Borehole LN-10
Thorlákshöfn
Geological report

Gudmundur Ó. Fridleifsson
Steinar Th. Gudlaugsson

Prepared for Norsk Hydro
1998 OS-98071
Gudmundur Ó. Fridleifsson
Steinar Th. Gudlaugsson

Drillhole LN-10  Thorlákshöfn
Geological report

Modified English translation based on the Orkustofnun Report (OS-88020/JHD-11B):
Search for warm seawater and hot water at Thorlákshöfn
Results from the 1987 drillings
by
Ólafur G. Flóvenz, Grímur Björnsson, Sæþór L. Jónsson, Ómar Bjarki Smárason,
Gudmundur Ó. Fríðleifsson and Hrefna Kristmannsdóttir

Prepared for Norsk Hydro

OS-98071  Desember 1998

ORKUSTOFNUN: Kennitala 500269-5379 - Sími 569 6000 - Fax 568 8896
Netfang os@os.is - Heimasíða http://www.os.is
The report is a shortened geological account on borehole data from well LN-10 in Thorlákshöfn. It is prepared in relation to Norsk Hydro's 1998 VSP-experiment. Two other wells in Iceland will be studied in the project. Well LN-10 was drilled in 1987 to 1096 m depth in an attempt to acquire geothermal water for fishfarming but results were negative. Geologically Thorlákshöfn is sited on a postglacial lava on the eastern flank of the active riftzone in western Iceland. The drilling and design of LN-10 is described along with lithological and geophysical logs and temperature profiles of the well, aquifers or feed points encountered during drilling, injection packer and pumping tests as well as chemistry of the water. LN-10 yields 27°C hot brackish water from aquifers below 150 m depth, but a very limited amount of water can be obtained by pumping. According to well test and model a steady watertable will be reached within a day for a pumping rate of 10 l/s. A neighbouring well, LN-8, is also shortly described for comparison and complementation.
LIST OF CONTENT

1 INTRODUCTION 3
2 GEOLOGICAL SETTING IN THORLÁKSHÖFN 3
3 BOREHOLE LN-8 - overview 5
4 BOREHOLE LN-10 5
  4.1 Drilling 5
  4.2 Lithology 5
  4.3 Geophysical well logging 6
  4.4 Temperature and aquifers 10
  4.5 Injection packer test 13
  4.6 Pumping test 13
  4.7 Chemistry of the water 13
5 CONCLUSION 14

TABLES

Table 1. Chemical composition of the water from well LN-10. 14

LIST OF FIGURES:

Figure 1 Location map of well LN-10 4
Figure 2 Lithological log of well LN-10 8
Figure 3 Geophysical logs of well LN-10 9
Figure 4 Temperature logs of well LN-10 during drilling 11
Figure 5 Temperature logs of well LN-10 at the end and after drilling 12
1 INTRODUCTION

Translation of the borehole data from well LN-10 in Thorlákshöfn is done in relation to Norsk Hydro's 1998 VSP-experiment. Two other wells will also be studied by Norsk Hydro, well LL-03 at Laugaland in Holt, and well HH-01 at Haukholt in Hrunamannahreppur. A shortened geological report is presented here for well LN-10, and translation of irrelevant data from the original report is kept at minimum.

Well number LN-8 in Thorlákshöfn, was deepened to 300 m depth in 1987 with financial support from a programme set up by the Icelandic government to study natural conditions for fishfarming. No significant aquifers, or a warm water reservoirs, were encountered by well LN-8, and the thermal gradient of near 100°C/km led Orkustofnun, the consultant, to the conclusion that further drilling for considerable quantity of warm water would not be successful. Nevertheless, the fishfarmers decided to drill a deep well, LN-10, the same year. The new well ended at 1096 m depth, and was cased down to 150 m. The result was negative. The ground sea available from surrounding shallow wells had an annual mean temperature of 6-7°C, which was a bit too low for the landbased fishfarm, which later went bankrupt as most other fishfarms at that time.

Well LN-10 was chosen by Norsk Hydro and Orkustofnun as a suitable target for the VSP-project. The location of well LN-10 is shown in Figure 1.

2 GEOLOGICAL SETTING OF THORLÁKSHÖFN

The Thorlákshöfn village is sited on a postglacial lava on the eastern flank of the active riftzone in western Iceland, the Reykjanes-Langjökull rift zone (see index map in Fig. 1). The following 70 m of the substratum are composed of a highly permeable pillow lava formation, originating from onshore postglacial lavaflows, which were rapidly quenched by flowing into the sea. Interbedded with and underlining the pillow lava formation are shallow-marine sediments. The unconformable "basement" underneath is composed of late Pleistocene lavas and hyaloclastites.

No central volcanoes are known from the immediate vicinity. Thorlákshöfn is located south of the South Iceland Seismic Zone (SISZ) which extends from the western rift zone across the South Iceland lowlands towards mount Hekla in the Eastern rift zone. The SISZ zone is characterized by numerous short open fissures, which strike perpendicular to the SISZ zone in numerous en echelon arranged fissure systems. The SISZ zone is characterized by a left lateral fault movement at depth, linking the Western and Eastern Iceland rift zones. While different, the SISZ zone is, in a broader context, an analog to the right lateral Tjörnes Fracture Zone in North Iceland, between the Eastern rift zone and the Kolbeinsey midoceanic ridge further north. Confined within the SISZ zone are numerous low-temperature geothermal fields, like the Bakki field, utilized for domestic heating in the Thorlákshöfn village; the Thorleifskot field, used by the Selfoss village (see Fig. 1); the Laugaland field in Holt, used by villages further east, and other low-temperature hydrothermal systems.
Figure 1  The location of well LN-10, Thorlákhöfn
3 BOREHOLE LN-8 - overview

Well LN-08 was drilled in 1987 to 299.7 m depth, cased by 16” cemented casing from the surface to 19.7 m, by 14” casing from the surface to 72 m depth, slotted from 39-72 m depth. A partly slotted 11 ½” casing extends from 72 m to 118 m. A 12 ¾” open hole extends further down to 148 m depth, and finally an 8 ½” hole was sunk to 299.7 m depth. The well yielded 150-200 l/s of 6.8°C hot saline water.

Drill cuttings were not collected from 0-72 m, but according to the rig crew a continuous pillow lava formation is present in this interval. 72-78 m: basaltic lava. 78-114 m: basaltic breccia and pillow lava. 114-150 m: layered sediment, ranging in grain size from silt to agglomerate. 150-208 m: 5-6 lava flows, medium to coarse grained olivine tholeiites. 208-220 m: hyaloclastite, breccia at top but sandy tuff at the base. 220-248 m: conglomerate. 248-276 m: 3 basalt lavas. 276-292 m: hyaloclastite sediment and conglomerate. 292-300 m: glassy basalt, possibly pillow lava.

Below the pillow lava formation from 75-300 m depth the temperature was found to rise linearly from 20°C to 33°C two weeks after drilling. This gives a similar thermal gradient as observed in well LN-10, which is the chief topic of this report.

4 BOREHOLE LN-10

4.1 Drilling and design

The drilling of well LN-10 began on 23rd October 1987. The drillbit and casing diameters are shown to the left of the lithological log in Fig. 2. A 17 ¾” drillbit was used to 1.8 m depth and a 16” cemented casing was put in place. Drilling continued with a 15” hammer drill to 20.7 m depth, continued further with a 15” rotary bit and mud circulation down to 150.5 m. A cemented 14” casing was then set to 150 m depth. A 12 ¾” rotary bit and mud circulation was used in drilling down to 323.6 m. An airlift flow test was undertaken there with the drillstring at 145 m. The well yield turned out to be exceedingly poor. Drilling therefore continued with an 8 ½” drillbit to 1096 m depth. Mud circulation was used to 561.4 m depth. Further below, saline groundwater, aided with airlift through a 9 5/8” temporary casing, was used as a drilling fluid.

4.2 Lithology

The drill cuttings were analysed some time after the drilling, resulting in the lithological log in Figure 2. The lithology of well LN-10 compares reasonably well with well LN-8.

2-20 m. Relatively coarse-grained fresh basalt lava.

22-28 m. Cuttings lacking.

28-58 m. Unaltered pillow lava formation, which should be reasonably permeable.

58-60 m. Thin sedimentary layer with molluscs. The sediment seems to be composed of hyaloclastite fragments cemented by a soft silica-rich mud.
60-114 m. Pillow lava formation, partly infilled by opaline silica which forms depositional layers in half filled or filled amygdales, causing porosity reduction.

114-146 m. Layered shallow marine sediment, with scattered fragments of altered basalt and molluscs in a silty sand, and fragments of altered basalt. Rock crystal and zeolites are seen in the amygdales. The near horizontal sediment rests unconformably on a slightly tilted lava pile.

146-206 m. Relatively unaltered coarse-grained lava flows, in places almost like pillow lavas in appearance (based on volcanic glass content). A sediment interbed is present at 190 m depth.

206-222 m. Pillow lava base from the same lava as above. The rock has suffered mild low-temperature alteration which presumably has caused some permeability reduction. Thomsonite and chabazite are found in amygdales.

222-252 m. Layered sedimentary tuff, with sand and silt lenses. Cemented by low-temperature minerals (diagenesis or burial metamorphism), compact and fairly dense in appearance. Thus fracture permeability is required for significant warm-water yield. This sedimentary tuff layer may have been aeolian in origin, deposited in a shallow water.

252-272 m. Two coarse-grained olivine tholeiite lava flows separated by a thin, brown and dense sedimentary layer. A small circulation loss was observed while drilling through the lower lavaflow.

272-290 m. Again, an exceedingly dense and fine-grained sedimentary tuff. Slightly coarser-grained near the bottom.

290-304 m. Lavaflow, scoriaceous at top.

304-316 m. Layered basaltic sediment, showing variation in grain-size, partly composed of rounded sand, pebbles or stones. Again, a small circulation loss was observed during drilling, and this seems to be one of the few aquifers in the borehole.

316-344 m. Apparently 2-3 lavaflows, but cuttings are lacking for a part of the interval. A change in drillbit from 12 ¼” to 8 ½” took place here.

344-372. Layered fine-grained tuff sediment, quite dense in appearance. Layering is pronounced in the upper part of the tuffbed, including grain size variation. The bottom 10 m are composed of homogeneous dark finegrained and cemented tuff.

372-404 m. Pillow lava underlain by tuffaceous sediment. Analysime is pronounced in amygdales, together with lightbrown, dense opaline-like precipitate, which reduces the permeability.

404-472 m. Coarse-grained lavaflows. Basaltic breccia in the middle part could be a pillow breccia, but red scoria grains are also seen. Low-temperature mineral cementation seems to be responsible for the lack of permeability. Chabasite is the most common zeolite and then thomsonite. Rust (oxidation product) is also seen, and calcite

472-498 m. Layered dense sedimentary tuff, pale green and cemented.

498-682 m. Lava pile, with thin scoriaceous interbeds and sparser sediments. Chabasite is the most common low-temperature zeolite.
682-700 m. Tuff layer, cemented and showing colour variation, pale green, spotted with white zeolite precipitates. Some reworking features seen, but insignificant. Most of the glass shards are altered, while dark fresh shards are present. A small circulation loss was observed here.

700-1075 m. Lavapile, similar to that described above, apparently involving series of shield lavas. Sparse sediment interbeds are seen. A small circulation loss was observed at one of the interbeds at 910 m depth. The sedimentary interbeds between 900 and 1000 m depth indicate low volcanic eruptive frequency, as drill cutting fragments of lignite were observed. Such an observation is rare in Icelandic drill cutting analysis.

A closing remark for the fishfarmers on the permeability properties of the volcanic succession cut by well LN-10 and the lack of aquifers. Firstly, porosity and permeability reduction due to low-temperature zeolitization is involved, and secondly, many of the sediment layers are relatively fine-grained, compacted and cemented, forming aquicludes for vertical fluid flow (convection). For serious exploitation (several l/s (tens of tn/h)) of hot water for fish farming or domestic use, the necessary fracture permeability is simply lacking at this location and further drilling in the vicinity probably pointless (as suggested by the result of well LN-8 in the first place).

The volcanic succession described above is a fairly typical Pleistocene lava succession. The lavas were formed during ice-free periods, in a similar setting as can be viewed in the volcanic rift zone just west of Thorlákshöfn today. The hyaloclastites were formed during glacial. The frequency of the reworked sedimentary hyaloclastites, and the lack of thick hyaloclastite formations, indicates the drillsite was flanking the eruptive volcanic ridges during glacial periods.

The reworked hyaloclastites are composed of basaltic clasts and glass. The low-temperature alteration is a typical diagenetic sequence, or burial metamorphic sequence, presently forming under static or conductive heatflow conditions, with relatively stagnant hydrous fluid within the rocks. The present thermal gradient is 90°C/km. This kind of geothermal system is not suitable for large scale exploitation, while small scale heat extraction is evidently possible. The regional zeolite zones in Eastern Iceland, for instance, are formed under similar condition.

4.3 Geophysical well logging

Geophysical well-logs are shown in Figure 3, i.e. a caliper log, natural gamma -, neutron-neutron - and resistivity logs. These were just mentioned in the original report and not discussed at length. Nevertheless, the neutron-neutron log indicated that the well penetrated a typical lava pile below about 500 m depth, where average lava flow thicknesses of about 10 m are indicated. Occasional spikes in the gamma-log were linked to silica rich marine sediments, or to slightly more acid lavas than the majority of the lavapile. Caving in the well below about 600 m depth is quite clear, and relates to the change in circulation fluid from mud to seawater.
Thorlakshofn well LN-10

Figure 2. The lithology of well LN-10
Thorlakshofn well LN-10

Figure 3. The geophysical logs of well LN-10
4.4 TEMPERATURE AND AQUIFERS (FEED POINTS)

In the drilling diary a circulation loss is mentioned at 54 m depth and total circulation loss was observed at 58 m depth. This was cemented. From 75-267 m no circulation loss was observed. The small loss at 267 m disappeared upon further mud drilling. A flow test was undertaken when the well was 323.6 m deep, showing insignificant yield from small feed points between 200-300 m depth.

During drilling between 323-561 m the circulation loss varied from 7-18 l/s, always disappearing upon further drilling. The rock formations were in part responsible for the loss, but most of the water was apparently lost through a poorly cemented casing, or a hole in the casing which was discovered later.

Below 561 m no circulation loss was observed until at 984 m depth. There a temperature increase of 1°C and a small increase in circulation-water was observed during the air-aided drilling, and possibly also from between 1050-1075 m depth. The circulating water (5-10 l/s) was about 22°C hot most of the time during, suggesting the feed points were above 300 m depth and insignificant below that depth.

The well temperature was measured six times during drilling. The first three measurements were done in relation to injection packer tests when the well was 561 m deep (Figure 4). From the temperature logs it appears the temperature will equilibrate at about 90°C/km. The shape of the temperature profile at the feed points above 300 m depth suggest the feed points relate to horizontal aquifers, rather than near vertical fractures. The shape of the temperature profile, from November 11th, suggests cold seawater seeps down from well LN-8 into LN-10 above 300 m depth. After the injection test the temperature log from November 13th clearly shows the injected water penetrated the formation at 270-300 m depth.

The temperature logs shown in Figure 5 were done at the end of the drilling and a month later. The first one was measured after a week-end's drilling stop. The well had clearly not recovered from the circulating water, the shape of the temperature profile not showing any significant feed points. The next temperature log was done December 15th after an airlift pumping test. Three small feed points are seen, at 300 m, 680 m and at 910 m depth. Otherwise the temperature log only reflects the cooling caused by the drilling. The third and final temperature profile is from January 19th, a good month after drilling. The well had clearly recovered and the temperature profile shows a smooth temperature gradient of 90°C/km. This gradient demonstrates that the heat flow towards the surface is dominated by conduction and rules out the presence of any convecting hydrothermal system at Thorlákshöfn.
Figure 4. Temperature logs of well LN-10 during drilling.
Figure 5. Temperature logs of well LN-10 at the end and after drilling
4.5 Injection packer test

A pumping test was done when the well had reached 561.4 m depth, by pumping air through the drillstring at 180 m, and at 240 m depth. The well yield was monitored by a V-shaped cross-section, at 20-30 m distance from the well. At first the flow was pulsating with 7 minutes interval, lasting for 2-3 minutes, yielding flow from 1-5 l/s, occasionally up to 20 l/s. With an additional airpump the flow could be stabilized at 5 l/s (18 tn/h), the water temperature varying between 16-18°C during the test.

Once it was clear that the well would only yield few l/s with serious drawdown, a pressurized pumping test was attempted. Based on the lithology and a caliper log, an injection packer was set at 170 m depth, and continuous pumping below the packer lasted for about 20-22 hours. Steady pumping of 40-50 l/s was maintained, at wellhead pressure of 30-50 bar.

In short - after conventional treatment of the data, it was clear that the packer test was unsuccessful altogether, and needs not be discussed further in the present context.

4.6 Pumping test

Well LN-10 was flow tested on February 15-16, 1988, in order to quantify the well yield at a given drawdown. Again, in short, the result of the test yielded the equation:

\[ \text{Drawdown} = -12 + 15Q \]

where Q is the pumping in l/s and the drawdown is in metres. The equation was considered optimistic for the longrun. A 10 l/s pumping, for instance, of only 27°C hot water, would result in 162 m drawdown, which was far from being economical.

4.7 Chemistry of the water

A water sample for chemical analysis was sampled during the flow test. The result is shown in Table 1. For comparison, a typical seawater analysis is also shown in the table.

The salinity of the brackish wellwater is half that of seawater. The analytical result further shows a clear mixing between different types of waters within the well. For example the silica concentration points to a water temperature of 40°C, the calcium concentration is an order of magnitude higher than that in seawater. Iron and manganese concentration are remarkably high and presumably unhealthy for direct use in fishfarming.
Table 1 Chemical composition of the water from well LN-10

<table>
<thead>
<tr>
<th>Sample</th>
<th>Well LN-10</th>
<th>Standard seawater (SMOW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
<td>880216</td>
<td>-</td>
</tr>
<tr>
<td>Temperature °C</td>
<td>27</td>
<td>-</td>
</tr>
<tr>
<td>pH°C</td>
<td>8.08/22</td>
<td>8.0/25</td>
</tr>
<tr>
<td>SiO₂</td>
<td>23.4</td>
<td>3</td>
</tr>
<tr>
<td>Na</td>
<td>4486</td>
<td>10800</td>
</tr>
<tr>
<td>K</td>
<td>117.5</td>
<td>390</td>
</tr>
<tr>
<td>Ca</td>
<td>1904</td>
<td>410</td>
</tr>
<tr>
<td>Mg</td>
<td>138.7</td>
<td>1290</td>
</tr>
<tr>
<td>Total CO₂ (calculated)</td>
<td>16.1</td>
<td>102</td>
</tr>
<tr>
<td>H₂S</td>
<td>&lt;0.03</td>
<td>-</td>
</tr>
<tr>
<td>SO₄</td>
<td>1220</td>
<td>2710</td>
</tr>
<tr>
<td>Cl</td>
<td>10066</td>
<td>19400</td>
</tr>
<tr>
<td>F</td>
<td>0.27</td>
<td>1.3</td>
</tr>
<tr>
<td>Fe</td>
<td>0.15</td>
<td>0.004</td>
</tr>
<tr>
<td>Mn</td>
<td>0.4</td>
<td>0.0004</td>
</tr>
<tr>
<td>O₂</td>
<td>0.5</td>
<td>-</td>
</tr>
<tr>
<td>Total dissolved solids</td>
<td>19572 (ppm or mg/kg)</td>
<td>35000 (ppm or mg/kg)</td>
</tr>
</tbody>
</table>

5 CONCLUSION

a) The well yields 27°C hot brackish water from aquifers below 150 m depth, especially from an aquifer at 270-300 m depth.

b) The well yield is poor and requires more than 15 m drawdown for each 1 l/s pumped.

c) The watertable can be simulated by a model of infinite horizontal aquifer receiving vertical inflow from above.

d) According to the well test and model, a steady watertable will be reached within 1/2 a day for a pumping rate of 10 l/s.

e) Well LN-8 is located at a distance of only 24.5 m from well LN-10. An interference between the wells during pumping is quite clear, and could result in cooling of wellwater in LN-10 upon longterm usage. The apparent interference was not tested further, but a testing method was discussed.

f) Further discussions on the wells in the original report was focussed on the possibility of finding hot water for fishfarming in the vicinity.