier (1999, 2007).

deep wells. Thus IDDP continued to welcome different kinds of international participation in the IDDP program (Friðleifsson et al., 2010). It has always been our belief that the geothermal community at large will benefit from the basic studies undertaken by the IDDP research and development (R&D) program to prove its concept of supercritical geothermal energy, introduced below.

2. The IDDP concept

Hydrous fluid systems at supercritical pressures can only be reached at great depths in natural hydrothermal systems in volcanic complexes, except those associated with some of the black smokers on the ocean floor at great ocean depths, due to the high water pressure. The minimum depths to the ocean floor needs to be around 3 km to reach the critical point for seawater, but for pure water the critical pressure and temperature is about 221 bar and 374 °C (see further discussion below).

In 1985, the well NJ-11 in the Nesjavellir Geothermal Field, on the Hengill central volcano in SW Iceland (Fig. 1), unexpectedly encountered very high pressure at a depth of only 2200 m which seemingly was due to supercritical fluid at temperatures of >380 °C (Steingrímsson et al., 1990). The fluid pressure and flow rates were so high that there was fear of losing control of the well, so the high pressure zone was shut off using a 600 m thick gravel pack as there was no way the high pressures could be safely managed in the well at the time, as the safety casing was far too shallow.

This experience stimulated thoughts in Iceland of deliberately drilling deep enough to produce supercritical fluids under controlled conditions. At that time Friðleifsson (1983a, 1983b, 1984) had completed a study of a fossil high-temperature geothermal system within the Miocene Geitafell central volcano in SE-Iceland. Amongst the chief findings was conclusive mineralogical evidence that heat transfer from hot intrusive rocks appeared, in many cases, to proceed via supercritical and/or superheated fluid layers within the hydrostatically controlled hydrothermal system. Thus it was just a question of time when researchers would propose a deliberate attempt to drill for supercritical fluids (Friðleifsson and Albertsson, 2000).

3. Supercritical conditions

At temperatures and pressures above the critical point of water (a liquid and its vapor phase) only a single phase, a *supercritical* fluid, exists. The critical point of pure water occurs at about 221 bars and 374 °C, but higher in waters with dissolved components. For example, the critical point for seawater is at ~298 bars and ~407 °C (Bischoff and Rosenbauer, 1984). While supercritical hydrothermal fluids in the Earth's crust are of scientific interest, there have not yet been any attempts to put natural supercritical fluids to practical use, even though there have been some discussions of their potential as a source of high grade energy (e.g. Yano and Ishido, 1998; Hashida et al., 2001).

Supercritical water has 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 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, 1984; Norton and Dutrow, 2001).

Fig. 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,