Geothermics 49 (2014) 2–8

Contents lists available at ScienceDirect

Geothermics

journal homepage: www.elsevier.com/locate/geothermics

The concept of the Iceland deep drilling project

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ARTICLE INFO

Article history:
Received 19 March 2012
Accepted 11 March 2013
Available online 8 April 2013

Keywords:
Iceland Deep Drilling Project
Supercritical geothermal fluid systems

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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http://dx.doi.org/10.1016/j.geothermics.2013.03.004

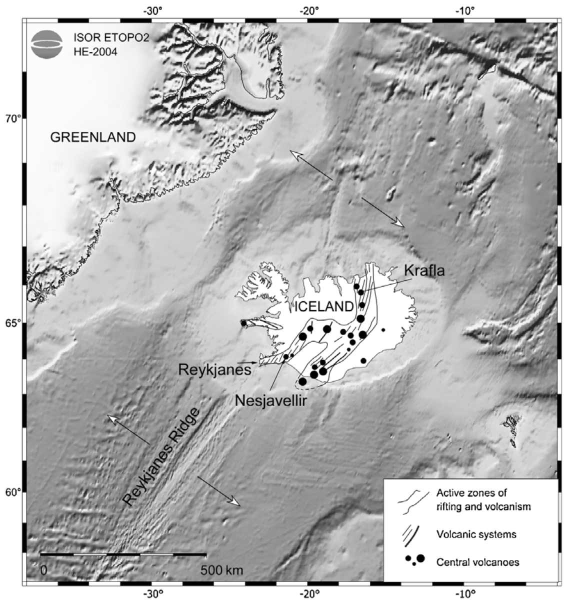

Fig. 1. The location of Iceland on the Mid-Atlantic Ridge. The arrows show the spreading directions (spreading rate ~2 cm/year) on the mid-ocean ridge crossing Iceland, which rises above sea-level due to an underlying hot spot or mantle plume. Due the plume numerous evolved central volcanoes (~100) developed 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.

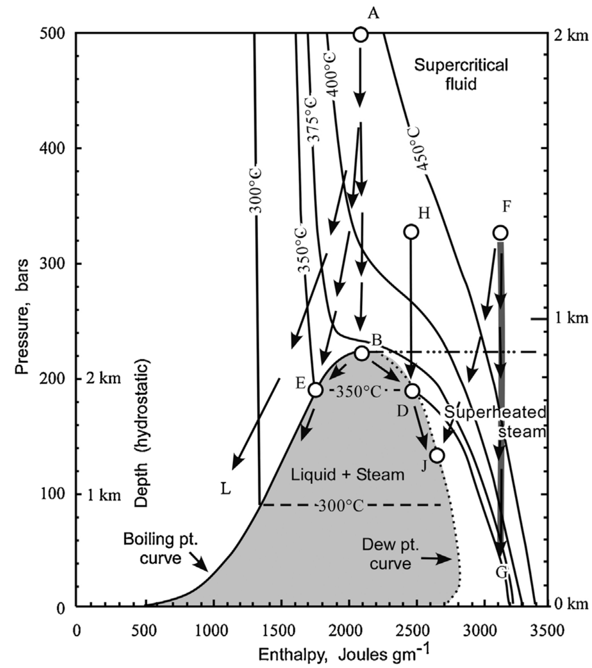

Fig. 2. Pressure-enthalpy diagram for pure H_2O with selected isotherms. The shaded area showing the conditions under which steam and liquid water co-exist is bounded on the left by the boiling point curve and to the right by the dew point curve. The arrows show various different cooling paths of ascending 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, water-dominated, geothermal reservoirs where boiling, typically 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 expanding and 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 Iceland Deep Drilling Project 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, resulting in a much greater power output than from a typical geothermal well.

The depth scales marked at the left and right sides of Fig. 2 correspond to pressures in hydrothermal systems – 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 °C hot hydrous fluids can be expelled directly into the oceans from 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 to depth curve (BPD-curve), and the critical point would be expected to 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 Fig. 2). Other scenarios are still possible, depending on how the hydrothermal system couples with a magmatic system, which are the only credible heat sources for such high-temperature hydrothermal systems.

For example Fig. 3A shows a simple convection model for a supercritical hydrothermal system, whereas Fig. 3B shows another possible scenario going through a conventional high-temperature system toward the brittle/ductile boundary approaching magmatic temperatures. The Boiling Point with Depth Curve (BPD-curve) governs the maximum temperatures attainable at all depths within liquid dominated hydrothermal fields, such as those in Iceland. If a dilute hydrothermal fluid in a natural system is at boiling temperatures from the surface, the critical point (C and CP in Fig. 3A and B) would be reached at about 3.5 km minimum depth, in meteoric fed systems. Boiling temperature profiles are common in the upper parts of the Icelandic geothermal fields, like Krafla and Nesjavellir, while the Reykjanes field more typically follows a path like the one between points A and B in Fig. 3A, in all wells drilled to date (RN-8-RN-30). Beyond the minimum depth of the critical point convection may continue downwards as between points A and B in Fig. 3A, to depths and temperatures at which permeability is destroyed either by mineralogical self-sealing or by transition from brittle to ductile behavior (Hashida et al., 2001; Fournier, 1999). If the temperature profile along line B-D (Fig. 3A) is at a shallower depth than 5 km, the supercritical conditions of interest to IDDP will be intersected by IDDP drilling.

Although the BDP-curve controls the maximum temperatures attainable within liquid dominated systems, if an igneous intrusion occurs within the system at shallow depths, which is quite common, the hydrostatically controlled temperature gradient becomes temporarily disturbed until convective cooling restores the BDP temperature gradient. Thus temporary superheated conditions may occur locally within hydrothermal systems. The question remains of how long such conditions survive before adjusting to the BPD-curve. This will vary depending on the shape and size of the magmatic heat sources, the lithological composition, and the presence and extent of cap rocks etc. For example, in the case of the Geitafell Miocene gabbro intrusion at 2 km depth, Friðleifsson and Björnsson (1986) calculated it would take almost 10,000 years to cool a gabbro intrusion of 1.25 km^3 to ambient temperatures of 225 °C. Supercritical and superheated fluid conditions at the margin of such major intrusions would exist for only a fraction of that time, possibly for several tens or hundreds of years before adjusting to surrounding hydrostatic control.

To deal with possible scenarios which IDDP drillers could possibly face in deep drilling, the four scenarios in Fig. 4 were created during the IDDP science workshop and were discussed in the Feasibility report (Friðleifsson et al., 2003). The first scenario shows a likely temperature path if IDDP were to drill into magma at ~2 km depth, the second shows the situation if the drilling occurred down a sub-vertical contact aureole of one such large magma intrusion. The third scenario shows the depth-temperature path if drilling passed the critical point and penetrated into magma at 4 km depth, and the fourth scenario shows the likely conditions within amphibolite facies rocks at supercritical temperatures above 400 °C. The brittle/ductile boundary for basaltic rocks lies between 600 and 760 °C (see discussion accompanying Fig. 5). Thus the target for IDDP drillholes was set at 400–600 °C. The favored scenarios for IDDP drilling were number 2 and 4 in Fig. 4. Accordingly, proposed sites for an IDDP drillhole at Krafla, where a magma intrusion was assumed at 3 km depth, were sited along the margin of that intrusion (Friðleifsson et al., 2003). However, after additional research and other reasons, the IDDP-1 was later sited differently (see Friðleifsson et al., 2014a), and incidentally ended in a scenario like scenario 1 in Fig. 4.

From the present knowledge on the Reykjanes and Hengill geothermal systems, it seems unlikely that future IDDP boreholes would experience a similar scenario as at Krafla in well IDDP-1 (i.e. drilling into magma), but rather that the future IDDP well would follow paths as illustrated by scenario 4, and possibly a combination of 2 and 4. Such a plume of superheated steam may possibly occur at both Reykjanes and Hengill at unspecified depth, especially if we encounter deep seated self-sealing zones at the bottom of the conventional 2-phase hydrothermal convection systems. Such self-sealing zone would rupture intermittently due to faulting and, as explained by Fournier (1999), would allow deep seated fluids to move to shallower levels, either as supercritical fluid or superheated steam.

4. The evolution of the IDDP

In 2000 an oversight committee, Deep Vision, with membership from a consortium of the three principal energy companies in Iceland (Hitaveita Suðurnesja (now HS Orka (HS), Landsvirkjun (LV), Orkuveita Reykjavíkur (OR) and the National Energy Authority of Iceland (OS), was established to plan drilling for supercritical geothermal resources and invite international participation (Friðleifsson and Albertsson, 2000)). Drilling and producing from very deep wells necessary presents both technical challenges and opportunities for important scientific studies. Deep Vision therefore welcomed participation by the international scientific community. Specifically, drilling to 4–5 km depths in high-temperature hydrothermal systems in Iceland, heated by shallow level magma intrusions, lying astride the Mid-Atlantic Ridge, should penetrate into root zones similar to those that feed the black smokers on oceanic spreading centers (Elders and Friðleifsson, 2010). In 2002 scientists and engineers from 12 different countries attended two workshops funded by the International Continental Scientific Drilling Program (ICDP), the first of these discussed the optimal strategy for drilling such deep hot wells and the second discussed the science program.

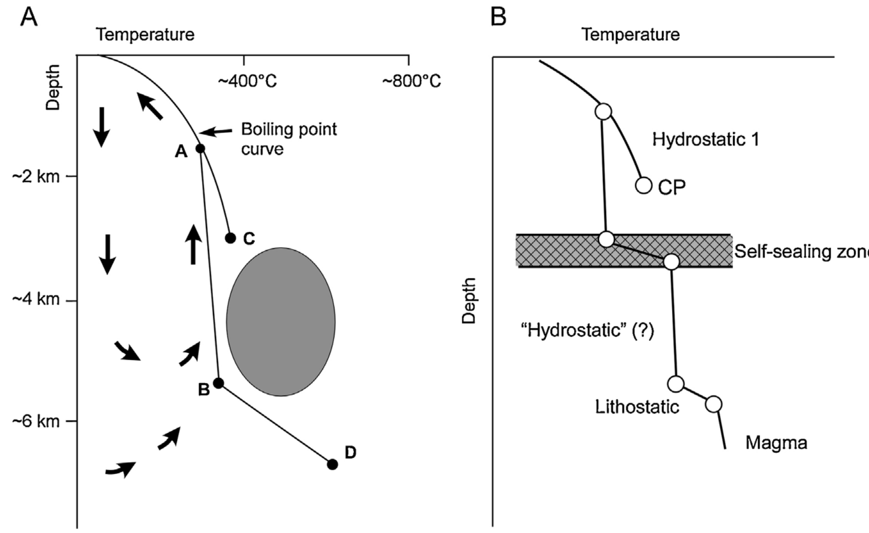

Fig. 3. **A and B.** Conceptual models A and B, the critical point is at point C and CP, respectively. The arrows in (A) indicate convection. The encircled field in (A) between points B, C and D indicate the field of interest to IDDP.

A feasibility report on the IDDP, commissioned by Deep Vision, was published by three working groups (1) geosciences, (2) drilling techniques, and (3) fluid handling and evaluation (Friðleifsson, 2003; Friðleifsson et al., 2003; Þórhallsson et al., 2003; Albertsson et al., 2003). These reports and updates on the IDDP are available at http://www.iddp.is. Part 1 identified three suitable locations in Iceland to site a deep well intended to produce supercritical fluids, within the high-temperature systems at Reykjanes, Hengill and Krafla, operated by the HS, OR and LV energy companies respectively.

In developed crustal genesis regions of Iceland, like at the proposed IDDP sites at Reykjanes, Hengill and Krafla it is hypothesized that the onset of semi-brittle state in crustal rocks occurs at the top of the lower crust. At approximately this depth the number of earthquakes starts to decrease. It lies at 4–5 km depth under the IDDP sites. The depth above which 90% of the seismicity occurs, was defined as the depth to the brittle-plastic boundary and the bottom of the seismogenic part of the crust (in Friðleifsson et al., 2003; Friðleifsson and Elders, 2005). This boundary lies between 6 and 7 km below the IDDP sites at Reykjanes and Hengill with a 1.5–2 km thick brittle-plastic transition zone above it. There are limited laboratory measurements available on the rheology of basaltic rocks, but arguments (I.Þ. Bjarnason, pers.com and in IDDP Feasibility report (Friðleifsson et al., 2003) have been put forward for a 600 °C temperature at the semi-brittle boundary and 760 °C at the brittle-plastic boundary in a 2 cm/year strain region like Iceland. None-double couple earthquakes in the mid-crust and in the top part of the lower crust in crustal genesis regions of Iceland suggest that hydrous phases may exist in the crust at depths where the average temperature exceeds 400 °C. Expected temperatures at all IDDP drill fields considered, range from 550 °C to 650 °C at 5 km depth, ±100 °C as shown in Table 1.

The three developed high-temperature geothermal areas selected by the IDDP, host contrasting stages of the tectonic development of the mid-ocean ridge. The Reykjanes site represents an immature stage of rifting with a heat source that is probably an active sheeted dike swarm. At Nesjavellir, the Hengill central volcano is the heat source for a geothermal reservoir in a graben that

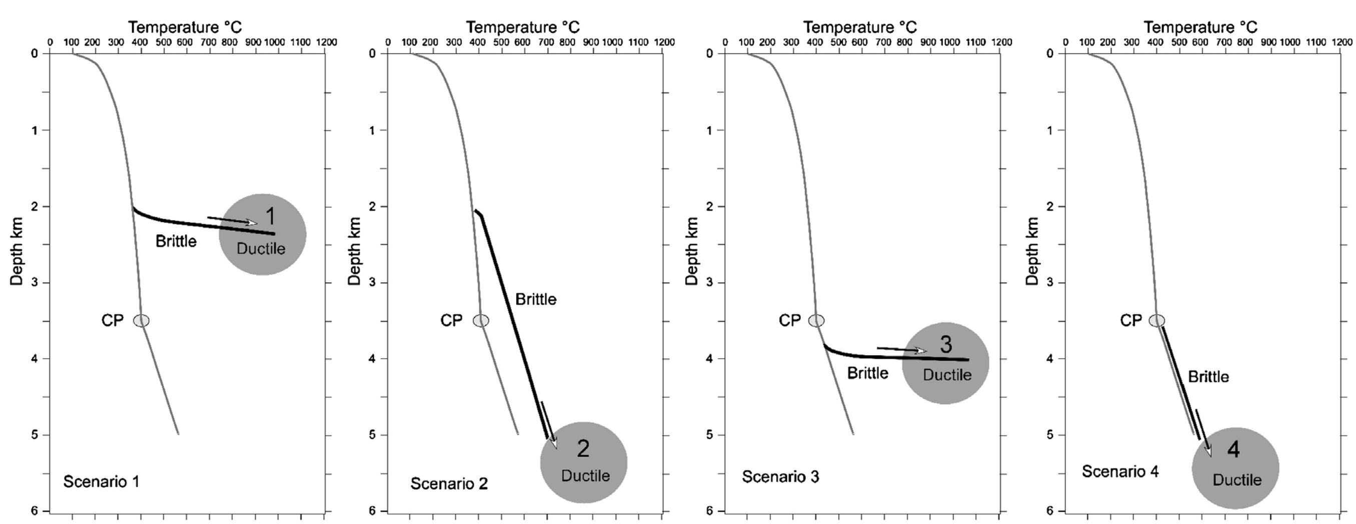

Fig. 4. Conceptual models along four different scenarios, 1, 2, 3 and 4. The first scenario shows a likely temperature path if we drill into magma at ~2 km depth or so, the 2nd if we drill downwards along a contact aureole of a large magma intrusion, the 3rd if we drill into magma at 4 km depth, and the 4th and final one if we drill beyond the critical point within the amphibolite facies rocks at supercritical temperatures (>400 °C). The brittle/ductile boundary for basaltic rocks lies between 600 and 700 °C (see discussion along Fig. 5).

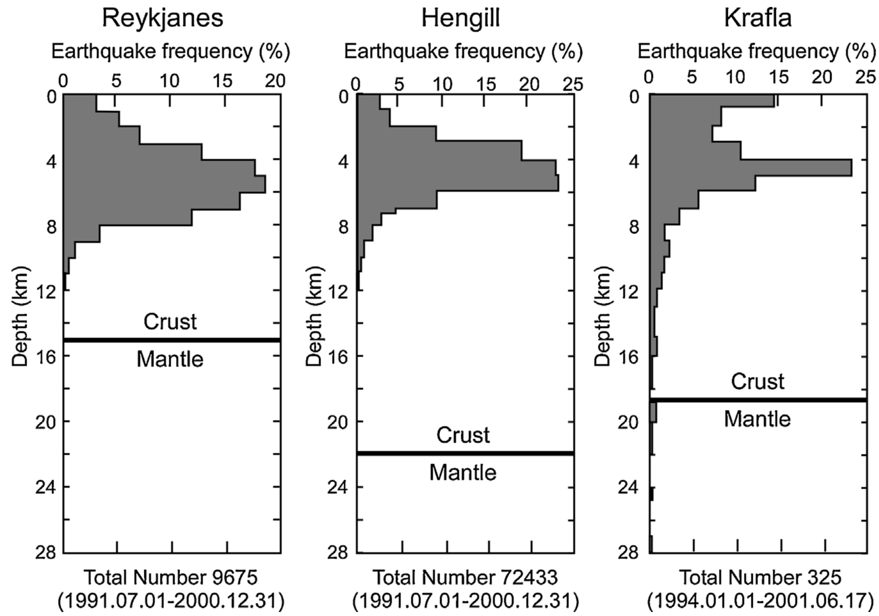

Fig. 5. Earthquake frequency with increasing depth on the Reykjanes Peninsula, Hengill and Krafla areas, recorded by the Iceland Meteorological Office (Guðmundsson et al., 2001). The approximate depth of the accumulated 90% of the seismicity measured from the surface, is defined as the brittle-ductile boundary. Notice the sharp drop in seismicity around this boundary, suggesting a high thermal gradient. (Figure from Friðleifsson et al., 2003, repeated in Friðleifsson and Elders, 2005).

has, in places, temperatures of >380 °C at 2.2 km depth. The Krafla high-temperature geothermal field is developed above a magma chamber in a mature, active, volcanic caldera where numerous wells have reached temperatures of >300 °C at depths of 2 km (Friðleifsson et al., 2003). In common with most high-temperature geothermal systems in Iceland, the systems at Hengill and Krafla contain dilute fluids only slightly modified by water/rock reactions and the possible admixture of magmatic gases. In contrast, and in keeping with its location on a narrow peninsula surrounded on three sides by the Atlantic, the Reykjanes system contains modified seawater.

One of the chief findings of the feasibility report was that a well that produces supercritical fluids would be expected to have a greatly enhanced power output relative to conventional high-temperature geothermal wells. Geothermal wells in Iceland today typically range up to 3.0 km in depth and produce steam up to 340 °C, or less, at a rate sufficient to generate about 4–10 MW of electricity. It is estimated that producing steam, at a rate of 0.67 cubic meters a second, from a well penetrating a reservoir with temperatures >450 °C, could generate 40–50 MWe (Albertsson et al., 2003; Friðleifsson and Elders, 2005).

5. First IDDP attempt at Reykjanes

In 2004 Hitaveita Sudurnesja Ltd. (now HS Orka hf), the operator of the Reykjanes Geothermal Field, offered that the IDDP could take over, as a “well of opportunity”, and deepen to 4–5 km a well at Reykjanes which was being drilled to 3.1 km depth by HS. The well, RN-17, penetrated Holocene lavas, hyaloclastites, marine sediments, pillow basalts, and both fine-grained basalt- and relatively coarse-grained diabase dikes, hydrothermally altered to epidote-actinolite stage (Friðleifsson et al., 2006). Unfortunately, in November 2005, during a production flow test of the 3.1 km deep well, it collapsed and became plugged and so, after attempts to recondition it in February 2006 failed, the reluctant decision had to be made to abandon the well for deepening. However, 3 years later the IDDP obtained ICDP-NSF funded spot core from the well RN-17B, a side track of the RN-17, at 2798–2808 m, corresponding to a vertical depth of about 2562–2570 m depth from the surface (TVD) (Friðleifsson and Richter, 2010). The first of ICDP-NSF funded spot cores were collected in April 2005 from the bottom of well RN-19 (Mortensen et al., 2006), and in May 2011 three successful spot cores were retrieved from the inclined well RN-30 from 2510–2533 m depth (Friðleifsson, 2011), corresponding to about 2250–2280 m depth from surface (TVD).

Since 2005 detailed IDDP-related petrological studies have been undertaken on drill cutting samples from well RN-17 and other wells at Reykjanes, as well as on all available drill cores. They have shown that the history of hydrothermal processes at Reykjanes is complex and the rocks exhibit varying degrees of greenschist facies alteration. Freedman et al. (2009) studied zoned epidotes in the trivariant assemblage epidote-prehnite-calcite-quartz-fluid and, using thermodynamic analysis calculated P_{CO_2} of the hydrothermal fluids in equilibrium, and showed that the P_{CO_2} of the fluids has increased during the evolution of the hydrothermal system, likely due to periodic magma injection.

Similarly, detailed studies of δD and δ^{18}O of minerals and fluids at Reykjanes by Pope et al. (2009) showed that, before the Reykjanes system was penetrated by seawater, it had been occupied by dilute meteoric water, probably glacial melt water. This was in line with earlier studies on fossil freshwater system at Reykjanes (e.g. Sveinbjörnsdóttir et al., 1986; Franzson et al., 2002). In the detailed study of Marks et al. (2010) on well RN-17, a new discovery of a high-temperature amphibole zone below 2400 m depth was reported as a transitional feature into amphibolite grade alteration. ^{87}Sr/^{86}Sr ratios within alteration minerals were observed to

Table 1
Results from the IDDP feasibility study of seismicity and rheology (Friðleifsson et al., 2003). The rheology temperatures values at 5 km in the last line, as shown ±100 °C.

	Reykjanes tip	Hengill	Krafla
Crustal thickness	15 km	22 km	19 km
Depth to lower crust	4–5 km	3.5–5 km	3–4 km
Magma storage		7–9 km	3–4.5 km
Extrapolated T at 5 km depth	>575 °C		
Semi-brittle depth	4–5 km	5–6 km	5–6 km
Brittle-ductile depth	6 km	7 km	7 km
Rheology T at 5 km depth	630–680 °C	550–600 °C	550–600 °C

significantly shift toward seawater values with increasing depth, and therefore confirming deep penetration of seawater into the present-day Reykjanes system (Marks et al., 2010). A detail petrochemical study of the exclusively basaltic host rocks in well RN-17 was undertaken by Ottolini et al. (2012, and references therein). All these IDDP related studies have been a preparation to study the details of the roots of the Reykjanes system at 3–5 km depth – hopefully within in the next couple of years or so.

6. The IDDP-1 at Krafla

The loss of the "well of opportunity" at Reykjanes in 2005 required a change in the work plan and so in 2006 Landsvirkjun, the operator of the Krafla Geothermal Field, offered a planned well to the IDDP for deepening, it was decided to move the site for the first deep borehole there. In Krafla a 60 MWe geothermal power plant is currently in operation. The Krafla volcano has a 300,000 years long history of predominately basaltic volcanic activity, most recently during 1975–1984 (Einarsson, 1991). Eruptions of the Krafla volcano are episodic occurring at 250 to 1000 year intervals, with each episode lasting 10–20 years. The presence of a magma chamber beneath the caldera at 3–7 km depth was inferred from S-wave attenuation during the 1975–84 eruptive cycle (Einarsson, 1978).

In 2009 the drilling of the first deep IDDP well (IDDP-1), designed to reach 4.5 km depth, was attempted at Krafla. The drilling, however, had to be terminated abruptly at only 2.1 km depth when the drill bit intersected 900 °C hot rhyolitic magma (Elders et al., 2011, 2014). The IDDP consortium decided to complete the well as a subcritical well designed to produce from the contact zone of the intrusion. This far the well has proved highly productive. Since November 2011 it has been kept producing at 10–12 kg/s restricted flow of dry superheated, but subcritical steam. Wellhead temperatures have been slowly rising, and since November 2011 reaching up to 450 °C, at wellhead pressure slowly rising up to 140 bar. The enthalpy approached 3200 kJ/kg, and the well appears capable to produce up to 35 MWe. Most of the papers in this Special Issue of Geothermics concern the IDDP-1 well. In the event that the IDDP-1 turns out not to be sustainable, the option remains to create the world's hottest Enhanced Geothermal System (EGS) at Krafla, just above the magma chamber (see Elders et al., 2014).

7. Future IDDP activities

Until late summer 2012 the plan was to take the IDDP-1 well into production for the current 60 MWe power plant at Krafla. That would have required the superheated steam to be treated by wet scrubbing (see Hauksson et al., 2014). Last autumn the IDDP-1 well had to be shut down due to valve failure, and when this is written it is not clear if the well will be taken into production again. Nevertheless, for Landsvirkjun, the field operator at Krafla, the result of IDDP-1 may lead to a new era in power production at Krafla. Investigating the extent of the hot contact zone of the intrusion and eventually drill more production and/or injection wells will be a high priority. In case the IDDP-1 well does not prove to be a sustainable production well, the Krafla field, as said above, could one day become the site of the world's first engineered geothermal system operating at, or near magmatic temperatures (see Elders et al., 2014). In 2014–2015 HS Orka, the field operator at Reykjanes, is seriously considering to drill an IDDP designated well there, suitable for deepening into the supercritical zone with participation by the scientific community (Friðleifsson et al., 2014b). In subsequent years a similar drilling program is expected to follow within the Hengill Geothermal Fields, operated by Reykjavik Energy.

8. Sustainability aspects of the IDDP

The definition in Brundtland's report of the World Commission on Environment and Development (1987) is: "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs." Contemporary discussions of sustainability are mainly concerned with ecological sustainability and sustainable economic development. "The economics of the coming spaceship earth states a concern for future generations that requires us to think more of the world as a closed system than an open system with unlimited sources of energy and waste-sinks" (Economist Kenneth Boulding).

There are two main concepts:

A. Sustainable development is understood as an economic and social development that maintains a certain level of human welfare.
B. Ecological sustainability is understood as human interaction with the environment that permits essential ecological states to be maintained.

In order to support sustainable development as set forth in Bruntland's report, projects like the IDDP are inevitable. To cope with the inherent time scale of sustainable development requiring long term planning (at least 100 years) society will need to harness deep seated renewable geothermal reservoirs. Long term, sustainable geothermal development will require drilling into the roots of the existing geothermal systems. IDDP is attempting to understand the mechanism of the chemical and heat transport of the renewable geothermal systems at plate boundaries.

9. Summary and conclusions

The concept of IDDP is simple. We suggest that supercritical condition can be reached by drilling deep enough into the three Icelandic high temperature systems under consideration, namely Krafla, Reykjanes and Hengill. We further suggest that supercritical conditions can be reached above 5 km depth, within the hottest parts of these fields. In the event an IDDP well does not intersect permeable rocks at supercritical condition at such great depths, we suggest it is likely that it would intersect superheated steam. In the event that sufficient permeability was not found, IDDP would attempt to inject water into the hot rocks for heat sweeping, and thereby enhance the performance of the conventional field above (i.e. establish an EGS systems). Nevertheless the concept behind the IDDP is to produce supercritical fluid to the surface in such a way that it transitions directly to superheated steam at subcritical pressures.

The industrial aim for the IDDP is to improve the economics and availability of geothermal resources, an environmentally benign source of sustainable energy. If producing electricity from supercritical magma-hydrothermal systems in Iceland is successful economically, it will make a positive impact on the geothermal industry worldwide, wherever suitable conditions occur at drillable depths. And finally, in order to support sustainable development in society, IDDP is inevitable.

Acknowledgements

We are grateful to the IDDP consortium for making the IDDP-1 possible. We thank the Deep Vision consortium consisting of three Icelandic Energy Companies, the National Energy Authority, and Alcoa, for the opportunity to deal with the challenge represented by the concept of the IDDP. Thanks are also due to the members of our Science Application Group of Advisors (SAGA) who have given freely of their time and experience. 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 made the down hole sampling and scientific research program of the IDDP possible.

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