

Iceland Deep Drilling Project (IDDP): Drilling Targets for Supercritical Fluid

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Abstract

This paper on the IDDP is one in a series of five in this conference volume. The primary objective of the IDDP is to find supercritical hydrous fluid at drillable depths, at 450-600°C, and to study its potential energy and chemical compositions. This is to be accomplished by drilling to depths of 5 km or less. Cemented casings to 3.5-4 km depth are necessary to case off the upper part of the hydrothermal system at subcritical condition. In this paper we discuss the background for the drill site selection in the Krafla, Nesjavellir and Reykjanes high-temperature geothermal fields. During 2001-2002, available data on surface and subsurface geology, geophysics, geochemistry and environmental aspects of the three fields of concern has been evaluated in a feasibility study. Four to six potential drill sites have been considered in each of the high temperature fields. The priority order for the recommended drill site for the first IDDP well is Nesjavellir, Krafla, Reykjanes. The reason for this priority order is mostly the desire to encounter supercritical fluid at as shallow a depth as possible, and to obtain supercritical fluid as dilute as possible. The same order also has technical and cost benefits, while the international science community may just as well like to see the wells drilled in the reverse order. A decision on whether to drill the first well remains to be made.

Keywords: IDDP, Supercritical, Energy, Nesjavellir, Krafla, Reykjanes.

1 Introduction

Over the next several years the Iceland Deep Drilling Project, IDDP, expects to drill and test a series of boreholes that will penetrate supercritical zones believed to be present beneath three currently exploited geothermal systems in Iceland, Krafla, Nesjavellir and Reykjanes. This requires drilling to depths greater than 4 to 5 km, in order to produce hydrothermal fluids at temperatures of 450 to 600°C.

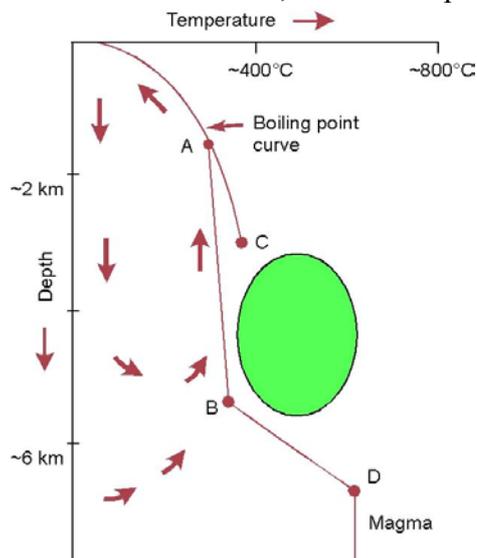
A two-year feasibility study was launched in early 2001 and concluded in early 2003. The report is divided into Part 1 on *geosciences and site selection* (Friðleifsson et al., 2003), Part 2 on *drilling technology* (Thórhallsson et al. 2003), and Part 3 on *fluid handling and evaluation* (Albertsson et al., 2003). This paper deals mostly with the results of Part I of the Feasibility Report, focussing in particular on the potential drillsites for 4-5 km deep boreholes within the Nesjavellir, Krafla and Reykjanes fields.

2 Prerequisite for siting an IDDP drillhole

A prerequisite for a successful operation of IDDP is the selection of the IDDP drillsites. In view of the high project costs (Thórhallsson et al., op.cit), well location is especially vulnerable to failure. The general approach of the group dealing with well

siting in the feasibility study, was to play safe and recommend the best possible location for the first IDDP wells.

To explain the situation, a simplified convection model for a hydrothermal system is shown in Figure 1. The encircled green area in the figure shows the pressure-temperature field of interest to IDDP. Also shown is the Boiling Point with Depth Curve (BPD-curve) that governs the maximum temperatures attainable at all depths within liquid dominated hydrothermal fields, such as the Icelandic fields under consideration. If a hydrothermal fluid in a natural system is at boiling temperatures from the surface down, the critical point (C) would be reached at about 3.5 km depth.



Such temperature profiles are the most common in the Icelandic fields, at Krafla and Nesjavellir down to 2,2 km depth, and down to 1300 m depth at Reykjanes. At Reykjanes, a convection temperature profile, like the one between points A and B in Figure 1, may exist to an unknown depth from 1300 m depth onwards. Once available, new temperature data from well RN-12 at Reykjanes, which was drilled in late 22, may possibly change this assumption. As yet, bottom hole temperatures in wells RN-10 and RN-11 are not well known.

Figure 1. Simple conceptual model of a hydrothermal convection cell, and the field of interest to IDDP (encircled). Temperatures and depth scales are approximate.

If the temperature profile at Reykjanes follows a curve like A-B in Figure 1, supercritical temperatures will not be reached until at some unknown depth along a line like B-D, possibly occurring deeper than 5 km. In that case the IDDP goal of reaching supercritical conditions would not be met by a 4-5 km deep well. If this turns out to be the case for the Reykjanes system, the system might be just as suitable for conventional production as it is today, and a by-product of the deep drilling would be to enlarge the productive field by a factor of 2-3 by showing that the depth interval between 2.5 to 5 km depth is both permeable and productive. If the temperature profile along line B-D is at a shallower depth than 5 km, which may also be the case at Reykjanes, and is the case at Nesjavellir and Krafla, the field of interest to IDDP in Figure 1, will be cross cut by drilling. In exceptional cases, supercritical temperatures may possibly be reached at a shallower depth still, above 3.5 km, as was the case in well NJ-11 at Nesjavellir (Steingrímsson et al., 1990). In general, however, supercritical conditions in hydrothermal systems, open or connected to the surface, should not be expected at much shallower depths than 3.5 km. Therefore, in siting the first IDDP well, the safest ground for attempting a successful well, is to plan an intersection with supercritical conditions within a hydrothermal upflow zone below 3.5 km depth.

Hitherto, the deepest high temperature well drilled in Iceland is well RN-12 at Reykjanes, 2500 m deep. The hottest well experienced so far, is well NJ-11 at Nesjavellir, ~380°C, and a well KJ-7 at Krafla, > 340°C. Accordingly, little knowledge exists of the temperature distribution and permeation properties of the rock formation below the three wells fields. However, the existence of permeable rock

formations in brittle basaltic rocks at supercritical temperatures can be inferred from the distribution of hypocentre depths of seismic activity within the fields studied, and we consider quite important. Figure 2 shows the earthquake frequency with depth distribution for all the three locations, monitored during approximately one decade since 1991.

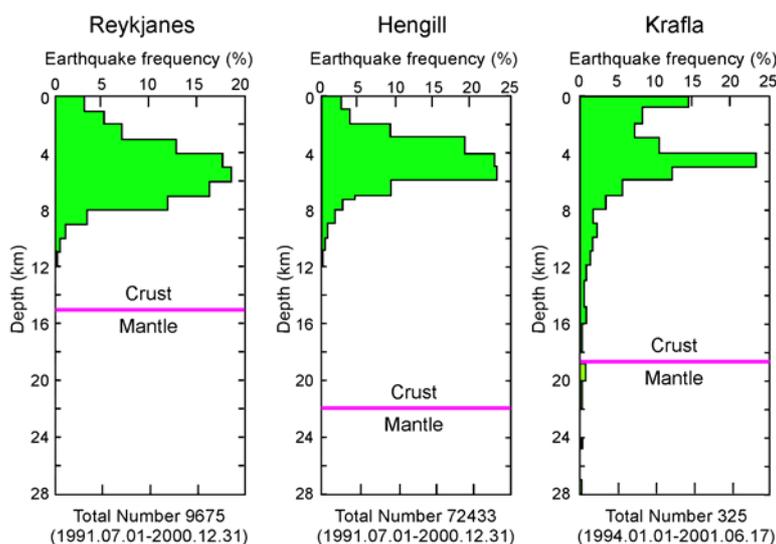


Figure 2. Earthquake depth frequency on the Reykjanes Peninsula, the Hengill and the Krafla areas.

In developed crustal genesis regions of Iceland, like at the proposed IDDP sites at Reykjanes, Krafla and Hengill, 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 frequency of earthquakes starts to decrease. It lies at 4-5 km depth under the IDDP sites. The depth above which 90% of the seismicity lies, is defined as the depth to the brittle-plastic boundary and the bottom of the seismogenic part of the crust. This boundary lies between 6 and 7 km below the IDDP sites 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 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/yr strain region like Iceland. None-double couple earthquakes in the midcrust 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 drillfields considered, range from 550 to 650°C at 5 km depth, +/- 100°C as shown in Table 1.

Table 1. Results of the study of seismicity and rheology.

| | 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 Temp. at 5 km Depth | ≥ 575°C | | |
| Semi-Brittle Depth | 4-5 | 5-6 km | 5-6 km |
| Brittle-Plastic Depth | 6 km | 7 km | 7 km |
| Rheology Temp. at 5 km Depth | 630-680±100°C | 550-600±100°C | 550-600±100°C |

3 The drillfields targeted for IDDP wells

The geological conditions of the three high temperature hydrothermal systems at Reykjanes, Nesjavellir and Krafla have been described (IDDP Feasibility Report, op.cit.). **The Reykjanes** system may adequately be described by a simple ophiolite model, a rift zone astride the Reykjanes Ridge. It contains saline fluid of oceanic origin. Apparently, the heat source is rather deep-seated, but from the seismic study, discussed above, the depth to the semi-brittle boundary, at about 600°C, may be at 4-5 km depth, and the depth to the brittle/plastic boundary at 750-800°C may be as shallow as about 6 km. Accordingly a drillhole targeted within the centre of the Reykjanes rift, e.g. by deepening of well RN-12, would enter the supercritical field above 5 km depth. Thus a temperature profile like B-D in Figure 1 would be encountered at 4-6 km depth. Nevertheless, there is conflict between this data and the present knowledge of the temperature distribution within the Reykjanes field as discussed above. Bottom hole temperatures from the 2.5 km deep well RN-12, are expected to be available within the next few months once the well has recovered from drilling, and will provide a better indication of the deep temperatures to be expected. In line with the discussion above, the most feasible drilling option for an IDDP well at Reykjanes would be deepening of well RN-12 by core drilling.

The well has the proper casing design, and can readily be deepened once a 10 3/4" casing has been inserted and cemented in. The 2000-year-old Stampar eruptive fissure has also been suggested as a feasible target for an IDDP well (Fridleifsson and Albertsson, 2000). Preferentially a 2.5 km deep well should be drilled there and compared to RN-12 before decision on the preferred site is made.

Table 2. Priority list of potential IDDP drillsites at Reykjanes.

| Drillsite | Priority | Temperature | Permeability | |
|----------------------------|----------|-------------|--------------|---------------------|
| Environ./geography/climate | | | | |
| RN-12 deep/no liner | 1 | High | High | Already 2500 m |
| Stampar step-out | 2 | High | High | Adequate – and a |
| RN-11 | 3 | High | High | Already 2300 m deep |
| Center elsewhere | 4 | High | High | Adequate |

The fluids encountered in the Reykjanes system so far are relatively saline and there is no reason to expect deeper fluids not to be saline too. For that reason the Reykjanes system resembles the ocean floor hydrothermal systems (black smokers), as well as saline fluids in most high-temperature systems worldwide. For both these reasons the Reykjanes system has the greatest international appeal, as compared to the Krafla and Nesjavellir systems both of which involve dilute fluids of meteoric origin.

Investigation of the **Hengill volcanic complex** indicates supercritical conditions at a shallower depth than 5 km, and perhaps at less than 3 km depth within **the Nesjavellir** field. The main hydrothermal upflow zone there, shown in a W-E

cross section in Figure 3, is the most feasible drilling target for IDDP. Because of an additional pressure head due to a 150 m higher elevation in Kýrdalur on the west side near well NJ-12, and the fact that two of the wells there are not being used by the Nesjavellir power plant, Kýrdalur is favoured as the optimum drill site for IDDP. In addition, assuming that the fluid in this main upflow zone at Nesjavellir is dilute fluid of the same type as observed elsewhere in the Nesjavellir system, the satellite nature of the system as an outflow from the Hengill center, makes it likely that the fluid has reached some sort of equilibrium after magmatic gases were emitted from a cooling magma reservoir. Therefore the fluids are not likely to be vicious. In addition, it is

likely that supercritical conditions at Nesjavellir can be reached at a relatively shallow depth. A new well near NJ-12 in Kýrdalur, is recommended, aiming to meet a supercritical zone at 3-4 km depth, while other options are considered.

The temperature of $>380^{\circ}\text{C}$ (Figure 3) was recorded in well NJ-11, which is believed to have met supercritical condition at a depth of 2.2 km (Steingrímsson et al., 1990). From the seismic study the depth to the semi-brittle boundary at $\sim 600^{\circ}\text{C}$ is believed to be some 5-6 km depth, and the depth to the brittle/plastic boundary 7 km. The potential drillsites at Nesjavellir are listed in order of priority in Table 3.

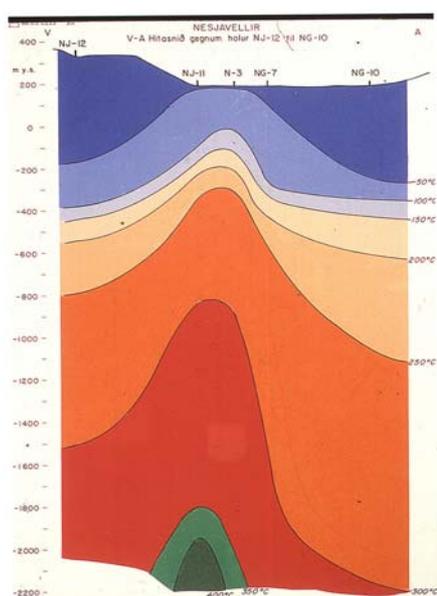
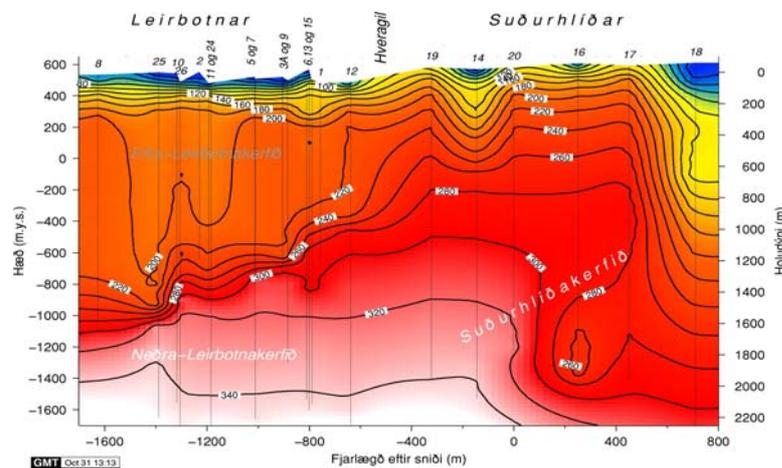


Figure 3. A measured and simulated temperature profile in a W-E cross section at Nesjavellir.

Table 3. Priority list of potential IDDP drillsites at Nesjavellir and Hengill .

| Drillsite | Priority | Temperature | Permeability | |
|-------------------------------|----------|----------------|----------------|----------------------------|
| Environ./safety./climate | | | | |
| Kýrdalur near NJ-12 | 1 | Higher | Higher | Depending but safe |
| Kýrdalur near NJ -17 | 2 | High | High | Depending but safe |
| Nesjavellir valley SE | 3 | Medium | High | Depending but safe |
| Nesjavellir valley NE | 4 | Lower | Medium | Depending but safe |
| Nesjavellir NJ-11 high P-T | 0 | Highest | Highest | Not safe yet due to |
| Hengill centre | ? | High | High | Undrilled field |
| Hengill south | 0 | Coldest | High | CP out of reach |

The heat source in **the Krafla** volcano, a cooling magma chamber below the drill field, is believed to be shallow and, accordingly, high temperatures are expected at quite shallow depths. The closeness to a magma chamber, and its recent activity, may possibly bring problems such as those encountered during the 1975-1984 volcanic episode. Then the hydrothermal fluids were seriously affected by volcanic gas, manifested in extensive deposits and acid fluids in some wells in a part of the drill field, even though the effect of the volcanic episode has diminished substantially in recent years. The reservoir fluid is apparently dilute and easy to handle but there are



signs from well KJ-12, which temporarily charged superheated fluid that at a greater depth there may exist more saline brine from which HCl-rich steam can boil. Magmatic gases only affected the westernmost drill field in Krafla, the Leirbotnar field, but left the Suðurhlíðar and Hvíthólar fields intact. The temperature distribution in the Leirbotnar and Suðurhlíðar fields is shown in Figure 4 in a W-E cross section (from Gud-mundsson, 2001). The main upflow zone at Hveragil, separating the two drill fields, Leirbotnar and Suður-hlíðar, is the most attractive drilling target for IDDP.

The temperature distribution in the Leirbotnar and Suðurhlíðar fields is shown in Figure 4 in a W-E cross section (from Gud-mundsson, 2001). The main upflow zone at Hveragil, separating the two drill fields, Leirbotnar and Suður-hlíðar, is the most attractive drilling target for IDDP.

Figure 4. Temperature distribution across the Krafla drill fields in an W-E cross section.

Looking at the temperature distribution within the Krafla drill field in Figure 4, it is pretty clear that only about 35°C higher temperature is needed to reach the critical point (C) below most of the drill field on the west side. In such a situation one might expect a minimum depth of 3.5 km or less to reach supercritical conditions. Most importantly, in a situation like this, an IDDP target should be an intersection with the main upflow zone, which has to be quite permeable. Preferentially, an intersection should be made at an unknown favourable depth, of 450-550°C, above the main heat transfer region between the heat source and the hydrothermal system. The same applies to the Nesjavellir and the Reykjanes drilling targets. In a priority order, the drilling targets in Krafla are listed in Table 4.

Table 4. Priority list of potential IDDP drillsites at Krafla.

| Drillsite | Priority | Temperature | Permeability | |
|------------------------------|----------|-------------|--------------|---------------------|
| Environ./geography/climate | | | | |
| Hveragil | 1 | High | Highest | Depending on siting |
| Hlidardalur | 2 | High | High | Adequate |
| Margin elsewhere north/south | 3 | Lower | Medium | Depending |

| | | | | |
|-----------------------------------|---|-------|-------|-----------|
| Center elsewhere summer/winter | 4 | High | Lower | Depending |
| KJ-18 summer/winter | 5 | Lower | Low | Depending |

4 Conclusion

While supercritical fluids are believed to exist deep within most of the active high-temperature systems in Iceland, only three or four exploited drill fields are sufficiently well studied to warrant siting 4-5 km deep wells to reach supercritical targets. Based on geoscience criteria only, the best locations, in order of priority, are Nesjavellir, Krafla, and Reykjanes. However, all three sites are attractive, and 4-5 potential drillsites have been selected within each of these fields. The highest ranked drillsites in each field are: (i) A new well near NJ-12 at Nesjavellir; (ii) A new well near Hveragil in Krafla; and (iii) Deepening of RN-12 at Reykjanes.

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5 References

- Albertson, A., Bjarnason J.Ö., Gunnarsson, T., Ballzus, C. and Ingason, K. (2003). *Part III : Fluid Handling and Evaluation, 33 p.* In: *Iceland Deep Drilling Project, Feasibility Report, G. Ó. Fridleifsson (ed.)*. Orkustofnun, OS-2003-007. Prepared for Hitaveita Sudurnesja Ltd., Landsvirkjun and Orkuveita Reykjavíkur.
- Elders W. A., Fridleifsson, G.O. and Saito, S. (2003). *The Iceland Deep Drilling Project: Its Global Significance.* (this volume)
- Fridleifsson, G.Ó., Albertsson, A. (2000). *Deep Geothermal Drilling at Reykjanes Ridge: Opportunity for an International Collaboration.* Proceedings of the World Geothermal Congress,, Kyushu-Tohoku, Japan, May 28-June 10, 2000. pp. 3701-3706.
- Fridleifsson, G.Ó., Ármannsson, H., Árnason, K., Bjarnason, I.P., and Gíslason, G. (2003). *Part I : Geosciences and Site Selection, 104 p.* In: *Iceland Deep Drilling Project, Feasibility Report G. Ó. Fridleifsson (ed.)*. Orkustofnun, OS-2003-007. Prepared for Hitaveita Sudurnesja Ltd., Landsvirkjun and Orkuveita Reykjavíkur.
- Gudmundsson, Á. (2001). *An expansion of the Krafla Power Plant from 30 to 60 MWe Geothermal Considerations.* *Geother. Resour. Counc. Trans.*, Vol. 25, August 26-29, pp.741-746.
- Steingrímsson, B., Guðmundsson, Á., Franzson, H. and Gunnlaugsson, E. (1990). *Evidence of a supercritical fluid at depth in the Nesjavellir field.* Proc. Fifteenth Workshop on Geothermal Reservoir Engineering Stanford University, Stanford California, January 23-25, 1990 SGP-TR-130, 81-88.

Thórhallsson, S., Matthíasson, M., Gíslason, T., Ingason, K., Pálsson, B., and Fridleifsson, G.Ó. (2003). Part II : Drilling Technology, 75 p. & appendix (45 p). In: Iceland Deep Drilling Project, Feasibility Report G. Ó. Fridleifsson (ed.). Orkustofnun, OS-2003-007. Prepared for Hitaveita Sudurnesja Ltd., Landsvirkjun and Orkuveita Reykjavíkur.