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Supercritical fluids, Iceland Deep Drilling Project, Reykjanes geothermal system - black smoker analog

ABSTRACT
The Iceland Deep Drilling Project (IDDP) is being carried out by an international industry-government consortium in Iceland, in order to investigate the economic feasibility of producing electricity from supercritical geothermal reservoirs. Modeling suggests that producing superheated steam from a supercritical reservoir could potentially increase power output of geothermal wells by an order of magnitude. To test this concept, the consortium planned to drill a deep well in each of three different geothermal fields in Iceland, namely, Krafla, and at the Hengill and Reykjanes fields in SW-Iceland. In 2009 the drilling of the first deep well, IDDP-1, was attempted in the active central volcano at Krafla in NE Iceland. However the drilling had to be terminated at 2.1 km depth when 900°C rhyolite magma was intersected. The well, IDDP-1, was highly productive, capable of producing some 25 MW\textsubscript{e} from 380°C superheated steam during a flow test undertaken in 2010. The well was shut in August 2010, to allow the wellhead and surface equipment to be modified to withstand corrosive fluids. Starting in May 2011 flow-testing, wet and dry scrubbing of the steam and a test of a heat exchange system will be conducted. This flow test is expected to last through the rest of 2011. Preliminary results from these tests should be available to report at the GRC Annual Meeting in October 2011. The second deep IDDP well, IDDP-2, could possibly be drilled to 4-5 km depth as early as 2012-2013, into the saline Reykjanes high-temperature field in SW-Iceland. The design of the IDDP-2 well will benefit from lessons learned during drilling of the IDDP-1 at Krafla.

Here we review the geological and geophysical characteristics of the Reykjanes field, based on pre-existing and very recent data. According to both 1 dimensional and 3 dimensional interpretations of the new magnetotelluric (MT) data, the IDDP-2 site is located above a major heat source occurring at some 10 km depth.

Introduction
The IDDP was initiated 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), as well as Orkustofnun (OS), the National Energy Authority of Iceland. The same year the basis for the IDDP concept of drilling for supercritical water (374°C and 222 bars for pure water) was further explained at the World Geothermal Congress (WGC) 2000 in Japan (Friðleifsson and Albertsson, 2000).
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). Our modeling indicates that a well producing supercritical water could have an order of magnitude higher power output than that from a conventional high-temperature geothermal well (Friðleifsson et al., 2003; Friðleifsson and Elders, 2005). However to reach supercritical conditions requires deep drilling, even in areas of high heat flow.

In 2007, Alcoa Inc. (Alcoa) (an international aluminum company) joined the consortium followed by Statoil (an international oil and gas company) in 2008. In 2007 the three Icelandic power companies announced their commitment to drill at their own cost a 3.5-4.0 km deep well in each of three geothermal fields operated by them. These wells were to be designed so that they would be suitable for deepening to 4.5-5.0 km. The drilling of one of these wells as a joint IDDP project would then be funded by the consortium, with additional funds from international science agencies. The first well in the series, IDDP-1, was drilled in 2008-2009 at Krafla in North-East Iceland. The next wells, IDDP-2 and IDDP-3, were planned to be at Hengill and Reykjanes, respectively (Figure 1). These drilling plans, however, were jeopardized later that year due to the economic crisis in Iceland. Landsvirkjun (LV), however, kept to its commitment to drill the IDDP-1 well at Krafla in 2008 and 2009.

From the outset, the IDDP consortium welcomed the inclusion of basic scientific studies in the IDDP (Friðleifsson and Albertsson, 2003; Elders et al., 2001; Friðleifsson and Elders, 2005). The guiding principle was that the incremental costs of drilling and sampling for the science program, and their subsequent study, should be met by the scientific community.

In 2005, a well of opportunity for IDDP for deepening, RN-17 at Reykjanes, was lost during a flow test. In June 2006, after considering all options available, it was decided to move the IDDP operations to Krafla (Figure 1). The plan was to rotary drill the IDDP-1 down to 3.5 km depth and cement in the steel casings funded by Landsvirkjun (LV). Then the IDDP consortium would fund deepening the well IDDP-1 to 4.5 km into the supercritical zone, and take a number of spot cores for scientific purposes. However, as discussed below, IDDP-1 well could only be drilled down to 2.1 km depth where it intersected 900°C hot magma, which resulted in terminating the drilling operation (Friðleifsson et al., 2010; Elders and Friðleifsson, 2010)

### The IDDP-1 Well at Krafla, NE-Iceland

The IDDP-1 well in Krafla was completed by Landsvirkjun (LV), the National Power Co., to 2.1 km depth in 2009. The drilling operation and the first results from that well have been described (Friðleifsson et al., 2010; Elders et al., 2010; and Elders et al., 2011). The general well design (Bórhallsson et al., 2010) had to be modified during drilling of the IDDP-1 well because of extensive problems during drilling of that well (Hólmegeirsson et al., 2010). In essence this involved inserting and cementing of the 13 5/8 inch anchor casing at 1949 m depth instead of the scheduled 2400 m depth. In retrospect it became apparent that these drilling problems were due to the proximity of a magmatic intrusion and drilling was terminated when molten magma flowed into the well at 2104 m depth. The well was completed with a 9 5/8 inch cemented sacrificial casing to 1960 m depth, followed by a perforated 9 5/8 inch liner down to the bottom fill (19 m), which was composed of quenched volcanic glass above the magma at 2104 m.

Spot coring in the IDDP-1 well, using NSF funds, was attempted but failed due to lack of well stability. However, earlier in 2008 an extremely successful spot coring test (funded by ICDP and NSF), had been undertaken in well RN-17B at Reykjanes. The core barrel was designed by the IDDP technical team and specially built for IDDP (Skinner et al., 2010 a, b), mostly funded by the ICDP award to the IDDP program.

In August 2009, after the well had been cooled by injection of copious amounts of cold water at 30-40 L/s during and after drilling, the IDDP-1 was allowed to heat. By January 2010 projections from repeated measurements of the rate of heating indicated that, by October 2010, undisturbed conductive heat transfer should increase temperatures to ~ 500°C at the bottom of the casing. In March 2010 a staged series of flow tests began, planned to continue for some months. By August 2010 the well was still heating under flowing condition and was producing dry superheated steam at 380°C at 18-19 bars wellhead P, and at a flow rate of 25 to 30 kg/s, potentially corresponding to some 25 MW e production capacity. The future of the well is still being evaluated and a series of tests will be performed during the 2011 flow tests and pilot production studies, briefly discussed below.

Well IDDP-1 has now been shut in since August 24, 2010. The flowline needed to be re-designed in an attempt to decrease flow velocity and thereby minimize erosion of the piping. Some minor modifications were also needed on the wellhead and flowline to prepare for the planned tests which include: (i) wet scrubbing of the steam; (ii) dry scrubbing of the steam; (iii) heat exchanger experiments; (iv) acid corrosion and particle erosion tests; (v) chemical monitoring; and (vi) reservoir response monitoring. The flow test will begin in early May 2011 and some results should be available for briefing at the GRC meeting in October 2011.

### The IDDP-2 at Reykjanes in SW Iceland

The HS ORKA HF energy company (HS), is the operator of the Reykjanes field, and is currently generating 100 MW e power by two high-pressure steam turbines, each rated at 50 MW e. Expansion plans involve adding a third 50 MW e steam turbine and an additional 30 MW e low pressure 2nd flash brine plant. This will require several new deep and shallow steam wells within the next 2-3 years, as well as deep re-injection wells. One of the planned deep production wells could become the IDDP-2 well. After testing, the IDDP-2 would, eventually, be used as a make-up well (or a reserve well), if for some reason the deep drilling experiment does not lead to economic production. Meanwhile, HS is considering finding funds for drilling the IDDP-2, a fully cased well of 3.5 km depth. This well would be available for the IDDP consortium for deepening to 4-5 km depth by using 8½” tricone bits and completed by inserting a 7” perforated liner, if feasible. Spot coring for scientific studies will be attempted below 2.5 km depth, to the extent that scientific funds allow at that time.
The chief motivation for HS Orka to undertake such a challenging drilling operation is to address several basic questions:

1. Where is, and what is the nature of the base of the convecting Reykjanes hydrothermal reservoir? Is it heated by superheated steam from below?
2. Can the deep heat sources be exploited by injecting fluid into the hot rocks beneath the most productive part of the well field?
3. Will productive permeability be found at these great depths within the approximate center of the fault-related up-flow zone?
4. Does a supercritical reservoir exist at 4-5 km depth under Reykjanes or does it lie deeper still?
5. What is the nature of the ultimate heat source of this saline ocean floor related hydrothermal system; is it a sheeted dyke complex or a major gabbroic intrusion?

Temperature logs after drilling should throw some light on these issues. In the event production of supercritical fluid is not achieved by the IDDP-2 well, the well could be converted either into a conventional production or an injection well, either by side-tracking out of the casings at conventional depths, or using unconventional depths for deep injection. With either end result, this experiment should result in a make-up or reserve buildup of volcanic strata within a submarine environment (e.g. Franzson et al., 2002, Franzson 2004, Friðleifsson and Richter, 2010). The deepest stratigraphic units, from 3 km depth up to some 1400 m are composed of pillow basalt formations, erupted in relatively deep waters. Then a few, but apparently subaerial lavas of Pleistocene age, occur in the stratigraphic sections in some of the wells up to ca 1100 m depth. From there up to ca 400 m depth the eruptive units are characterized by relatively shallow water lithology composed of phreatic tuffs interbedded with shallow marine fossiliferous sediments. From there and up to ca 60 m depth, sub-glacial and/or submarine hyaloclastite formations characterize the stratigraphic succession, while the youngest of these form low profile hyaloclastite ridges poking up through a Holocene lava flow series (Figure 2, overleaf). From the lithology, the subsidence rate was estimated to average some 0.6 cm/year, while the extension rate of the slow spreading Reykjanes ridge is about 1.8 cm a year (Friðleifsson and Richter 2010). The intrusive rock intensity within the sheeted dike complex varies from well to well, but often the dikes appear in relatively dense dike swarms, 100-200 m thick, with thick intervening intervals of dike-free pillow basalt formations (e.g. Friðleifsson et al., 2005, Helgadóttir et al., 2008). The volcanic activity acts as a heat source for the geothermal system since considerable portions of the magma cools within the system as intrusions. Frequent, but generally small, earthquakes cause movements on the fractures and maintain good permeability.

The hydrothermal alteration pattern has been studied in all drillholes, and reported in numerous papers along with the lithologic logs and other data. Only some of these are included in the reference list below (e.g. Franzson et al., 2002, Franzson 2004, Friðleifsson et al., 2005, Helgadóttir et al., 2009). In addition, and in relation to the IDDP, quite a few more detailed mineralogical studies have added knowledge on the secondary mineralogy of the Reykjanes field (e.g. Freedman et al., 2008, Pope et al., 2009, Marks et al., 2010). The alteration pattern is characterized by zeolite and greenschist facies mineralogy. Epidote occurs at exceptionally shallow depth at Reykjanes, or
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just below some 300 m depth in some cases, representing fossil Pleistocene thermal condition within the geothermal system, when an ice-sheet added to the hydrostatic pressure. The present-day saline hydrothermal system was at that time fed by meteoric fluids, as seen from isotopic- and fluid inclusion studies (Sveinbjörnsdóttir et al. 1986, Franzson et al. 2002, Pope et al., 2009). Smectite-zeolite facies mineralogy occurs from the surface down to the epidote zone in some cases. Epidote and mixed-layered-clays may coexist from there down 500 m depth or so, where chlorite-epidote zone takes over down to ca 1200 m, followed by epidote-actinolite zone down to 3 km depth, apparently (e.g. Friðleifsson et al., 2005). 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 that is transitional into amphibolite grade alteration. 87Sr/86Sr ratios within alteration minerals were observed to significantly shift towards seawater values with increasing depth, and therefore confirming deep penetration of seawater into the Reykjanes system (e.g. Friðleifsson et al., 2005). The highest temperature measured so far, 345°C, is from the bottom of well RN-17B, at about 2.8 km true vertical depth, and the temperature profile above still represents an adiabatic thermal gradient. The temperature distribution within the Reykjanes field is better viewed on an isothermal map at shallower depth, as show in Figure 4 for

Temperature-Pressure Distribution and Seismic Activity

Within the drill field, from ca 500 m down to some 900 m temperature and pressure follow the boiling point curve (see e.g. Figure 4), as a response to steam bubbles ascending from depths carrying heat upwards through the geothermal system. Intermittently, boiling conditions may reach up to the surface within the steam heated fumarole field, which is surrounded by a cold groundwater system, that in turn is composed of a thin film of meteoric water (inland), that floats on cold ground-seawater which filters through the porous rocks of the Reykjanes peninsula (e.g. Sigurðsson 2010). Intermittent seismic activity commonly results in vigorous boiling and geyser activity on the surface, that may last for a decade or two according to historical records. The last seismic episode occurred in 1967, and the 2nd last in 1919. During such seismic events related to seafloor spreading and normal faulting, the deep underlying liquid dominated geothermal system is brought to boiling conditions due to a temporary pressure drop in the deep reservoir. Geothermal exploitation has a similar effect by enhancing boiling in the deep reservoir. This has resulted in vigorously increased fumarole activity on the surface, as observed in the wake of the 100 MWe Reykjanes power plant commissioning in 2006. The relatively dense tuffaceous and sedimentary succession at 400-1000 m depth forms a kind of a cap rock on the deep reservoir, made denser by calcite, anhydrite and quartz mineralization. Steam to some extent manages to rise up through fractures, but a dry steam cap has already developed at ~ 900-1100 m depth in the center of the geothermal field.

Below 900 m depth, the Reykjanes system is liquid dominated with temperatures rising along an adiabatic thermal gradient from some 270-290°C up to 320°C in a freely convecting hydrothermal system. This extends down to 2.5 km depth, at least (e.g. Figure 3), but with increasing depth the temperatures are expected to eventually rise towards magmatic temperatures. Exactly how, and at what depth, is simply not known at present, so modeling might be of help. Possibly the change from adiabatic gradient to a conductive thermal gradient rising towards magmatic temperatures, could occur over a relatively short depth interval, while the path of the temperature increase could be quite different. Incremental steps between convective and conductive heat paths could also be the case and other scenarios are quite possible. The highest temperature measured so far, 345°C, is from the bottom of well RN-17B, at about 2.8 km true vertical depth, and the temperature profile above still represents an adiabatic thermal gradient. The temperature distribution within the Reykjanes field is better viewed on an isothermal map at shallower depth, as show in Figure 4 for

Figure 2. Geological of the Reykjanes peninsula map (from Saemundsson 2011), which is mostly covered by Holocene lavas. NE-SW trending subglacial hyaloclastite ridges, less than 20,000 year old, poke up through the lava field at Valahnúkur-Vatnshell, and Raubhólar-Sýrfell. Eruptive fissures occur on both side of these ridges, the older one on the east side from Skálafell to Melur onwards, and the younger one on the west side, called the Stampar eruptive fissure zone. The youngest eruption there dates back to 1226 AD. Drillhole locations and well trajectories are also shown. The proposed site of the IDDP-2 well is between well RN-14B and RN-9, marked by x. The red line shows the extent of low resistivity at 800 m depth.
In 2008, HS Orka hf, recruited ISOR to experiment with MT-survey profiling at Reykjanes-Eldvörp-Svartsengi geothermal fields. The survey gave quite promising results along the test profiles (Rosenkjær and Karlsdóttir 2009). Following that a more detailed MT-survey was undertaken at Reykjanes in 2010, which immediately revealed quite interesting results, exemplified by Figures 5 and 6 (from Karlsdóttir and Eysteinsson, 2010).

The low resistivity image at 10 km depth under Reykjanes can be interpreted to represent a deep seated heat source of some sort, either a large cooling magma body (gabbroic) at 1600 m depth. For comparison, also shown in Figure 4 are MT resistivity contours at 1600 m depth, rising from some 5 ohmm up to some 18 ohmm. The 13 ohmm contour forms a kind of a ridge between the >300°C thermal peak on the east side and the <260°C low on the west side. Possibly, close attention to 3D MT pattern could be used to deduce the likely thermal condition with increasing depth, while such a study is not available at present. The >300°C contours in Figure 4 form a peak around well RN-10 and a NE-SW ridge from the fumaroles field east of well RN-17 towards wells RN-12 and the other wells just east of the proposed site for the IDDP-2 well.

**Geophysics**

Since the 1970s, surface resistivity surveys have been carried out in the Reykjanes field and surroundings. The earliest ones were direct current (DC) methods with Schlumberger configuration, but the later were TEM (transient electromagnetic), and then very recently MT (magnetotelluric) surveys. The early surveys delineated a low resistivity field centered on the furmarole field. The interpreted low resistivity field at 800 m depth has an areal extension close to 10 km² (red line on Figure 2). The shape of the surfacing resistivity structure indicated a main upflow zone along the older NE-SW eruptive fissure zone intersected by shorter N-S trending upflow zone in the central part of the field (Karlsdóttir, 2005).

Until very recently, MT-surveys have not been applied in near shore environments in Iceland. The benefit of an MT survey is to image the upper crustal resistivity structures down to depths of 20-30 km or more. In 2008, HS Orka hf, recruited ISOR to experiment with MT-survey profiling at Reykjanes-Eldvörp-Svartsengi geothermal fields. The survey gave quite promising results along the test profiles (Rosenkjær and Karlsdóttir 2009). Following that a more detailed MT-survey was undertaken at Reykjanes in 2010, which immediately revealed quite interesting results, exemplified by Figures 5 and 6 (from Karlsdóttir and Eysteinsson, 2010).

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**Figure 3.** Temperature profiles from well RN-12 and well RN-15. They are typical for the temperature distribution within the upper part of the geothermal system at Reykjanes, rising to some 270-290°C at 1 km depth and then only by some additional 10-20°C for the next 1.5 km.

**Figure 4.** A map showing drill hole locations (Rn-number – and apparent location of inclined wells at 1600 m depth, e.g. Rn-22s). The isotherms drawn are based on well temperature-logs and evaluation of the formation temperatures at 1600 m depth. The isotherms show a cooling “pond” at well RN-16 (~255°C) and a thermal peak at RN-10 (~310°C). The grayscale shades show MT-resistivity contours from <5 ohmm to ~18 ohmm. The potential location of IDDP-2 is shown by a star close to Rn-14.
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The approximate location of IDDP-2 is inserted by a star on Figure 5 and by a black arrow down to 5 km in Figure 6. One possibility to interpret Figure 6 is to postulate that a 5 km well would reach the bottom of the conventional convecting hydrothermal system, and that the thermal plume above the heat source at 10 km could be composed of either supercritical or superheated steam, conveyed upwards along the main fracture system. For the time being, we conclude this discussion by referring back to the IDDP feasibility report (Friðleifsson et al 2003) for consideration, where interpretation of the seismic character at Reykjanes gave our seismologist (Ingi P. Bjarnason) reason to estimate the depth to the brittle/ductile boundary at Reykjanes could be close to 6 km at Reykjanes, semi-brittle depth 4-5 km, and extrapolated temperature at 5 km depth close to or above 575°C.

Conclusions

The site selection for the IDDP-2 drillhole is under review. The prime candidate is essentially the same as the 1st priority site suggested for the Reykjanes field in 2003. More recent drillhole data and new MT surveys have amplified the justification for selecting that site. Deep drilling to 4-5 km depth is an important part of the HS Orka hf exploration strategy for enhanced power production, either by direct use of high energy steam, or by attempting to enhance the field performance by re-injecting geothermal fluid deep into “super” hot rocks. HS Orka has plans to increase power production at Reykjanes from the current 100 MWe to 150 MWe by adding a 3d turbine and several new production wells. The realization of the IDDP-2 well at Reykjanes may well fit it into the drilling program for the expansion of the Reykjanes power plant.

The next phase of flow testing and pilot studies for energy production from the IDDP-1 well at Krafla will be concluded in 2011, including wet- and dry scrubbing of the steam, heat exchange experiments and other studies. The IDDP-1 well appears capable of some 25 MWe production from superheated steam heated by a shallow level magma body 20 m below the bottom of the well. The conclusion of these experiments is awaited with some excitement as it may lead to a new methodology of power production at Krafla. In the event that the IDDP-1 well turns out not to be sustainable for production, the option for creating the world hottest EGS system would still be open.

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