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GeoScience Division

Borhole HH-01
Haukholt í Hreppum
Geological Report

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Prepared for Norsk Hydro

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Grensásvegi 9, 108 Reykjavík

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Abstract:
The report provides geological background information for the interpretation of a VSP-experiment carried out in 1998 by Norsk Hydro in well HH-01 at Haukholt in South Iceland. Well HH-01 was selected for the experiment mainly because it provides easy access to a typical pile of volcano-clastic rocks formed subaquatically/subglacially. Haukholt is located within volcanics belonging to the Plio-Pleistocene Hreppar formation. At Haukholt, the volcanics dip approximately 8° to the NW and some 400-500 m have been eroded from the original depositional surface. Well HH-01 encountered an exceptionally high, near linear geothermal gradient of 130-140°C/km indicating a stagnant (convection free) fluid system. The succession of rocks penetrated by the well consists of primary hyaloclastite formations, reworked (sedimentary) tuffs and lavas. Based on the analysis of cuttings, 59 rock units have been identified. They have been grouped into 13 volcanic formations: five lava formations (totaling 330 m in thickness), four primary hyaloclastite formations (480 m) and four formations of reworked tuff (536 m). A cursory study of the the hydrothermal alteration minerals indicates that the wellhead is located within the chabazite-thomsonite alteration zone, whereas most of the remaining succession falls within the mesolite-scolecite zone. The deepest part of the well, below 1265 m, lies within the laumontite zone.

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	Project manager's signature: Steinar Þór Guðlaugsson
	Reviewed by: Authors

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1. INTRODUCTION

In 1998 Norsk Hydro carried out VSP-measurements in cooperation with Schlumberger in three Icelandic wells, HH-01 Haukholt, LN-10 Thorlákshöfn and LL-03 Laugaland. Orkustofnun provided assistance in the selection of appropriate wells and logistics support during the operation itself. As a part of the project, Orkustofnun was also to provide a summary report in English on available drillhole data for each of the wells. The present report on the Haukholt well is the last of the three reports. The other two are a summary for well LL-03 (Elsa G. Vilmundardóttir et al., 1999), and well LN-10 in Thorlákshöfn (Gudmundur Ó. Fridleifsson and Steinar Thór Gudlaugsson, 1998).

Well HH-01 is located in a low-temperature area in the Hreppar district, South Iceland (Fig. 1). The nearest geothermal field is at Jata, about 3 km to the southeast and Laugar, about 5.5 km to the south (Fig. 1). Only one well has been drilled at Haukholt, its geothermal gradient turned out to be unusually high or about 140°C/km. This seems to be caused by the well's location in the vicinity of one of the hottest low-temperature systems in the country, namely that of Laugar and Jata mentioned above (Kristján Sæmundsson, 1998)

Well HH-01 was selected as a suitable target for the VSP-experiment mainly because it penetrates a thick and fairly regular stratigraphic succession of subaquatic volcanoclastics. The lithology is fairly well constrained by cuttings sampled at a 2 m interval, while geophysical logs (except temperature) were lacking prior to the VSP-experiment. The logs obtained during the VSP-experiment fall outside the scope of the present report. Thus the lithostratigraphy rests solely on the drill-cutting analysis carried out specially for this report. As yet, no thin sections have been made for studies on lithofacies, rock composition or hydrothermal alteration. Accordingly the cutting analysis and the lithological logs can be improved by more detailed studies of the cuttings (thin sections, XRD, more detailed lithostratigraphic analysis and interpretation of the depositional environment) and integration with the geophysical logs.

2. GELOGICAL SETTING

The Haukholt farm is located in volcanics of mainly Pleistocene age but extending back to late Pliocene. Belonging mainly to the Matuyama epoc they are about 2 Ma old on the surface, but the earliest part belongs to the late Gauss magnetic epoc and is about 3 Ma old. The volcanics belong to the socalled Hreppar formation and dip about 8° to the northwest. They are composed of hyaloclastite formations with lava interbeds, the latter signaling interglacials in most cases. As discussed below, a considerable part of the volcanoclastic rocks in the well represent reworked hyalocrystalline tuffs, interbedded with primary volcanoclastic rocks and lavas. The nearest volcanic centre or central volcano, the Laxárdalur central volcano, is located some 20 km to the south from Haukholt. Accordingly, rocks of intermediate or acidic compostion are not to be expected, except perhaps as relatively thin acid tephra layers.

High-temperature geothermal systems are more or less confined within volcanic centres, such as the Laxárdalur central volcano, and only low- (<100°C) or intermediate-temperature (~100-200°C) zeolite alteration zones are therfore to be expected at Haukholt. The depth of erosion is not known in detail but is estimated from the presence of a chabacite-thomsonite zeolite zone on the surface, the degree of tilting of the strata and the erosional morphology to be approximately 400-500 m (Kristján Sæmundsson, pers. comm., 1999). Well HH-01 at Haukholt showed an exceptionally high thermal gradient of 130-140°C/km in a fluid system interpreted to be stagnant (convection free) down to at least 1 km depth. The system is believed to be located at the margin of the neighbouring low-temperature field at Laugar and Jata, which involves exceptionally high reservoir temperatures of about 150°C.

The objective of the drilling at Haukholt was to intersect a water-conducting fault or fracture with acceptable yield of water. Sofar the hotwater yield is considered insufficient.

3. BOREHOLE HH-01

3.1 Drilling and design

The well was drilled in three phases by two drillrigs; by Ýmir from 30.04-07.05.1997, and by Azi from 25.11-17.12.1997, and from 23.04-22.05.1998. The present total depth is 1346 m. An overview of the drillbits and casing depths is shown in table 1.

The first 5.6 m were drilled by a 10 3/4" Holtehammer, and cased simultaneously. A 9 7/8" cussion drilling followed to 101,1 m depth, and a cemented 8 5/8" casing was installed to the same depth. The well wettened from the beginning, a 14,5°C feedpoint was met at 50 m depth, the water inflow gradually increasing downwards. The welded casing reaches to 100.3 m depth. Depth from the wellflange is 101.1 m.

The 7 1/4" cussion drilling from 101 m depth to 452.5 m depth took only 3 days. Late in the evenings the drillpipes were filled with cold water and the well temperature measured inside the drillpipes each morning. No significant water feedpoint was met, until at 408 m depth, 1-2 l/s, where an increase in hydrothermal precipitates for the following 10 m was noted in the driller's log. The bottom temperature at 452 m was 60.7°C.

A second drillrig, Azi, was brought to the well for deepening to about 1000 m. A 7" cussion drilling was applied to 606.5 m depth where a lack of airpressure forced a change in drilling program to rotary drilling by a 6 3/4" drillbit and water circulation. No drilling problems were met during the rotary drilling. The circulating water was heated by about 5° during the round trip, down and up the well, and no circulation losses were recorded in the drillers log down to 990 m depth. The bottom temperature after this phase was 133.7°C. Two minor feedpoints were detected in the temperature log, one at 502 m (72°C) and the other at about 900 m depth (113°C).

Table 1. *Well HH-01, overview.*

Year drilled	1997 and 1998
Rigs	Ýmir and Azi
Total depth	1346 m
Drillbits used	10 3/4" to 5.4 m (cussion) Ýmir 9 7/8" to 101.5 m (cussion) Ýmir 7 1/4" to 452.5 m (cussion) Ýmir 7 " to 606.5 m (cussion) Azi 6 3/4" to 1346 m (rotary) Azi
Casing	10 3/4" to 5.4 m cemented 8 5/8" to 101.1 m ---"----
Cemented interval	none below casing
Borehole geology	0-100 m lavas, 100-350 m hyaloclastites, 350-374 m lavas, 374-478 hyaloclastites with lava interbeds, 478-530 m lavas, 530-790 m reworked tuffs and volcanoclastic sediments, 790-900 m hyaloclastites, 900-932 m lavas, 932-1046 m volcanoclastic sedimentary rocks, 1046-1168 m lavas, 1168-1312 m volcanoclastic sedimentary rocks, 1312-1328 m hyaloclastite, 1328-1346 m volcanoclastic sedimentary rocks,
Cuttings	Every 2 m
OS logs	Temperature

The third and final drilling phase commenced several months after the second phase. An 8" wellhead valve was installed. Static water table was at 18.7 m depth. No problems were encountered during drilling. An air-driven flow test was undertaken at 1291.7 m depth, after which an additional drilling day added 50 m to the depth. The final depth reached was 1346.2 m. A second flow test was undertaken, and the well temperature measured. The bottom temperature measured 162°C, and a small additional feed point showed up at 1265 m depth.

3.2 Lithology

3.2.1 Lithology description (Fig. 2)

0-2 m Cuttings lacking.

1) 4-100 m A suite of interglacial tholeiitic lava flows

The lava flows are often scoriaceous at top, fine-grained and rather fresh looking. Amygdales show low temperature alteration. Most common secondary minerals are opaline silica and low teperature form of calcite (dog-tooth silica). A coarser-grained tholeiite lava is found between 34-44 m depth and is underlain by a thin sedimentary interbed.

2) 100-350 m Hyaloclastite with volcanoclastic sedimentary interbeds

100-108 m Reworked hyaloclastite.

108-200 m Hyaloclastite. Between 108-156 m depth tuff showing signs of incipient alteration especially in small amygdales and cracks, which are most conspicuous between 118-138 m depth. The tuff is grey with the exception of the uppermost 4 m which have reddish brown hue. Zeolites, calcite and pyrite seem to be the most common alteration minerals. Between 156-200 m depth dominantly a pillowlava and a tuffbreccia.
Slight hydrothermal alteration is most conspicous between 156-166 m. Zeolites, scolecite and or heulandite and also calcite are common, but pyrite and smectite are present also. The alteration minerals are linked to fracture fillings.
200-212 m Reworked hyaloclastite. White fillings in narrow fractures and vesicles.
212-350 m Hyaloclastite. Between 212-262 m depth brown tuff (palagonite). Secondary fillings of zeolites (stilbite) and calcite in some vesicles, others are empty.
262-272 m Breccia. Cuttings smaller than above. Relatively large amygdales of zeolites (stilbite) and calcite are abundant.
272-294 m Greyish brown tuff. Secondary minerals, zeolites (stilbite) and calcite, are more conspicous than above.
294-324 m Tuff, black, dense, glassy with a network of light brown rims. At 304 m depth relatively big cuttings of secondary minerals abound. The rock might be fractured at this interval.
324-334 m Breccia. At 332 m large round fillings of zeolites (stilbite) and calcite occur.
334-350 m Tuff.

3) 350-374 m Olivine tholeiite lava

Vesicles are often empty. Low temperature minerals as thomsonite and scolesite occur.

4) 374-478 m Hyaloclastites with lava interbeds

374-384 m Reworked tuff with tachylitic glass. Analcime, thomsonite and chabasite occur but also seladonite and pyrite.
384-394 m Tuff and tuffbreccia, Between 382-394 m depth mostly dense and grey. Some oxidation seen.
394-408 m Vesicular tuffbreccia. Secondary minerals zeolites, (chabasite) are conspicuous between 404-406 m depth.
408-418 m Coarse-grained volcanoclastic sedimentary layer, possibly tillite. Basalt fragments are common. Oxidation is common and also white mineralization (zeolites and calcite).
A feed point is located at 408 m depth.
418-430 m Tholeiite. Scoriaceous and oxidized at top. Dense and fractured between 420-424 m depth. Vesicular and oxidized below 424 m depth. Zeolite and calcite fillings.
430-440 m Reworked tuff.
440-478 m Dark grey tuff. Fillings of stilbite, calcite, seladonite, smectite and red clay. At 442 m depth and between 444-450 and 460-478 m depth the rock is fractured with white fillings of zeolites and calcite. Secondary fillings are biggest and most abundant at 450 m depth.

5) 478-530 m A suite of tholeiite lava-flows and interbeds.

478-484 m Coarse-grained interbed.
484-486 m Cuttings lacking.
486-494 m Dense tholeiite lava.
494-496 m Cuttings lacking.
496-504 m Dense tholeiite lava.
504-508 m Interbed, finegrained, including oxidized scoria. Secondary fillings of zeolites and smectite.
508-514 m Grey tholeiite lava.
514-520 m Interbed with scoria. A feed point was detected at 520 m depth.
520-530 m Dark grey tholeiite lava probably two lava flows with thin interbed at 526 m depth.

6) 530-790 m Reworked tuffs

530-540 Fine-grained, probably lacustrine volcanoclastic sediment.
540-574 m Tuffaceous sedimentary rock with tachyllitic glass. Secondary fillings of zeolites and seladonite occur. Fracture fillings at 570 m depth.
574-578 Volcanoclastic sedimentary rock with grains of light coloured tephra. Fracture fillings at 476 m depth.
578-588 m Cuttings lacking.
588-596 m Light brown silty sedimentary rock.
596-602 m Fine-grained (sandy) sedimentary rock rich in basalt fragments.

Secondary fillings of zeolites and seladonite occur.
602-606 m Tholeiite lava Grey, dense and rather coarse grained tholeiite with narrow fracture fillings. Oxidation occurs. Intrusion is not excluded, but probably we are dealing with a thin lava bed.
606-608 m Fine-grained sedimentary rock
608-610 m Cuttings lacking
610-640 m Tuffaceous sedimentary rock, with scatter of tachylitic glass.
640-642 m Cuttings lacking.
642-716 m Volcanoclastic sedimentary rock, rather coarse-grained. Basalt fragments dominate but tuff cuttings are common also. Narrow fracture fillings are found between 674-676 and 704-706 m depth.
716-722 m Volcanoclastic sandstone.
722-744 m Rather coarse-grained volcanoclastic sedimentary rock. Basalt fragments are dominating but tuff cuttings are also common.
744-752 m Volcanoclastic sedimentary rock, oxidation occurs.
752-790 m Volcanoclastic sandstone. Secondary fillings are more common than in the sediment above.

7) 790-900 m Primary tuff.

Dark brown, homogenous tuff. Scatter of secondary minerals indicating a network of narrow fractures. Small cuttings.
A feed point is observed at 900 m depth.

8) 900-932 m Tholeiite lava flows and interbed.

900-904 m Interbed, coarse-grained, probably tillite.
904-932 Tholeiite lava. Possibly three lava flow with contacts at 912 and 920 m depth. Between 904-912 and 920-932 m depth scoriaceous cuttings are common. White fillings and also pyrite, seladonite and smectite are commom.

9) 932-1046 m Volcanoclastic sedimentary rock, showing some stratification.

932-990 Rather coarse-grained volcanoclastic sedimentary rock. The sediment is mostly composed og basalt and tuff fragments. Black shining tachylitic glass is abundant between 936-950 m depth and can be seen amongst the cuttings down to 987 m depth, possibly due to contamination from the layer above. Between 946-950 m depth white fillings are abundant.
990-1028 m Volcanoclastic sand- and siltstone. Secondary fillings are scanty.
1028-1046 m Reworked tuff. Secondary fillings are scanty.

10) 1046-1168 m Tholeiite lava flows and interbeds

Secondary fillings are scanty. Zeolites (stilbite?, scolecite?, pyrite and smectite).

1046-1094 m Possibly a suite of lava flows with thin interbeds in between and cuttings of scoria are common.

1094-1118 m Coarse-grained interbed.
1118-1126 m Tholeiite lava.
1126-1132 m Interbed.
1132-1140 m Tholeiite lava.
1140-1148 m Interbed.
1148-1168 m Tholeite lava flows with thin interbeds.

11) 1168-1312 m Volcanoclastic sedimentary rock

Fine-grained reddish brown siltstone and/or sandstone. Reddish brown oxidation is conspicous. Secondary minerals are scarce, but from 1272 m depth laumontite is the most conspicuous secondary mineral. Pyrite, seladonite and smectite are also seen.
At 1265 m depth a small feed point was detected.

12) 1312-1328 m Hyaloclastite

Greyish tuff, hydrothermally altrered. Laumontite is the most conspicuous secondary mineral, but also pyrite, seladonite and smectite are found.

13) 1328-1346 m Volcanoclastic sedimentary rock

Cuttings of light and dark coloured sedimentary tuff. Probably more coarse-grained than than above. Among the secondary minerals, laumontite, pyrite, seladonite and smectite are found.

Bottom of borehole

3.2.2 Alteration zones

The rocks exposed on surface contain chabasite and analcime in lava vesicles, implying the surface rocks are within the chabazite-thomsonite alteration zone (40-70°C). The presence of this zeolite zone on the surface today witnesses that erosion in the order of 400-500 m has taken place, assuming the alteration zone was formed under burial condition and a fossil thermal gradient of 90-100°C/km.

Within the well today, the characteristic minerals of the slightly higher-temperature mesolite-scolecite zone (70-90°C), are found sporadically down through the well down to 1265 m depth. Laumontite precipitates and fracture fillings occur from that depth downwards. Accordingly the laumontite zone (110-180°C) is present below 1265 m depth.

This result is a bit contradictory. According to the fossil thermal gradient (of Matuyama age) of say 100°C/km and 400 m of erosion during Pleistocene, the first signs of laumontite should be found at 600-700 m depth within the well. Today, under the influence of much higher thermal gradient (about 130°C/km), laumontite should be formed from below 900 m depth downwards. The 1265 m depth to the laumontite zone to-day only suggests a thermal gradient of about 90°C/km. The contradiction may imply that a relatively recent heating of the geothermal system has taken place, but obviously more detailed mineralogical study of the drillhole cuttings is needed before concluding on the secondary mineralization.

3.2.3 Chemistry, temperature and aquifers (feed points)

The well yield was about 1 l/s of 30°C at a 200-300 m drawdown, which is exceptionally low for a hot water well. The low temperature of the water was partly caused by cooling of the hot water by the pumped air. The geothermal fluid has not been sampled. The feedpoints detected as circulation loss/gain during drilling, and as inversion points on the temperature logs, are only 4, i.e. at 408 m (52°C), 520 m (72°C), 900 m (113°C) and at 1265 m depth (162°C), see Figure 3. The first three feed points are all located at stratification boundaries, while the last one at 1265 m depth seems to be related to a fracture or a fault.

From the viewpoint of burial metamorphism, the well is interesting in being a deep geothermal gradient well, with more or less stagnant formation water. This allows for comparison between formation temperature and the zeolite alteration zones. From relative time sequence studies of amygdales and fracture fillings it should further be possible to date the present-day geothermal system roughly by more detailed study. As discussed in chapter 3.2.2 the wellhead is located within the chabazite-thomsonite zone originally formed at 400-500 m depth under a much lower thermal gradient than presently found in the Haukholt well. Most of the rock penetrated by the well, however, falls within the second zeolite zone (mesolite-scolecite zone), characterized by scolecite-mesolite, stilbite and heulandite, almost from the surface down to 1265 m depth, according to the cutting analysis. The third and final zone crossed by the well is the laumontite zone, from 1265 m downwards. Chabazite and analcime occur at high levels within the mesolite-scolesite zone, but a more detailed mineralogical study is required to assess the degree of overprinting and the accurate depths of the zonal boundaries.

The transition from the scolecite-mesolite zone to the laumontite zone, set at 110-120°C, involves a dehydration reaction of heulandite to laumontite, and the only zeolite that thrives with laumontite at higher temperatures is mordenite. The transition to the last and final zeolite zone, the wairakite zone, takes place at 180-200°C, and is characterized by the dehydration of laumontite to wairakite. Wairakite has not been found in this well, but no thin sections have been made nor any XRD studies of the drill-cuttings. However, in view of the 162°C bottom temperature and the high thermal gradient of 130 °C/km, the wairakite transition should be met at about 1500 m depth, unless an aquifer of lower temperature that 180°C is met before.

The interesting bit about this well from the hydrothermal point of view, rests in its hot and stagnant fluid system. Further deepening by some 200-400 m is a tempting suggestion in that respect, e.g. to see if the high thermal gradient relates to a flow of hotter water at depth. It is not clear if the originally targeted fault has been cut by the drillhole, while the feed point at 1265 m is the only candidate met sofar.

4. CONCLUSIONS AND RECOMMENDATIONS

Well HH-01 encountered an exceptionally high, near linear geothermal gradient of 130-140°C/km indicating a stagnant (convection free) fluid system.

The succession of rocks penetrated by the well is estimated to be 2-3 Ma old. It consists of primary hyaloclastite formations, reworked (sedimentary) tuffs and lavas. Based on the analysis of cuttings, 59 rock units have been identified. They have been grouped into 13 volcanic formations: five lava formations (totaling 330 m in thickness), four primary hyaloclastite formations (480 m) and four formations of reworked tuff and volcanoclastic sediments (536 m).

A cursory study of the hydrothermal alteration minerals indicates that the wellhead is located within the chabazite-thomsonite alteration zone, whereas most of the remaining succession falls within the mesolite-scolecite zone. The deepest part of the well, below 1265 m, lies within the laumontite zone.

The lithostratigraphy reported here rests solely on the drill-cuttings analysis. No thin sections have been made for studies of lithofacies, rock composition or hydrothermal alteration. The lithostratigraphy could, however, be improved considerably by more detailed studies of the cuttings (thin sections, XRD) and integration with geophysical logs. This would increase the depth resolution in the lithostratigraphical column and enable better interpretations to be made of the nature of the different rock units. In particular, it should be possible to determine the depositional/emplacement environment of the volcanics with more confidence. The degree of lateral change in morphology, porosity and density is expected to differ strongly between, say, primary pillow breccia and fluviatile/lacustrine tuff deposits, and this is in turn expected to have a strong influence on seismic wave propagation. If such lithostratigraphical differences become an issue in the interpretation of the VSP-experiment, a more detailed study of cuttings and logs is recommended.

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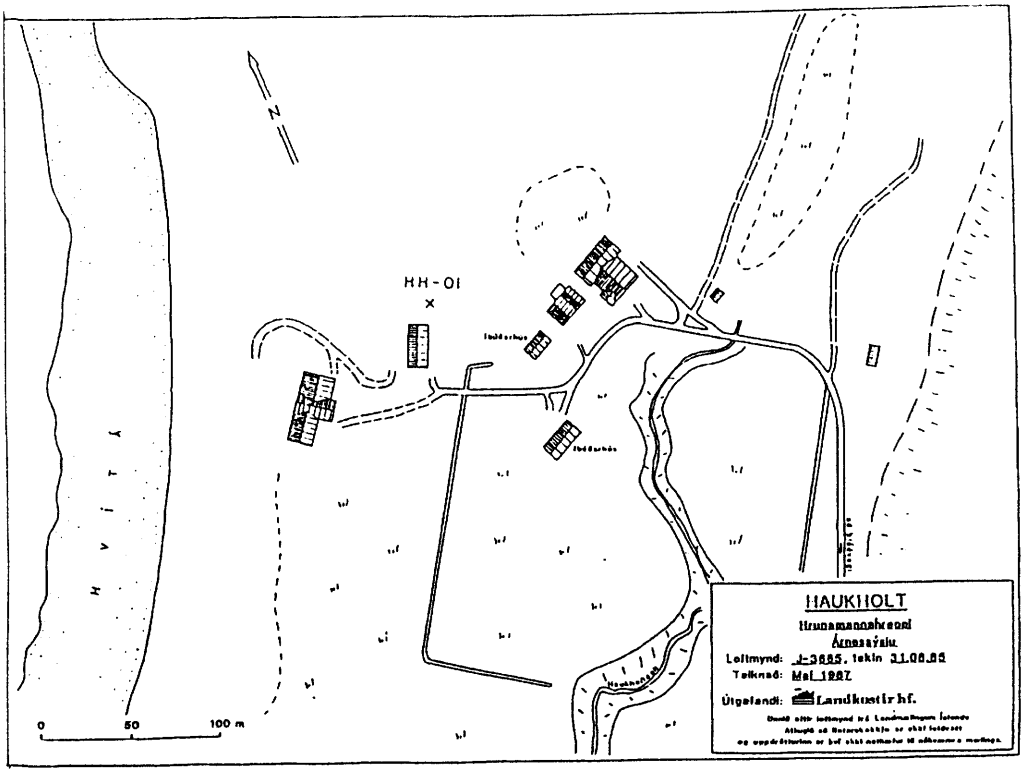

Figure 1a. Haukholt farm, sketch drawn after aerial photo.
X Approximate location of HH-01.

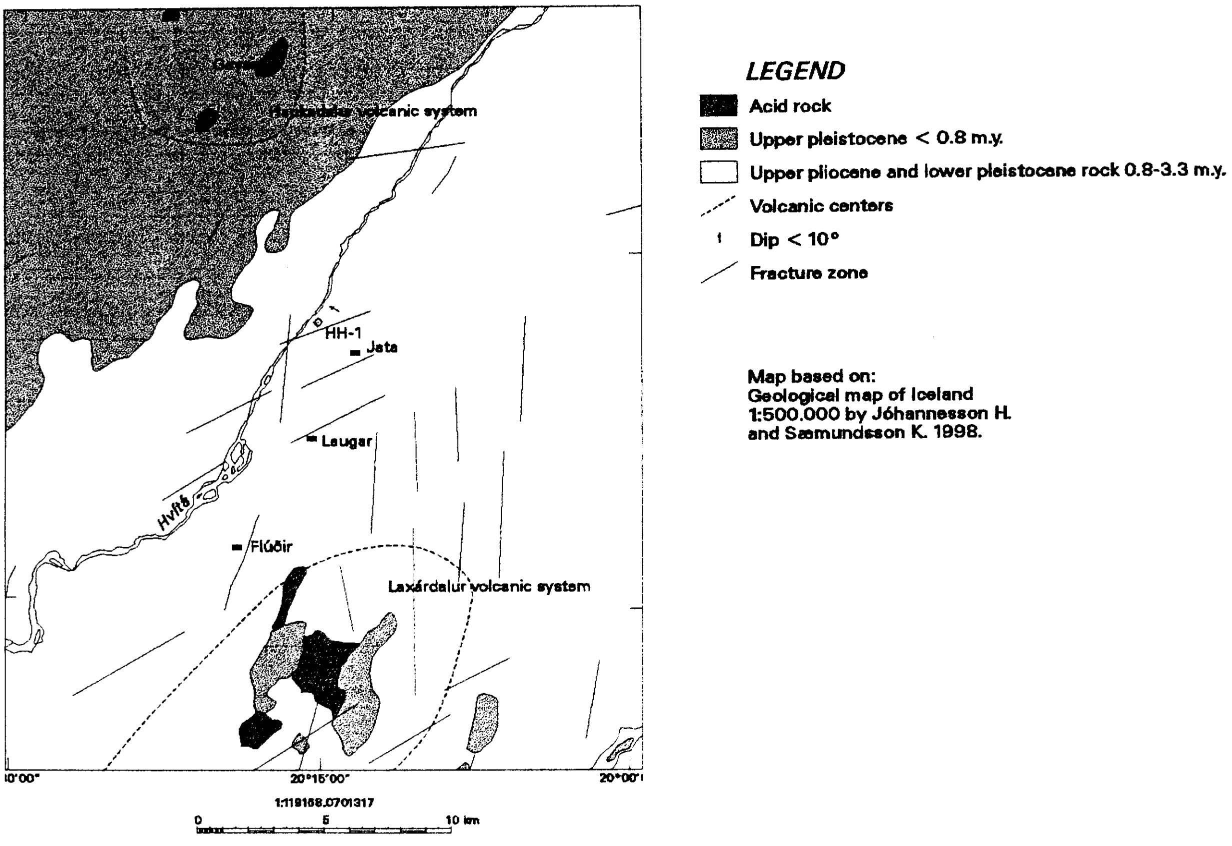

Figure 1b. Location map and geological setting.

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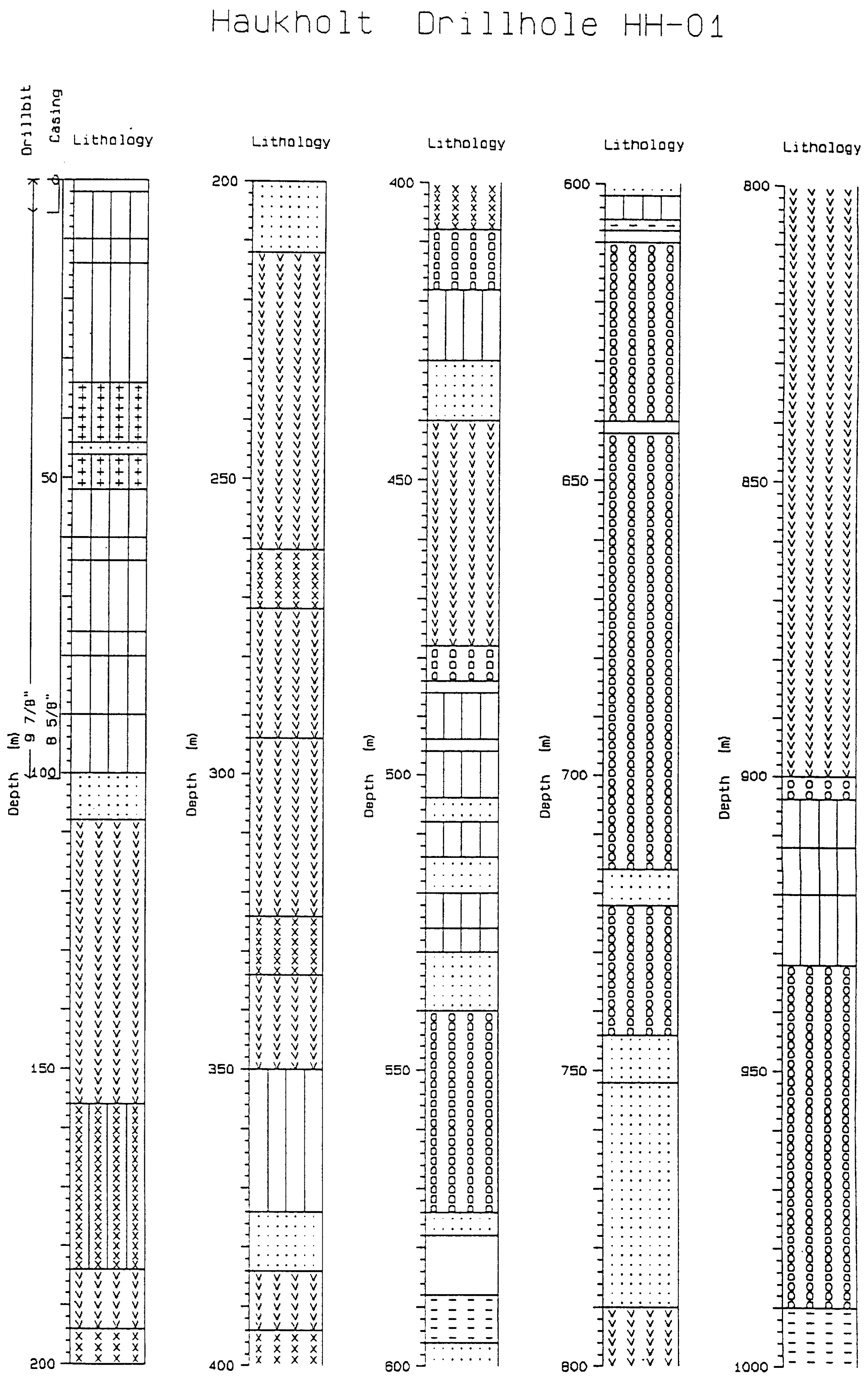

Figure 2. Lithology log from well HH-01.

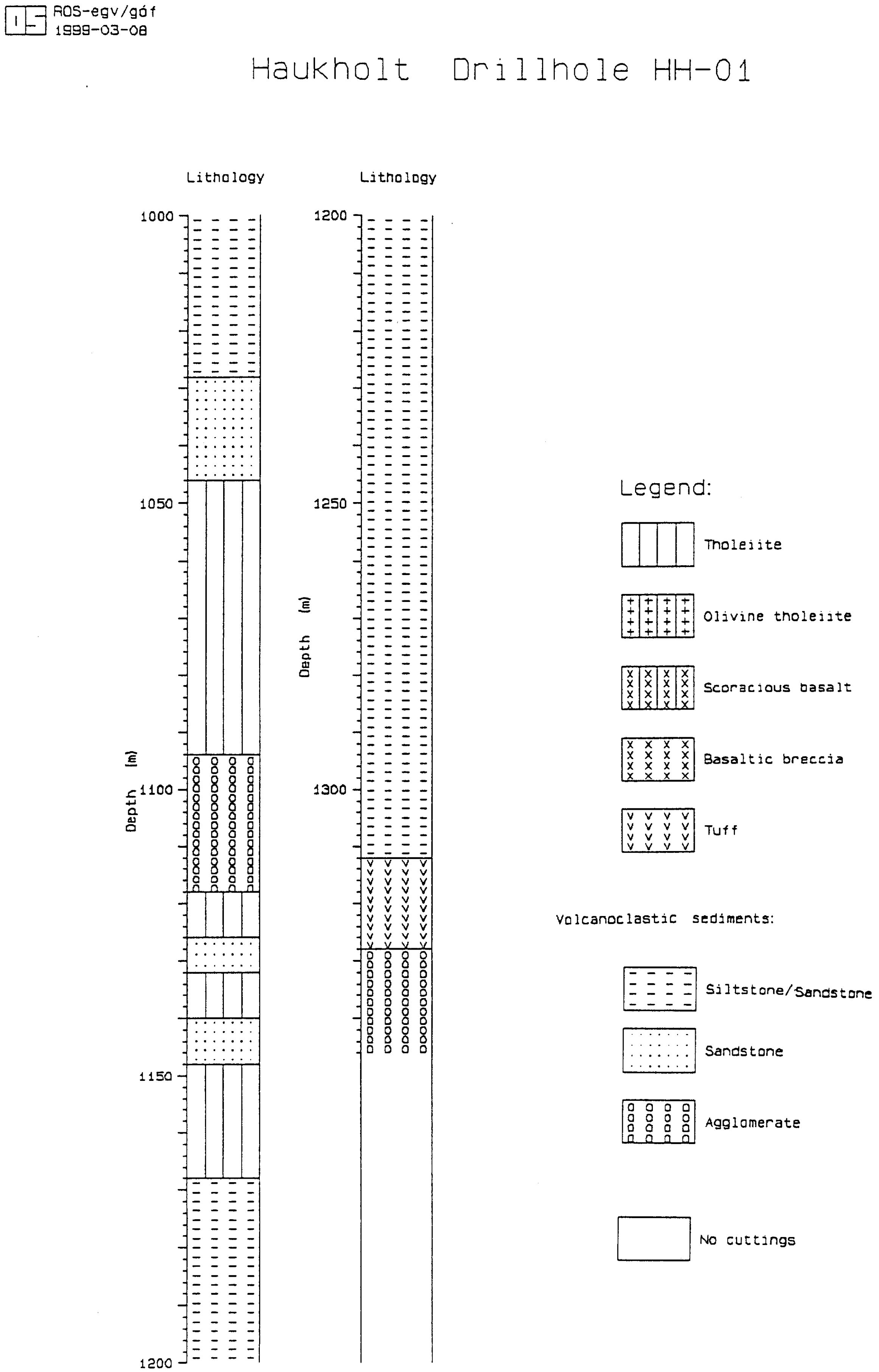

Figure 2 cont. Lithology log from well HH-01.

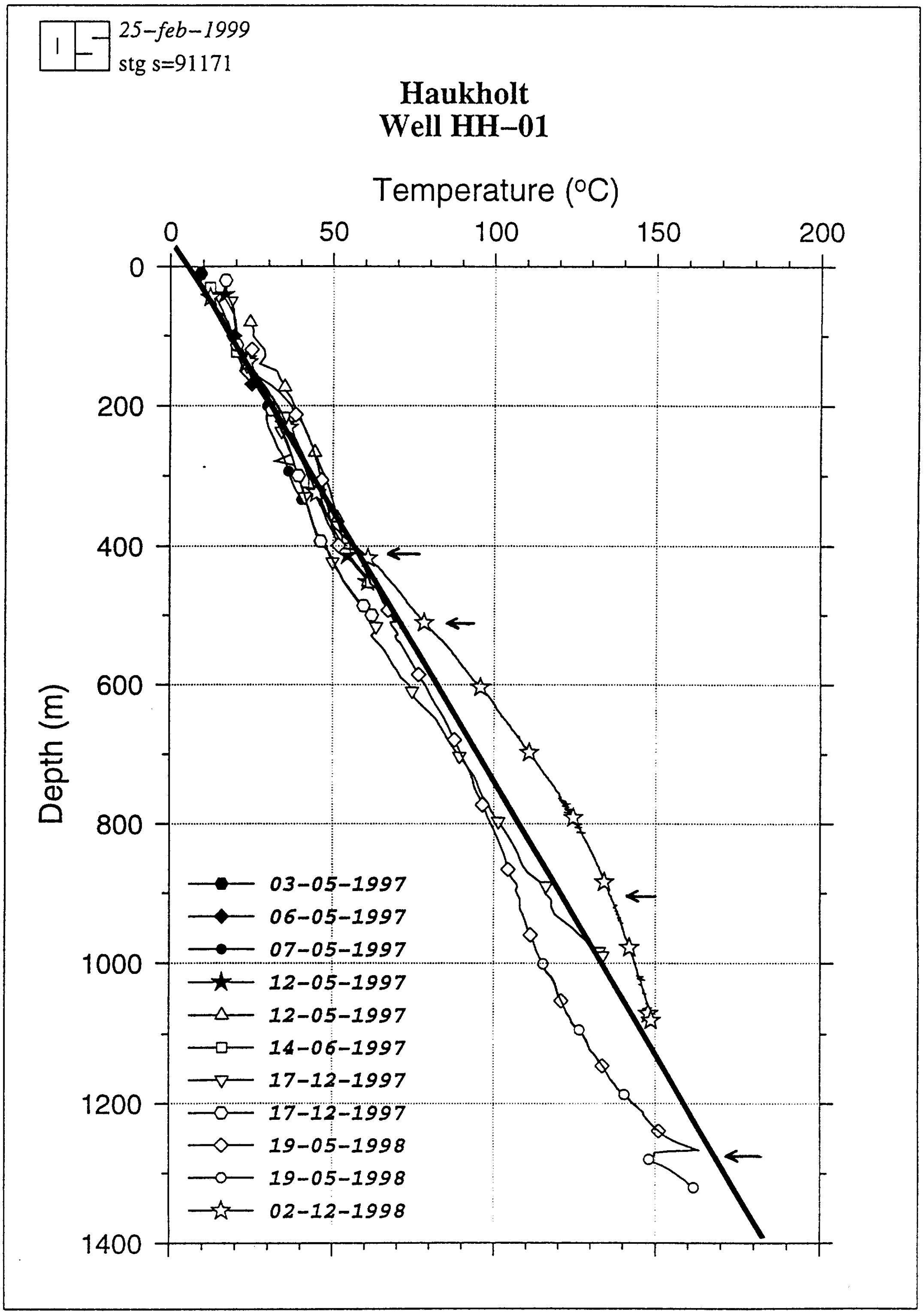

Figure 3. Temperature logs from well HH-01.

Estimated formation temperature ~130°C

← Feed point