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Drilling into magma and the implications of the Iceland Deep Drilling Project (IDDP) for high-temperature geothermal systems worldwide

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ABSTRACT

Drilling deeper in high-temperature geothermal systems by the IDDP is aimed at increasing the power output of shallower high-temperature geothermal fields by an order of magnitude without increasing their environmental footprints. The main thrust of the IDDP is to develop deep supercritical systems, but an unexpected encounter with a shallow body of magma demonstrated that very high power outputs are also possible from the contact zone of an intrusion. In the future it may be feasible to produce energy directly from magma. Favorable environments to implement these concepts are likely worldwide wherever active volcanoes and young volcanic rocks occur.

1. Introduction

Because of Iceland's steep topography and high precipitation, about 70% of its electrical generating capacity is hydroelectric. Similarly, because of its favorable volcanic geology (and low population), Iceland leads the world in geothermal development on a *per capita* basis (Fig. 1). Direct geothermal use heats about 90% of its buildings, and approximately 30% of its electrical production is geothermal (Flóvenz and Steingrímsson, 2009; Arnórsson et al., 2008). Therefore, this island nation is deeply invested in renewable, sustainable, and low cost primary energy. This has attracted energy intensive industries, for example, three different international companies operate aluminum smelters in Iceland, and discussions of adding more are underway, so that more electrical capacity will be needed. However, the strong environmental ethos among the Icelandic electorate will limit damming of more wild and scenic rivers. Thus geothermal resources play an increasing role in Iceland's energy mix, and there are plans to expand several "conventional" high-temperature (240–340 °C) geothermal fields, such as Reykjanes, and new ones are being explored and developed. Nevertheless, even in Iceland there is a limit to the extent, lifetime and number of these geothermal resources. Increased awareness of environmental protection and newly defined national parks prevent development of many of the more scenic high-temperature geothermal fields. Thus there is a growing interest in sustainability and in exploring alternatives. As outlined by Friðleifsson et al. (2014a) elsewhere in this issue, an industry-government consortium, the Iceland Deep Drilling Project (IDDP), is participating in these efforts by investigating deeper, "unconventional," supercritical, high-temperature geothermal systems potentially capable of very high power outputs.

2. High-temperature geothermal systems in Iceland

Among the possible reasons for the greater abundance of hydrothermal systems in Iceland relative to their abundance on "typical" mid-ocean ridges (Beaulieu, 2010) are (1) the high heat flow associated with frequent volcanicity, related to a hot spot, or a rising mantle plume, under Iceland, (2) more frequent seismicity, and (3) higher permeability than that of typical oceanic crust. A contributing factor is that Iceland was heavily glaciated in the past two to three million years, and the last glaciation, which lasted for 105 years, ended only 104 years ago (Símonarson and Eiríksson, 2008). As pointed out by Böðvarsson (1982), this had a profound effect on Iceland's long-lived hydrothermal systems. For example, during times of ice cover, recharge by glacial melt water occurred under higher hydrostatic pressures. The weight of the ice would elevate the hydrostatic pressures within the subglacial hydrothermal systems, and their pressure (P) temperature (T) regime would respond accordingly. Deglaciation lowered the hydrostatic pressures, and post-glacial rise of sea level compensated this pressure only to minor degree. These pressure changes occurred in a time frame that is orders of magnitude shorter than thermal relaxation times. This seems to be a likely explanation

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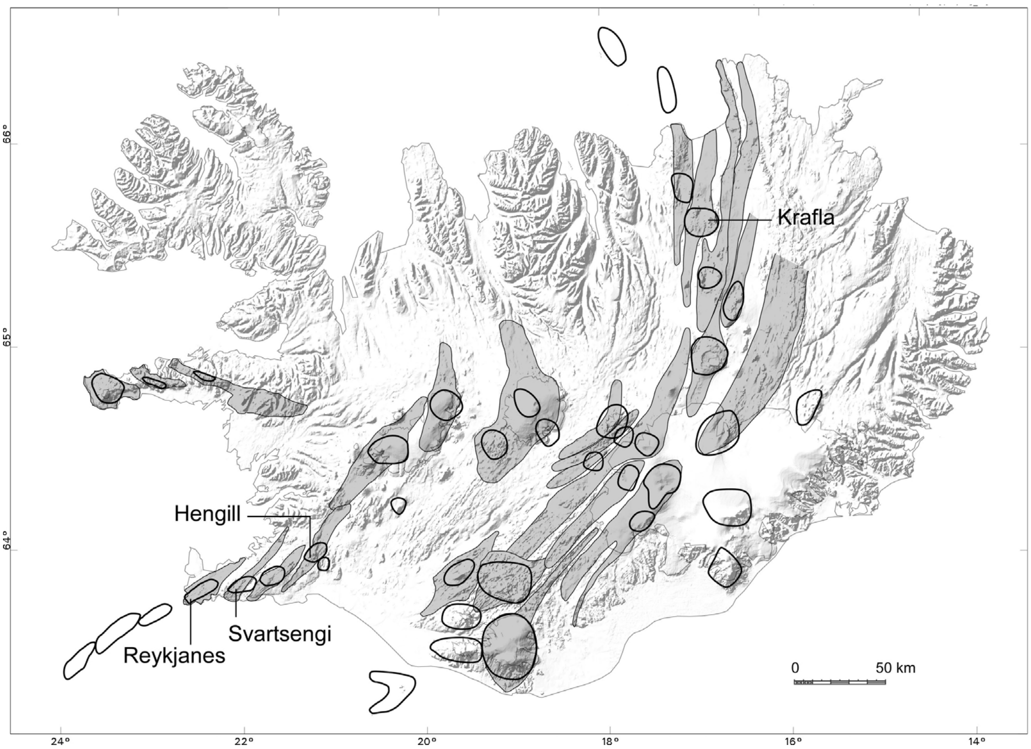

Fig. 1. Iceland lies at the coincidence of a mantle plume and the Mid-Atlantic Ridge spreading axis and has numerous fissure swarms and active volcanic systems and central volcanoes (irregular ellipses) within in its high-heat flow rift systems (shaded). The geothermal systems of Reykjanes, Svartsengi, Hengill and Krafla mentioned in the text are also shown.

Adapted from Elders and Friðleifsson (2010), Fig. 2.

for the observation that the discharge regimes of many of the high-temperature systems in Iceland follow the boiling point to depth curve (BPD-curve) that defines the upper PT limit of thermal gradients in an advecting/convecting two-phase system.

In Iceland, high-temperature geothermal systems (>200 °C at 1 km depth) are common in the Upper Pleistocene and Holocene (<0.8 Myr) neovolcanic zones of rifting and volcanism. Some 30 volcanoes have erupted in post-glacial time with about 2400 eruptions in the last 11 ka, averaging one every four years in historic time of 1 ka (Fig. 1; Arnórsson et al., 2008; Thordarson and Höskuldsson, 2008). These geothermal systems, with two exceptions, Reykjanes and Svartsengi, differ from mid-ocean ridge hydrothermal systems in that they contain modified dilute meteoric water, with total dissolved solids of less than 1000 mg/L rather than containing modified seawater. The geothermal fluid at Reykjanes is modified seawater, whereas Svartsengi contains fluid that is 2/3 seawater and 1/3 of meteoric origin (Elders and Friðleifsson, 2010).

After a two year long feasibility study by IDDP (Friðleifsson et al., 2003), three geothermal fields, Krafla, Hengill (Nesjavellir) and Reykjanes, were selected as being the most suitable to drill deeper to develop supercritical geothermal resources (Fig. 1). In 2009, the first deep borehole, the IDDP-01, which is the subject of this special issue of Geothermics, was attempted at the Krafla volcano where Landsvirkjun operates a geothermal field, with an area of approximately 40 km^2, supplying a 60 MWe power plant. While continuing research and development of the well IDDP-01, the next goal of the project will be to attempt to reach supercritical conditions in a 4–5 km deep hole exploratory borehole at Reykjanes in SW Iceland (Friðleifsson et al., 2014c). In the near future a third deep well will be drilled at Hengill, in one of the largest developed geothermal fields in Iceland (Fig. 1). In addition, there are many other high-temperature geothermal systems in Iceland where supercritical fluids are thought to occur at drillable depths.

3. Supercritical geothermal resources

The main motivation of the IDDP is to investigate the power potential and economics of the temperature–pressure regime of *supercritical* fluids (Friðleifsson and Elders, 2005; Friðleifsson et al., 2014a). The critical point for pure water occurs at 374 °C and 22.2 MPa, but is higher for solutions containing dissolved salts (Fig. 2). For example the critical point for seawater is at 407 °C and 29.8 MPa (Bischoff and Rosenbauer, 1984).

An aqueous hydrothermal fluid at supercritical conditions with a temperature of 400 °C and a pressure of 25 MPa has more than five times the power-producing potential of liquid water at a temperature of 225 °C (Tester, 2006, p. 24). An IDDP feasibility study indicated that, at the same volumetric flow rate, a geothermal well producing supercritical fluid would have an order of magnitude higher power output than a conventional high-temperature geothermal well producing steam (Friðleifsson, 2003). Not only do such fluids have higher enthalpy than conventional geothermal reservoir fluids, but they also exhibit extremely high rates of mass transport due to the greatly enhanced ratios of buoyancy forces to viscous forces in the supercritical state (Dunn and Hardee, 1981; Fournier, 1999; Fournier, 2007; Hashida et al., 2001; Yano and Ishido, 1998). The IDDP feasibility study (Friðleifsson, 2003) also indicated that to reach supercritical pressures would require drilling to a minimum depth of 3.5 km, depending on the fluid pressure (see Fig. 4 of Friðleifsson et al., 2014a).

Among the *potential* advantages of the approach of accessing hotter and deeper geothermal resources are (1) Improvement in the ratio of drilling costs to power output per well. Although deeper wells would be more expensive, this could be offset by high enough outputs per well. (2) Improvement in the power output of existing geothermal fields without increasing their environmental footprints. (3) Improvement in the lifetime of existing geothermal

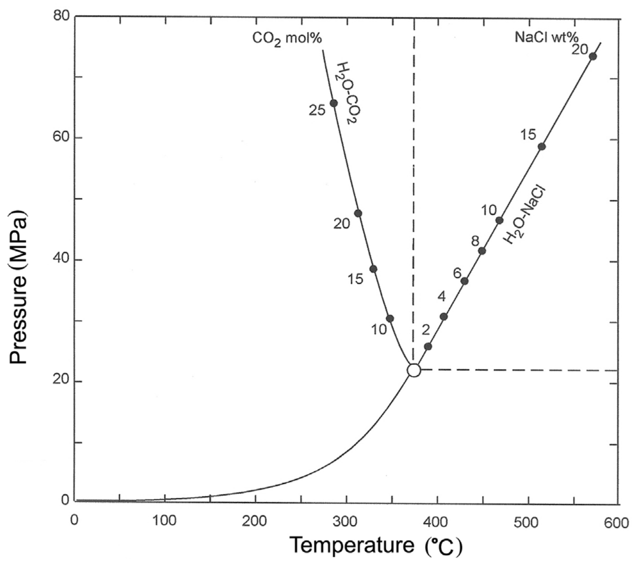

Fig. 2. The boiling point curve and critical point curves for water. The critical point for pure water is indicated by the open circle at 374 °C and 22.1 MPa. As shown by the relevant critical point curves for H_2O–NaCl and H_2O–CO_2, dissolved salt increases the temperature and pressure of the critical point whereas dissolved gas reduces the temperature and elevates the pressure of the critical point (Hashida et al., 2001).

fields by increasing the size of the producible resource by extending it downwards. (4) Accessing a deeper, hotter, environment for injection. (5) Improvement in the economics of geothermal power production. As mentioned above, higher-enthalpy aqueous working fluids in a turbine have a higher thermodynamic efficiency (or heat-to-power efficiency) and therefore should potentially yield more favorable economics. Higher temperatures of the working fluid result in higher exergy (i.e., availability of maximum electrical power production potential for a given flow rate). This is the main incentive to develop supercritical geothermal reservoirs. The Iceland Deep Drilling Program aims to produce supercritical fluid to the surface such that it transitions directly to superheated steam.

4. Occurrence of supercritical aqueous fluids

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, and for pure water the critical point would be reached at about 3.5 km depth (Fig. 2). On the other hand, if the fluid pressure is buffered by cold water, such as on the ocean floor, the critical pressure in a hot enough reservoir containing pure water would be reached at about 2.3 km depth, and for fluids with seawater salinity at 3 km depth. That is the reason why submarine hydrothermal vents, or black smokers, on mid-ocean rifts can expel very hot hydrous fluids directly into the ocean without boiling occurring. On mid-ocean ridges venting of hydrothermal fluids occurs at varying rates and temperatures, but the maximum temperatures are usually limited to 350–400 °C (Kelly et al., 2001). Nearly all black smoker discharges on mid-ocean rifts are subcritical as many of them occur at depths shallower than the critical pressure of seawater. However, the salinity of the fluids discharged can be either more, or less, saline than seawater by a factor of two or more and some have only 10% of seawater salinity (Van Damm, 1990). In these cases the chemistry of these high-temperature discharges makes clear that phase separation of dilute and hypersaline fluids is occurring under supercritical conditions, deeper in their flow systems (Kelley and Delaney, 1987). This is evidence that the supercritical state plays an important role in the evolution of mid-ocean ridge hydrothermal systems.

In 2005 and 2006, for the first time, direct observation and sampling of submarine hydrothermal vents discharging fluids lying at, or above, the critical point of seawater were carried out. These occur at 5° south on the Mid-Atlantic Ridge (Koschinsky et al., 2008). This vent field is characterized by multiple discharges with variable temperatures at water depths of ~3 km. One vent discharges reduced-salinity fluid at stable temperatures of 407 °C and exhibits vigorous vapor phase bubbling, indicating phase separation above the critical point. Another vent had a measured temperature of 464 °C which falls well into the supercritical field for seawater. According to Koschinsky et al. (2008), the activity of these supercritical vents was triggered by a seismic episode in 2002, so the supercritical discharge had persisted for at least four years.

To date, we know of no direct observations of natural supercritical aqueous fluids on land. However, emissions of natural superheated steam probably derived from the decompression of supercritical fluids have been observed both in volcanic fumaroles and in wells drilled in high-temperature geothermal fields. For example, in 1985 while drilling well number NJ-11 in the Nesjavellir geothermal system, on the north-east side of the Hengill central volcano in Iceland, at a depth of only 2.2 km, high-pressure superheated steam at temperatures >380 °C entered the well. Steingrímsson et al. (1990) inferred that this came from a supercritical reservoir. Because the well casing was inadequate to handle the high pressures encountered, the well was completed at a shallower, lower-pressure, zone to produce a steam plus water mixture. In 2005, the IDDP ruled out using a location at Nesjavellir as a site for deep drilling because of environmental concerns.

5. Drilling magma at Krafla

In June 2009, the exploratory borehole IDDP-01 at Krafla, in north-east Iceland, the first deep well designed to explore a supercritical geothermal reservoir, failed to reach its target as drilling had to be terminated at a depth of only 2.1 km when magma unexpectedly entered the borehole (Hólmgeirsson et al., 2010; Pálsson et al., 2014).

The geothermal field within the Krafla caldera was chosen by the IDDP because supercritical conditions were thought to be likely there at less than 4 km depth (Friðleifsson et al., 2014b). Basaltic rocks in the main reservoir are altered to epidote-actinolite mineral assemblages, and temperatures can reach 340 °C at depths as shallow as 2 km. Produced geothermal fluids are dilute solutions of meteoric origin. However, during and after a recent eruptive episode, significant concentrations of magmatic CO_2 and HCl occurred locally (Ármannsson et al., 1989). The Krafla volcano has a 300,000 year long history of predominately basaltic volcanic activity, most recently during 1975–1984, the so-called Krafla Fires (Sæmundsson, 1991). A large magma chamber at 3 to7 km depth beneath the volcano was detected during the 1975–1984 eruptions by S-wave attenuation (Einarsson, 1978, 1991). An internal report to Landsvirkjun, based on magneto-telluric surveys (MT-TEM), mapped a low-resistivity zone at varying depths, believed to correlated with the magma body. The IDDP-01 well was sited above what was interpreted to be a depression between two shallow lobes of low resistivity in the MT-TEM model, where the depth to the magma chamber was estimated to be ~4.5 km (Friðleifsson et al., 2014b). The plan was to cement a production casing to ~3.5 km depth and then continue to 4.5 km in order to thoroughly explore supercritical conditions. The operating company, Landsvirkjun, was to fund drilling of the well to 3.5 km, and the IDDP consortium would then fund its completion to 4.5 km depth.

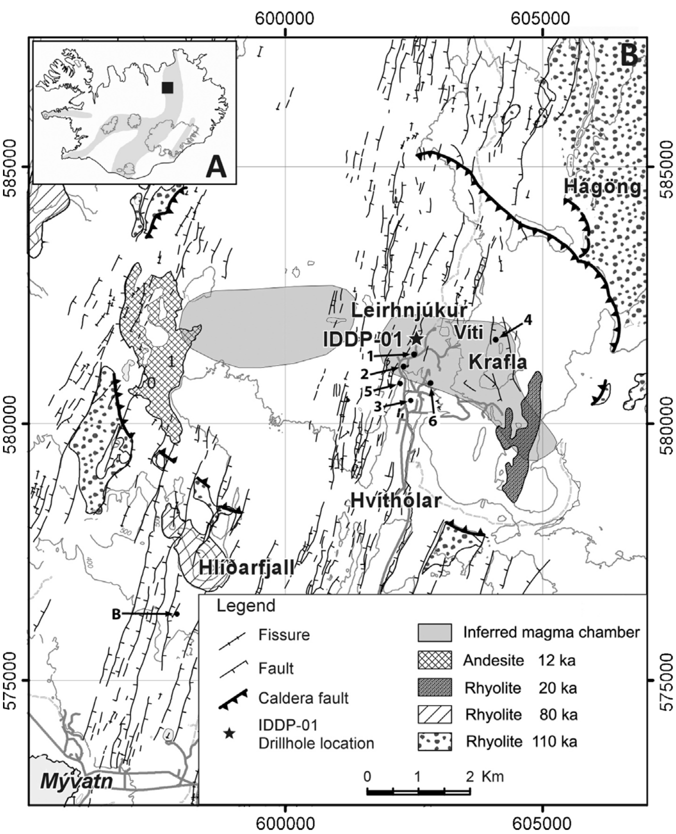

Fig. 3. (A) (inset) The filled square shows the location of Krafla in the neovolcanic rift zone in NE Iceland. (B) Simplified geological map of the Krafla volcano showing faulting associated with rifting and with the boundary of the caldera. The surface rocks are dominantly tholeiitic basalts and hyaloclastites, with lesser amounts of felsic rocks, whose ages are indicated (Data from Saemundsson, 2008). The location of the inferred magma chamber is from Einarsson, 1978. The location of the IDDP-01, is shown as a star, SW of the magma-phreatic explosion crater Víti. Numbered circles are other Krafla wells mentioned in the text, where 1 = KG-25, 2 = KG-04, 3 = KG-10, 4 = KJ-36 (deviated to NW), 5 = KJ-39 (deviated to SE), 6 = KJ-09, and B = location of the well in the Bjarnaflag geothermal field at Namafjall.

The well is sited within the Krafla caldera, between the Víti eruptive crater that formed at the outbreak of a series of basaltic eruptions in 1724–1729, and Leirhnjúkur, the site of the 1724–1729, and the 1975–1984 eruptive sequences (Fig. 3). IDDP-01 is 105 m north of the 2105 m deep well K-25 that was abandoned because of HCl corrosion of its casing, a recurrent problem in this area of Krafla (Einarsson et al., 2010). Such acid gases had been encountered at Krafla in a flow test of the well KJ-36 in December 2008. That well has a surface location about 700 m east of the IDDP-01 well but, unlike the IDDP-01 which is vertical, KJ-36 is inclined to the NW for a length of 2500 m to intersect fissures associated with an eruption in 1724 AD and a second 2000 year old eruptive fissure 250 m further west. It produced high-pressure, superheated, steam that condensed by mixing with two phase fluid from shallower feed zone and contained HCl at a concentration of 400–900 mg/kg. Experience from other wells indicates that hot saturated and/or superheated steam, that when condensed is acidic, can be produced from deeper than 2.2 km depth over a wide area in the vicinity of the site of the IDDP-01 well (Einarsson et al., 2010).

In the spring of 2009, drilling of the IDDP-01 exploratory borehole progressed reasonably well until 2066 m depth when drilling progress became abnormally slow due to multiple problems, including partial collapse of the borehole causing the drilling assembly to get stuck several times. Below 2000 m, the rocks recovered were almost unaltered basalt dikes and fine-grained, partially granophyric felsite (Mortensen et al., 2014; Schiffman et al., 2014). In this zone the drilling assembly became irretrievably stuck twice, first at 2093 m and then at 2096 m, requiring two side tracks (Hólmgeirsson et al., 2010; Pálsson et al., 2014). In late June 2009, the reason for these acute drilling problems became apparent; we were drilling through the contact zone of a magmatic intrusion. On the third leg, at 2104 m depth, the rate of penetration and the torque increased and the drill bit began sticking. When the drill string was pulled up a few meters and lowered again, the hook load suddenly declined, drill torque increased dramatically and the drill bit was stuck again at 2095 m. When full circulation of drilling fluids was restored, it became clear that rhyolitic magma had flowed into the open drill hole and had quenched to glass. At first white pumiceous glass cuttings were returned, followed by much more abundant, dark brown, bubble-poor obsidian glass (Mortensen et al., 2014). After freeing the drill string and running in again, the top of the fill was at 2077 m. It was clear that magma had filled at least the lowest 10 m of the hole.

If this rhyolite body was intruded at the time of the 1975–1984 basaltic eruptions and if it cooled conductively, for it to be still molten the intrusion must be at least some tens of meters thick (Axelsson, 2014). This intrusion was not detected by earlier geophysical exploration or by drilling in the nearby geothermal wells, K-25 and K-36, both of which are deeper than the IDDP-01. In retrospect it is apparent that the drillhead assembly in the first two legs of the IDDP-01 well had also became stuck in magma, but without return of drill cuttings so that the magma was not sampled.

As described elsewhere in this special issue of Geothermics (Pálsson et al., 2014), the IDDP-01 was completed at a final vertical depth of 2072 m with a slotted liner to produce through a 9 5/8 in. casing from the apparently 500 °C contact zone above the intrusion (Axelsson, 2014). In January 2010, an attempted pressure and temperature logging run encountered a constriction developed in the casing at a depth of 690 m that prevented passage of the logging tool. Subsequent flow tests of the well still produced dry superheated steam with a temperature of up to 450 °C, but at subcritical pressures, given the shallow depth of the heat source. In spite of the restriction in the casing, the steam flows at a rate sufficient to potentially generate between 25 and 35 MWe of electricity, depending on the turbine configuration that would be used (Ingason et al., 2014).

6. The rhyolite magma

As the nature, analysis, and origin of the rhyolitic magma and the rocks in the upper contact zone above the magma in the IDDP-1 have been reported by Elders and Friðleifsson (2010), Elders et al. (2011), Zierenberg et al. (2013) and Schiffman et al. (2014), they will be described only briefly here. The quenched magma is primarily a poorly vesiculated, sparsely phyric, black, subalkaline rhyolitic obsidian with high silica (75.1 wt.%) and low TiO_2 (0.3%) (Elders et al., 2011). The sparse phenocrysts include titanomagnetite, plagioclase, augite and pigeonite, with minor amounts of apatite, and scarcer zircon and pyrrhotite. Pyroxene geothermometry indicates that the temperature of the magma exceeds 900 °C. Paired compositions from the cores of pyroxene crystals indicate crystallization temperatures of 930–990 °C, whereas the compositions of the rims suggest 890–910 °C (Elders et al., 2011; Zierenberg et al., 2013).

The rhyolite glass contains ~1.77 wt.% H_2O and 85 mg kg^{-1} of CO_2, independent of the degree of vesiculation. The high OH to H_2O ratio suggests that the magma was quenched at temperatures between 760° and 940 °C. The calculated saturation pressure of this magma at 900 °C would be 39 ± 6 MPa. However, hydrostatic pressure at 2100 m must be about 21 MPa (the pressure of a cold water column), and lithostatic pressure should be >56 MPa (for an overburden with a density of 2.7). It appears therefore that the pressure

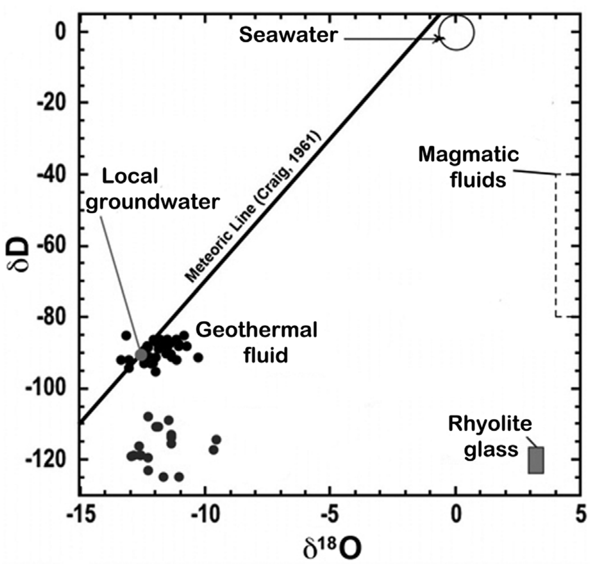

Fig. 4. The average hydrogen and oxygen isotopic composition of rhyolite glass from IDDP-1 compared to geothermal epidote and other potential sources at Krafla. Also shown are the $\delta^{18}O$ and δD of local groundwater in the Krafla geothermal system, the meteoric water line, seawater, and the range of values generally accepted for magmatic fluids (Pope et al., 2009; Craig, 1961).

of the magma at intrusion was between hydrostatic and lithostatic (Elders et al., 2011). The drill bit apparently penetrated an impermeable zone near the magma interface. There have been earlier speculations that pressures at a magma–hydrothermal interface could oscillate between lithostatic and hydrostatic (Fournier, 2007), particularly at supercritical conditions (Norton and Dutrow, 2001), but we are not aware of any previous instance where this was observed directly by drilling.

Stable isotope data (Pope et al., 2009; Elders et al., 2011), summarized in Fig. 4, strongly support the interpretation that the bimodal basalt-rhyolite volcanism at Krafla is the product of basalt intrusions partially melting hydrothermally altered basalts at depth. Hydrogen isotope ratios in the rhyolitic glass demonstrate very low values of $\delta D = -121 \pm 2‰$, remarkably similar to those of hydrothermal epidotes from Krafla geothermal wells (Pope et al., 2009). Such hydrogen isotope ratios could not be produced from hydration by local geothermal waters or by mantle-derived waters; instead, they indicate that the rhyolite magma inherited hydrogen from hydrothermally altered basalts. Similarly, the oxygen isotope ratio of the rhyolite glass ($\delta^{18}O = 3.1 \pm 0.06‰$) is also consistent with melting of hydrothermally altered basalt. Similar anomalously low $\delta^{18}O$ values observed in unaltered surface rhyolites at Krafla are consistent with low $\delta^{18}O$ hydrothermal alteration minerals in the subsurface also contributing oxygen to those rhyolite lavas (Pope et al., 2009). These stable-isotope data strongly support interpretations based on major- and minor-element chemistry that the bimodal basalt-rhyolite volcanism at Krafla is the product of basalt intrusions partially melting hydrothermally altered basalts at depth (Jónasson, 2007; Elders et al., 2011; Zierenberg et al., 2013).

7. Additional evidence for shallow magma at Krafla

Reaching magma at such a shallow depth was unexpected, although perhaps not entirely unprecedented. Larsen et al. (1979) described how, in 1978 at the onset of the Krafla Fires, the 1978–1984 eruptive series, 2–3 m^3 of basaltic tephra were ejected from a geothermal production well in the Bjarnaflag geothermal field, at Namafjall, some 5–6 km south of the main production field of Krafla (location B in Fig. 3B). A second instance of intrusion into an existing geothermal well during the Krafla fires may also have occurred. During a cleaning operation of well KJ-09 in Leirbotnar field (location 6 in Fig. 3B), fresh basaltic glass was encountered (Guðmundsson et al., 1983). Additional direct evidence of the presence of shallow magma in the geothermal system was found in the well KJ-39, 2.5 km south east of the IDDP-01 (location 5 in Fig. 3B). In November 2008 while drilling at a depth of 2.6 km, a temperature of 386 °C was measured within the drill string while circulating drilling fluid. When tripped out, the drillhead assembly contained quenched rhyolitic glass (SiO_2 74 wt.%), with relict crystals of fresh basaltic minerals (Mortensen et al., 2010).

Mortensen et al. (2014) point out that superheated steam, that when condensed is corrosive, is present in a wide area of the Krafla Geothermal Field. For example, near the IDDP-01 the wells KG-25, KG-04 and KG-10 (locations 1, 2, and 3 in Fig. 3B) and the well KJ-36 deviated to the northwest, just east of the explosion crater Víti (location 4 in Fig. 3B) may also be heated by the same, or a similar, shallow rhyolite intrusion. This seems to indicate that molten, or recently crystallized, shallow intrusions responsible for superheated conditions are fairly widespread at Krafla and this could have important implications for the development of its geothermal resources. Perhaps, in the future, very high-enthalpy useful energy could be extracted economically by drilling directly into these shallow magmatic intrusions.

8. Magma energy

Among the many thousands of geothermal wells drilled worldwide, it is perhaps surprising that encounters with magma are extremely rare. Apart from Krafla, we know of only one previous instance of magma flowing into a geothermal well during drilling. In 2005 drilling in the Puna geothermal field in Hawaii encountered dacite magma at 2488 m depth (Teplow et al., 2009). The lower part of that well was abandoned, and it was completed as an injection well at 2124 m depth, well above the dacite intrusion.

For more than a decade, the US Department of Energy had a "Magma Energy Program" aimed at extracting high-enthalpy energy directly from magma, using a downhole heat exchanger (Chu et al., 1990; Eichelberger and Dunn, 1990; Hardee, 1982, 1988). After a nation-wide study (Luth and Hardee, 1980), the Long Valley Caldera of California was chosen as the optimum site in the USA to drill into magma. A well designed to reach a depth of more than 6 km was begun, but was abandoned before reaching its target depth due to funding problems (Bender-Lamb, 1991). Clearly Krafla is a much more attractive site to test the concept of magma energy, in spite of the problems encountered in drilling the IDDP-1 well. However it remains to be demonstrated that quenching and drilling into magma is technically and fiscally feasible and that it is possible to engineer a cracking front that propagates into the magma to enhance recharge and heat exchange.

9. Permeability at high temperatures

Just like their submarine equivalents, high-temperature hydrothermal systems on land seem to have an upper temperature limit of ~400 °C (Rybach and Muffler, 1981). This seems to imply that: (1) permeability effectively ceases at that temperature due to transitions from brittle to ductile behavior; (2) permeability is limited by self-sealing due to hydrothermal alteration at higher temperatures; or (3) temperatures are controlled by transitions from subcritical to superconvecting supercritical conditions.

A major concern in developing both supercritical and magmatic geothermal resources is the nature of permeability at high temperatures. The temperature of the transition from brittle to ductile or plastic behavior depends on the silica content of the rock, and the generally accepted temperatures for this transition to occur are about 380–400 °C in rhyolites or granites rocks and at 500–600 °C in basalts or gabbros (Byerlee, 1968; Fournier, 2007). However, in Iceland, seismic evidence indicates that fracturing persists to depths of ~8 km beneath the high-temperature geothermal systems in Iceland, where temperatures are estimated to be greater than 700 °C (Bjarnason, in Friðleifsson et al., 2003, pp. 73–78; Friðleifsson and Elders, 2005). Clearly fractures can form and persist for some period of time within rocks that should be deforming plastically in a longer time frame.

An example of a geothermal exploratory well that penetrated the brittle-plastic transition was illustrated by one of the most interesting, and ambitious, exploratory drilling projects of the last two decades. This was a 3.7 km deep exploratory borehole at Kakkonda, in the Hachimanti Geothermal Field, at Kakkonda Iwate Prefecture, Japan, that penetrated into a cooling granitic intrusion (Muraoka et al., 1998). This well penetrated an entire shallow hydrothermal convection zone, an entire contact metamorphic aureole, and part of a subsolidus cooling neo-granitic pluton (tonalite with a K-Ar age of 0.19 Ma) that is apparently the heat source for the hydrothermal system above. At 3100 m depth, where a 380 °C temperature occurred, a transition from brittle to ductile conditions was observed and the temperature gradient became conductive. Temperatures reached >500 °C at 3729 m, but at the bottom of the borehole the permeability was extremely low and the hole suffered rapid plastic deformation (Muraoka et al., 1998). For this reason, the drill hole was completed as a production well in the shallow hydrothermal system above. The bottom of the hole was dry; therefore, although the pressures and temperatures were in the supercritical regime, supercritical fluids were not observed.

Seismic data acquired in 2005 for the Reykjanes Peninsula in southwest Iceland show a clustering of seismicity beneath the geothermal areas of Svartsengi and Krýsuvík and a clear spatial relationship between areas of high seismicity and areas of low *Vp*/*Vs* ratios (Geoffroy and Dorbath, 2008). This pattern of seismicity provides strong confirmation that abnormally high fluid pressures may exist under some geothermal systems in Iceland. Geoffroy and Dorbath (2008) suggest that this seismicity is linked to high fluid pressures at depth where hydrothermal fluids exist as deep as the base of the brittle crust. They further propose that these fluids are probably in the supercritical state with high pressures intermediate between hydrostatic and lithostatic. They suggest that a dual fluid reservoir exists. Down to 3 km depth the fluids are brines at boiling point conditions in a hydrostatic state that are convecting by thermohaline circulation. They infer that high-enthalpy, high-pressure, supercritical fluid exists in the deeper reservoir below 3 km. Such fluids dramatically increase the potential for rock fracturing by stress-corrosion micro-cracking (Hashida et al., 2001). Geoffroy and Dorbath (2008) further speculate that, during dilatational earthquake activity, denser cold fluids from the upper reservoir would recharge the lower reservoir, leading to separation of a vapor phase that carries heat into the upper reservoir. Similar processes may be involved at spreading mid-ocean ridges allowing seawater to efficiently cool the upper oceanic crust.

10. Wider applications of the IDDP concept

The broader implications of the IDDP are twofold; scientifically it will permit major advances in our understanding of active hydrothermal processes that are important on a global scale, and secondly, if the industrial aims are successful, the resulting technology could have impact on improving the economics of high-temperature geothermal resources in a wider region, and thereby make accessible larger sources of deep geothermal energy that hitherto have not yet been developed. If the IDDP is successful in showing that producing supercritical geothermal resources is technically feasible and economic, this concept could have wider applications worldwide wherever there are suitable young volcanic rocks. These occur along plate boundaries and at the head of mantle plumes, the so-called hot spots. In these regimes there is also the prospect of encountering still-molten igneous intrusions, as occurred in the IDDP-01 well at Krafla.

Because of the high costs of deep drilling, the logical places to start would be in high heat flow geothermal fields that have already been thoroughly explored by drilling to depths of 3 km and where the necessary infrastructure is already in place. Plans for deep drilling to explore for deeper, much higher enthalpy, geothermal resources are already underway in the Taupo Volcanic Zone of New Zealand, "Higher and Deeper Exploration Sciences" (Project HADES – www.gns.cri.nz/hades), and in Northeast Japan the "Beyond Brittle Project" (Project JBBP – www.jbbp.kankyo.tohoku.ac.jp/jbbp) is an ambitious program attempting to create an enhanced geothermal system (EGS) in ~500 °C rocks. The concept is to create an EGS project within a hot cooling pluton by using hydrofracturing to create a bowl-shaped heat exchange zone in which injected fluids would circulate, to be retrieved as superheated steam (Muraoka, personal communication, 2012 and 2013).

In addition to Iceland, New Zealand and Japan, there is an abundance of likely candidates in other countries that already have a well-established geothermal electric industry, such as Indonesia, the Philippines, Russia (Kamchatka), Italy, Mexico, and the western United States. For example, the geothermal systems near Larderello in Italy, the Geysers Geothermal Field in California, USA, and the Cerro Prieto Geothermal Field in Mexico are likely candidates.

Many members the geothermal community reacted favorably to a publication (Tester, 2006) that suggested that the greatest opportunity for future growth of geothermal resources lies in the development of "enhanced geothermal systems" (EGS). Several projects are underway, or planned, to drill into 200 °C at depths as high as 5 km and create permeability by hydraulic fracturing of granitic, or other low-permeability rocks. However, drilling to 5 km or less to produce from a supercritical regime in high heat flow systems or even from a magmatic intrusion, where that is possible, is obviously a more attractive target. If sufficient permeability and recharge are not present then hydrofracturing and injection could be viable options. At Krafla investigating the extent of the hot contact zone of the intrusion and eventually drilling one or more production and/or injection wells is a high priority. Krafla could one day become the site of the world's first enhanced geothermal system operating at, or near, magmatic temperatures. Thus the EGS concept may become an incremental stage in the development of the IDDP.

11. Scientific significance of supercritical hydrothermal systems

In addition to exploring for new and enhanced sources of energy, this series of IDDP boreholes in Icelandic geothermal fields, including a return to the seawater system at Reykjanes (Friðleifsson et al., 2014c), will allow a broad array of scientific studies involving water/rock reactions at high temperatures. These boreholes will be the first opportunity worldwide to investigate more directly the coupling of hydrothermal and magmatic processes in volcanic systems in a mid-ocean ridge-like environment.

Since the first discovery of black smokers on the Galapágos Rift in 1977, more than 300 sites of high-temperature hydrothermal venting have been discovered in the oceans (Beaulieu, 2010). It is evident that supercritical fluid-rock interactions are important in the overall heat and fluid budgets of mid-ocean ridges. It is clear that studying analogous systems on land in Iceland is much more practical than drilling from ship in 2–3 km of water. These supercritical zones are most important for the practical goals of the IDDP. It is predominantly there that mobile fluids are heated and interact chemically with their host, where most of the geologically important heat transport, chemical alteration, and hydrothermal ore formation take place, and where abundant supercritical fluid and/or superheated steam could be produced for power generation.

12. Sustainability and the IDDP

A widely used definition states, "*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 sustainable economic development, and with environmental sustainability. There are two main concepts: (1) Economic and social sustainability is development that maintains a certain level of human welfare. (2) Environmental sustainability is human interaction with the environment that coexists with essential ecological systems. Meeting the inherent time scale of sustainable development calls for long-term planning (at least 100 years), and, as far as geothermal development is concerned, harnessing deep seated renewable geothermal reservoirs seems to us logical and perhaps inevitable. Drilling into the roots of the existing geothermal systems will permit longer-term, and more sustainable development of the resources.

13. Summary and conclusions

The opportunities presented by the IDDP have the potential to yield important advances 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 (Hannington et al., 2012). The Icelandic energy industry has invited both industrial companies and the international scientific community to participate in the project. A major share of the costs of drilling wells as deep as 4.5 km is borne by industry, and the scientific program also benefits from the extensive practical experience of the industrial partners.

Amongst approaches to improve the economics of the geothermal industry, three are fairly obvious: (i) to reduce the cost of drilling and completing geothermal wells, (ii) to cascade the usage of thermal energy by using the effluent water for domestic heating and for industrial processes, (iii) to reduce the number of wells needed by increasing the power output of each well, by producing supercritical fluids and/or dry superheated steam. The potential impact of utilizing geothermal resources at supercritical conditions could become quite significant. Not only would this call for re-evaluation of the geothermal energy resource base on a local scale, but also on a global scale. Accessing supercritical fluids within the earth could yield a significant enlargement of the accessible geothermal resource base.

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