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GEOTHERMAL INVESTIGATIONS AT THE ÁSGARDUR FARM, REYKHOLTSDALUR, W-ICELAND

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ABSTRACT

The Ásgardur area in the Reykholtsdalur Valley belongs to the Reykholt thermal system. The present geothermal investigation of the Ásgardur farm is based on soil temperature and geomagnetic measurements. Geological and tectonic studies were also included. The geothermal activity seems to be related to a northeast trending fault and a north-northwest trending fracture. The general description of geothermal manifestation in the area is given. As a result of this investigation, a production well was located.

1. INTRODUCTION

This study deals with the Ásgardur geothermal area in Borgarfjördur, West Iceland. It is a small area situated in between the much larger Deildartunga and Runnar geothermal areas. All these areas belong to the Reykholt geothermal system in Borgarfjördur, which is the largest low-temperature thermal system in Iceland. The Ásgardur field with a few warm springs and several boreholes has not before been investigated in any details. The main spring has the name Hamralaug.

1.1 General aspects

The work is based on the analysis of soil temperature measurement data and geomagnetic measurements and interpretation of previous and new analytical data. The material will be presented as follows:

- Mapping of the soil temperature around the geothermal springs;
- Geomagnetic measurements and mapping;
- Tectonic study in the field using aerial photographs and geomagnetic data.

The new data used in the report were taken from actual measurements made by the author, southeast of the Ásgardur farm in the Ásgardur geothermal area in Borgarfjördur.

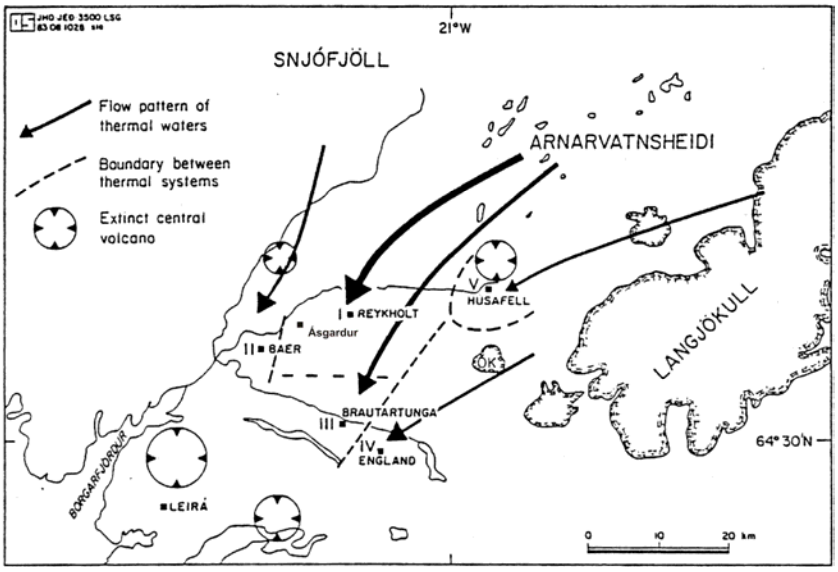

FIGURE 1: The flow pattern of the thermal waters in the Borgarfjördur region

An extensive resistivity survey was made in Borgarfjördur in the late 1970s (Georgsson et al., 1978; Georgsson, 1985). Based on these measurements, it has been suggested that northeasterly trending faults operate as the channels for regional flow from the highlands north or northeast of the district towards the thermal fields (see Figure 1). In the lowlands, these aquifers are intersected by young, open fractures with north-northwesterly trends. There, the geothermal water flows to the surface. The hot and warm springs of the major thermal fields in Borgarfjördur are aligned along these young fractures. The best example of this is the Deildartunga area and its hot springs (Georgsson et al., 1978).

1.2 Background and objective

The aim of the present work was to give the author practical training in geothermal exploration, including geological mapping with analysing geological structures, mapping of surface geothermal manifestations, soil temperature surveys and flow rate measurement of springs. The UNU Geothermal Training Programme duration was six months beginning in April, 2004. The first 2-3 months were used for course work, field excursions and practical training in various geothermal disciplines. The remaining 3 months were used for practical training in geothermal exploration, the results of which are described in this report.

Mongolia is the home country of the author. Recently, a pre-feasibility study "Geothermal project in Tsetserleg, Mongolia" was published. It was executed through Icelandic - Mongolian cooperation and written by specialists from the Icelandic companies ISOR - Icelandic Geosurvey, Fjarhitun Geothermal Consultants, and Rafhönnun Consultant Engineers in Iceland, on the one hand, and Mongolian specialists from the Renewable Energy Corporation, on the other. The report concludes that there are significant indications that geothermal energy can be economically developed in Tsetserleg and several other towns in the Khangai area, where the main geothermal activity is (Elíasson et al., 2004).

After having completed the present work, the author hopes to be able to use this knowledge for geothermal research work in Mongolia.

1.3 Previous work

The Ásgardur farm was established in 1944 and has from the beginning used geothermal water from the Hamralaug hot spring for house heating. The water is flowing from the spring to the house but the head is low and so is the water pressure. In a description from 1944, the first temperature measurements appear, given as 67°C (Icelandic Research Council, 1944). Table 1 lists the known temperature measurements.

TABLE 1: Temperature measurements in the Hamralaug hot spring and the well HA-01

Date	Hamralaug (°C)	HA-01 (°C)	Reference
1944	67°C		Icelandic Research Council, 1944
14/5/1959	71.5°C		Gunnlaugsson, 1980
25/8/1962	71°C		Sólmundsson, 1962
1964		72°C	Iceland Drilling Co., 1965
1978	71	72.2°C	Georgsson et al., 1978
~1982	76.5		Georgsson, L.S., personal comm.
15/2/1979	63		Gunnlaugsson, 1980
21/6/1995	74.7	71.9°C	Torfason, 1995
5/10/2004	69°C		Erdenesaikhan Ganbat

In 1964-1965, seven boreholes HA-01 to HA-07 were drilled at the Ásgardur area (Table 2). The aim of the drilling was to find more warm water and hopefully with higher pressure. The depths reached were from 6 m to 86.5 m. These holes have never been mapped nor surveyed in order to find their coordinates. Some of them are lost and but some others are still to be seen and the author tried to identify them and find out their coordinates by a simple GPS meter.

The drillholes HA-01, HA-02, HA-03 and HA-04 were all located close to the Hamralaug hot spring. HA-01 reached the highest temperature, 72°C, and it was the only one of them that was flowing but the flow rate was very low. Therefore, it was never harnessed and the natural hot spring is still in use for the house heating in Ásgardur. The drillers made a short description of the layering in the holes. The water table in the boreholes is at ground surface level, and indicates that the geothermal system is at low pressure.

The Hamralaug hot spring and the boreholes around it are located in a swamp, and there are about 25 m down to bedrock. The temperature and the runoff of the hot spring are varying from time to time and depend on the general groundwater level. At high level, the runoff is high and the temperature low; but at low level the runoff is also low and the temperature high (Table 1). According to Orkustofnun's data bank, the temperature has been measured there to be up to 76.5°C, and the discharge was estimated to be about 0.25 l/s, such guesses are rather inaccurate. In the Orkustofnun report from 1978 (Georgsson et al.), Hamralaug has a temperature of 71°C, but water discharge was rather low.

TABLE 2: Drillholes in the Ásgardur area

Wells	Location	Year of drilling	Depth (m)
HA-01	Ásgardur, at Hamralaug	1964/12	32.5
HA-02	Ásgardur, at Hamralaug	1964/1	45.5
HA-03	Ásgardur, at Hamralaug	1964/1	25
HA-04	Ásgardur, at Hamralaug	1964/1	23.35
HA-05	Bali (summer house)	1965/5	85
HA-06	Ásgardur, lost	1965/5	86.5
HA-07	Ásgardur, near Bali	1965/12	23
KL-01	Hamrar	1997	120
KL-02	Hamrar	1997	99
KL-03	Hamrar	1997	81
KL-04	Hamrar	1997	8

Well drillings for HA-05, 06 and 07, were carried out in 1965. One of the wells gave 2 l/s of 54°C warm water. This is the well HA-05 near the summer house, Bali. It is now harnessed for the house. Four additional boreholes were drilled in the area in 1997 in order to find cold drinking water for the community. Very little information is available about that activity.

2. THE GENERAL GEOLOGY OF THE STUDY AREA

Iceland is a part of the North-Atlantic oceanic lithosphere. The Mid-Atlantic Ridge crosses it from southwest to northeast where the spreading axis appears as a zone of active rifting and volcanism. According to the theory of plate tectonics, the island is drifting out from the volcanic zones in both directions. The spreading rate is 1.8 cm/yr. The continuous volcanism immediately fills up the gap between the plates. The age of the bedrock roughly reflects the drift. The rocks are youngest in the active volcanic belts but get older as the distance from the zones increases, the oldest rocks being found in the East and in the Westfjords. Considerably old bedrock also is found in the Borgarfjördur region. The bedrock of the study area in Ásgardur is supposed to be 4.8-4.9 million years old (Mc Dougall et al., 1977).

The geothermal areas in Iceland are divided into high-temperature and low-temperature areas (Bödvarsson and Pálmason, 1961). The high-temperature areas are situated inside the volcanic zones. The temperature within them is over 200°C at 1 km depth. Over 30 such areas are known in Iceland (see Figure 2), and many of them are very powerful. They will not be discussed here. The low-temperature areas are found outside the volcanic zones. The temperature within these geothermal systems is generally lower than 150°C at 1 km depth. The low-temperature areas are fracture- dominated, and derive their heat from the hot crust by active and localized convection flow of the groundwater in near-vertical fractures and regional heat flow (Bödvarsson, 1982; Björnsson et al., 1990). Away from this fractured zone, the bedrock is impermeable and heat transfer is dominated by conduction. At shallow depths, the source of heat is convection, and in the low-temperature areas the fluid escapes to the surface through narrow fractures as hot springs, so there must also be a recharge to the system. The recharge is either from the general groundwater flow or from the surface through some parts of the fracture system. The low-temperature areas are mostly in Plio-Pleistocene and Tertiary volcanic formations.

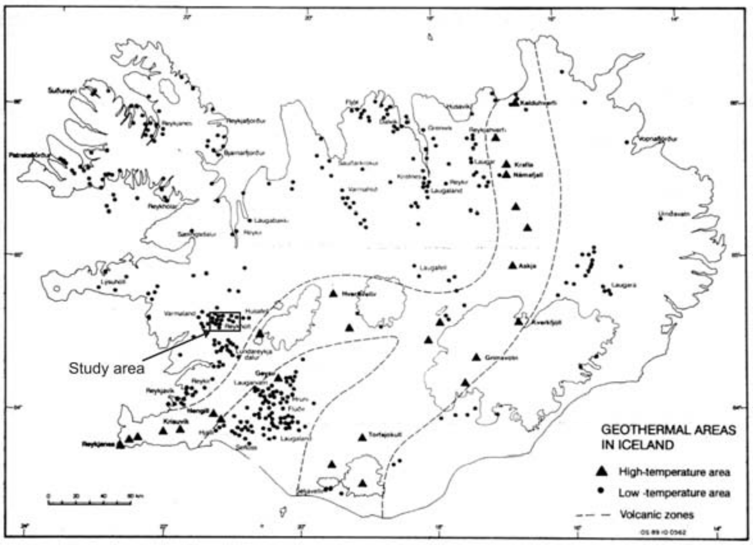

FIGURE 2: Geothermal areas in Iceland and the location of the Reykholt geothermal system.

The study area (Figure 3) is a part of the largest low-temperature system in Iceland, the Reykholt geothermal system. The basement of the Borgarfjördur region consists of late Tertiary basaltic lava flows. The axis of the Borgarnes anticline (Saemundsson, 1979) runs NE-SW 17 km to the west and marks the western margin of the geothermal manifestations. East of the anticline axis, the lavas dip 6-10°SE, towards the active Reykjanes-Langjökull rift zone. There are a great variety of faults and joints in the region. The NE-SW trending faults correspond to the fissure swarms of the active rift zone. These are accompanied by dyke swarms. The area comprises many thermal fields along with

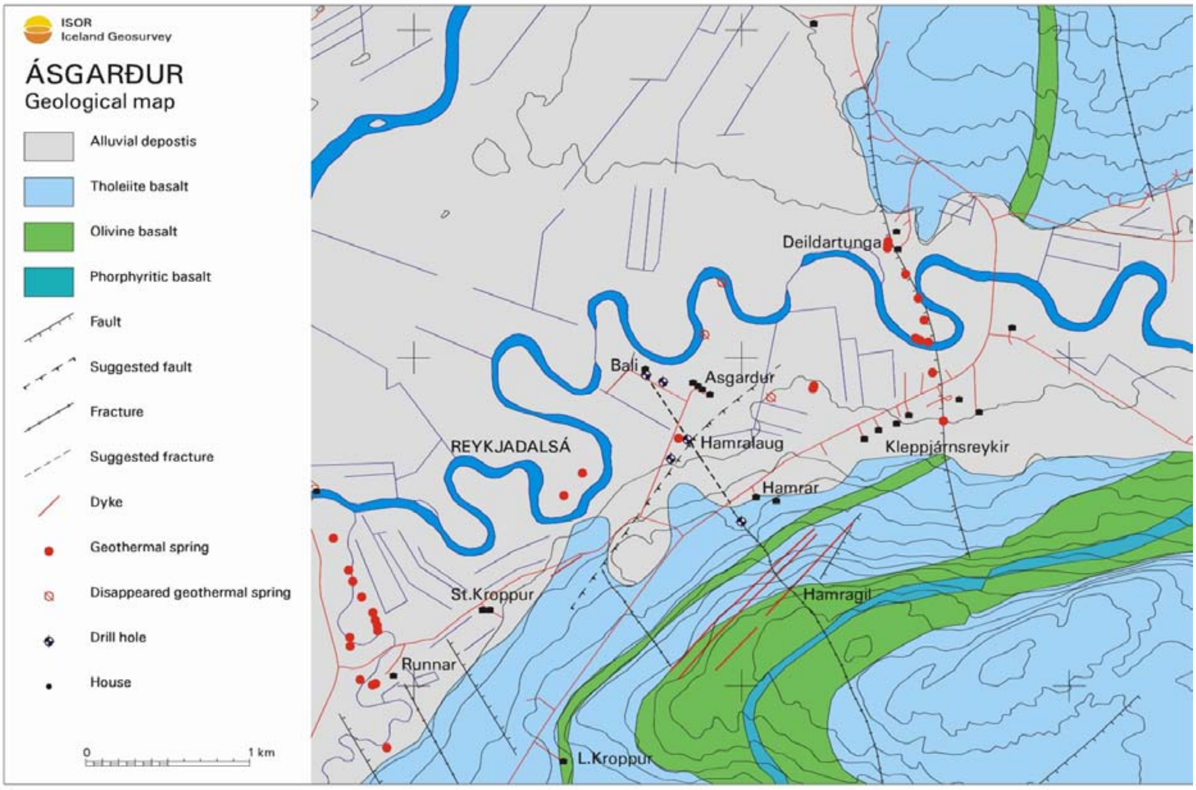

FIGURE 3: Geological map of the Ásgardur area including the Deildartunga and Runnar geothermal areas (modified from Georgsson et al., 1978)

numerous minor hot and warm springs. The thermal water is of meteoric origin and has fallen as precipitation on the Arnarvatnsheidi highlands (see Figure 1) northeast of the lowlands (Georgsson et al., 1984). Groundwater is supposed to percolate down to the depth of 1-3 km where it is heated by the regional heat flow. From there, it flows laterally for about 50 km to the southwest, driven by the hydrostatic gradient. The main aquifers are suggested to be north-easterly trending faults and dikes. In the lowlands, they are intersected by open north-westerly to northerly trending fractures which allow the thermal water to flow to the surface. The Deildartunga geothermal area is 1100-1200 m long trending north to northwest between the farms Deildartunga and Kleppjárnsreykir (Hróarsson and Jónsson, 1992). It is located only 1400 m east of the Ásgardur field. The main spring, the major Deildartunga hot spring area, is discharging 180 l/s of boiling water. The second largest spring is the Kleppjárnsreykir hot spring that discharges 70 l/s. The whole area has a natural discharge of over 250 l/s (Georgsson et al., 1978). Compared to this, the Ásgardur area is very small, discharging only a few litres per second. The natural discharge of the Reykholt system is equivalent to about 400 l/s of boiling water. The highest reservoir temperature exceeds 140°C. The temperature decreases in all directions from the centre of the system in the Reykholt geothermal system (Georgsson et al., 1984). The base of Reykholtsdalur Valley is covered by a few tens of metres of unconsolidated, finiglacial marine and fluvial sediments, which prevent direct observation of the relationship between hot springs and the basement features.

2.1 Seismicity

Most of the seismicity of Iceland is related to the Mid-Atlantic plate boundary that crosses the country. In Iceland, the plate boundary is displaced to the east by two major fracture zones: The South Iceland seismic zone in the south; and the Tjörnes fracture zone in the north. The largest earthquakes in Iceland occur within these zones and they may exceed magnitude 7 on the Richter scale.

Many of the earthquakes have been associated with faulting, and the faults generally seem to be oriented NS or NE-SW. The distraction zones are elongated in the North-South direction, but the south Iceland seismic zone as a whole has an E-W orientation. Most of the faults are arranged en-echelon. This structure appears on many different scales, ranging from metres to kilometres, and suggests right lateral movement on N-S striking faults. The sense of motion implies a least compressive stress in a horizontal NW-SE direction and a maximum compressive stress in a NE-SW direction (Björnsson et al., 1979).

Earthquakes are an essential part of the geothermal systems. They break up the bedrock by faulting and fissuring and make it permeable. Inside these fissured zones, the groundwater can reach to depths picking up extra geothermal heat. Seismic activity away from the plate boundaries is rare, but in Borgarfjördur such activity occurs, and that might be the reason for the high productivity of the geothermal areas there. In 1975, earthquakes up to 5.5 on the Richter scale shook the district (Einarsson et al., 1977).

2.2 Faults and fractures

The Reykholt area is characterized by many faults and fractures. Firstly, there are the easily recognized NW-SE to N-S trending faults and fractures. Secondly, there are NE-SW trending normal faults. They are not easy to see in the landscape but have been revealed by geophysical methods such as resistivity surveys and geomagnetic measurements. Tectonic maps of Reykholt and the surroundings show prominent faults with a northeasterly trend between 8° and 70° (Georgsson et al., 1978; 1985). The northeasterly (N30°-45°E) trend is related to the growth of the Hengill-Langjökull volcanic zone. Younger faults related to the zone would be expected to form a conjugate set, with N-S and WSW-ENE trends.

Exposures close to the geothermal anomalies are found only at Reykholt. There the main thermal anomaly is clearly related to a fracture trending N38°-40°E. Several faults are seen on the existing tectonic maps trending towards Reykjavellir, but in the field they can only be traced to within 1-1.5 km distance from the thermal area.

Figure 4 shows an overview of the Hamrar farm and Hamragil gully. The direction of fracture in Hamragil is N37°W. The fracture crosses the Hamralaug hot spring and continues to the Bali farm (see Figure 3) and its productive well.

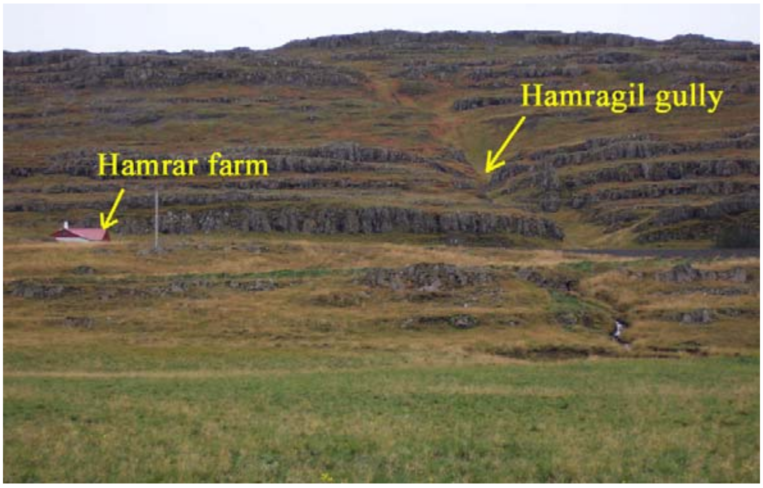

FIGURE 4: The Hamragil gully, view towards southeast (photo taken September 26, 2004)

3. GEOTHERMAL ACTIVITY IN THE ÁSGARDUR AREA

The small Ásgardur geothermal area is located in between the much larger Deildartunga and Runnar geothermal areas. The Ásgardur area is comprised of both hot and warm springs. Springs are classified as warm springs if the temperature is in the range of 10-50°C, but as hot springs if it is 50-

100°C. The locations of the springs are shown in Figure 3. The maximum temperature of Hamralaug hot spring has been measured as 76.5°C. Maps showing the geothermal areas in Borgarfjördur indicate four warm or hot springs in the Ásgardur area (Georgsson et al., 1984). In this investigation, only two of the springs were identified. The main spring is Hamralaug, and it is described in Section 1.3. The second one is shown in the swamp west of the farm. It actually was found to be farther east than the old map indicates. There the temperature is 14°C and the flow rate is very low (<0.1 l/s). The third one is shown on the river bank north of the farm. It is said to have disappeared after the drilling in 1965. The fourth one was on the river bank farther north. It was not found and might be submerged by the river.

The chemical composition of thermal water from Hamralaug hot spring is listed in Table 3. For comparison, typical Icelandic spring water is also shown. The geothermal water is much higher in most elements.

TABLE 3: Chemical composition of the Hamralaug hot spring and drillhole (Gunnlaugsson, 1980)

Location	**Date**	**Temp. (°C)**	**pH**	**°C/ pH**	**SiO_2**	**Na**	**K**	**Ca**	**Mg**	**CO_2**	**SO_2**	**H_2S**	**Cl**	**F**	**TDS**
Hamralaug (Ásgardur)	15.2.1979	63	9.61	21	123	72.2	1.9	3.3	0.01	19.1	54.5	0.44	34.4	2.2	305
Hamrar	14.5.1959	71.5	9.47	-	123.6	-	-	-	-	-	53.8	-	37	2.1	304
Reykjavík cold springs	1986	3.5	8.9	21	13.1	10.7	0.5	3.8	1.0	14.7	3.1	-	10.3	0.02	65

4. GEOTHERMAL EXPLORATION

4.1 Purpose

The aim of the project was to find the connections between the geothermal activity near the Ásgardur farm and the tectonics and stratigraphy of the area. This was done by:

- Mapping the geothermal springs and borehole area (define the coordinates of each)
- Temperature and runoff measurements
- Mapping the soil temperature contour lines around the area of the geothermal springs
- Geomagnetic measurements and mapping
- Tectonic study in the field and by interpretation of aerial photographs
- Stratigraphical study

4.2 Temperature and runoff measurements (flow rate) in HA-05

The well HA-05 at Bali is constantly flowing. A small part of the water is used for house heating but the rest is not used and flows to the river. The overflow was measured. The time (in seconds) that was necessary to fill a 10 litre plastic pail was measured using a stopwatch. Five individual flow rate measurements were taken and the average was used in the final calculation of the flow rate (Table 4). To find out the total production of the well, the flow to the house must be added. It is estimated to have been 0.5 l/s. Thus the total production was 1.7 l/s.

TABLE 4: Coordinates of wells and their temperature and flow rate

Well	Location	Coordinates	Depth (m)	Flow rate and temperature
	Hamralaug hot spring	N64°39'09''W21°26'06.4''		69°C
HA-01	Ásgardur, at Hamralaug	N64°39'09''W21°26'06.4''	30	0.12 l/s of 71.9°C
HA-02	Ásgardur, at Hamralaug	N64°39'09.2''W21°26'06.9''	45.5	
HA-03	Ásgardur, at Hamralaug	N64°39'09.2''W21°26'06.8''	25	59°C
HA-04	Ásgardur, at Hamralaug	N64°39'09.4''W21°26'06.5''	23.35	9.5°C at 4 m
HA-05	Bali	N64°39'21.5''W21°26'26.6''	85	1.7 l/s of 54°C
HA-06	Ásgardur, lost	?	86.5	
HA-07	Ásgardur, near Bali	N64°39'20.1''W21°26'18.6''	23	
KL-01	Hamrar	N64°38'53.2'' W21°25'40.2''	50	7.5°C
KL-0?	Hamrar	N64°39'01.1''W21°25'05.4''		Fresh water

4.3 Temperature measurements in the wells

Temperature logs were carried out in one of the KL (cold water) wells (Figure 5) and four of the Ásgardur wells, HA-01-04 (Figure 6), by a temperature measurement reel that was lowered down in to the holes. These logs give important information.

HA-01: From the surface down to 20 m the temperature is stable around 75°C. Below 20 m temperature drops from 75°C to 65°C at 35 m. This indicates a warm water inflow at 20 m depth.

HA-02: From the surface down to 30 m is a normal temperature gradient. Then below 30 m the well has a constant temperature of 54°C. The log indicates an up flow from the bottom of the hole up to 30 m where warm outflow seems to occur.

HA-03: The borehole has a strange log. At 20 m there seems to be a warm inflow but between 10 and 20 m a cold inflow cools the hole from 68 to 62°C. Above 10 m, hot inflow warms up the hole which reaches a maximum temperature of 69°C at the groundwater table.

HA-04: The hole seems to be closed at 4 m. The log is too short for any suggestions.

The temperature measurements indicate that the warm upflow in the bedrock is not right below the Hamralaug hot spring. The geothermal fracture seems to be somewhere aside it, and the warm water seems to flow laterally from it towards the spring. No temperature log is available from HA-05 at Bali, but it seems to have cut the geothermal fracture.

One KL-well is located near the Hamrar farm south of Ásgardur (its number is not known). Its temperature was measured by the author on Oct. 5 2004. The temperature log is given in Figure 5. The reverse geothermal gradient is noticeable, and is most probably caused by shallow inflow of warm water from the nearby Hamragil fracture.

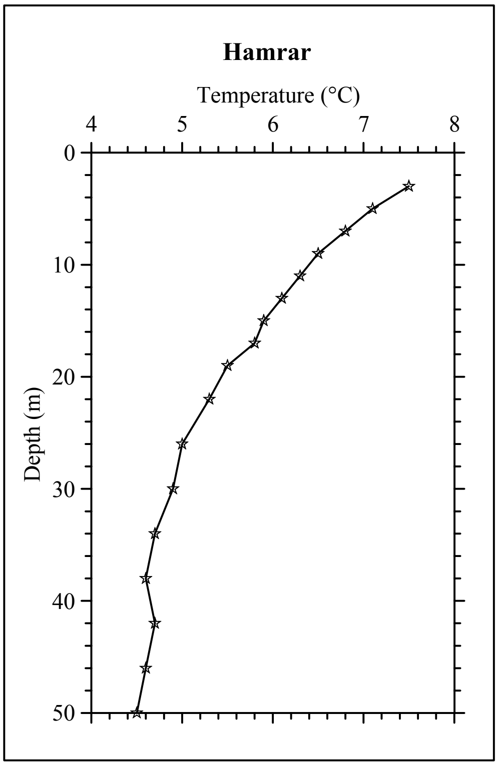

FIGURE 5: Temperature log in the KL well near Hamrar farm, from Oct. 5, 2004; note the reverse gradient

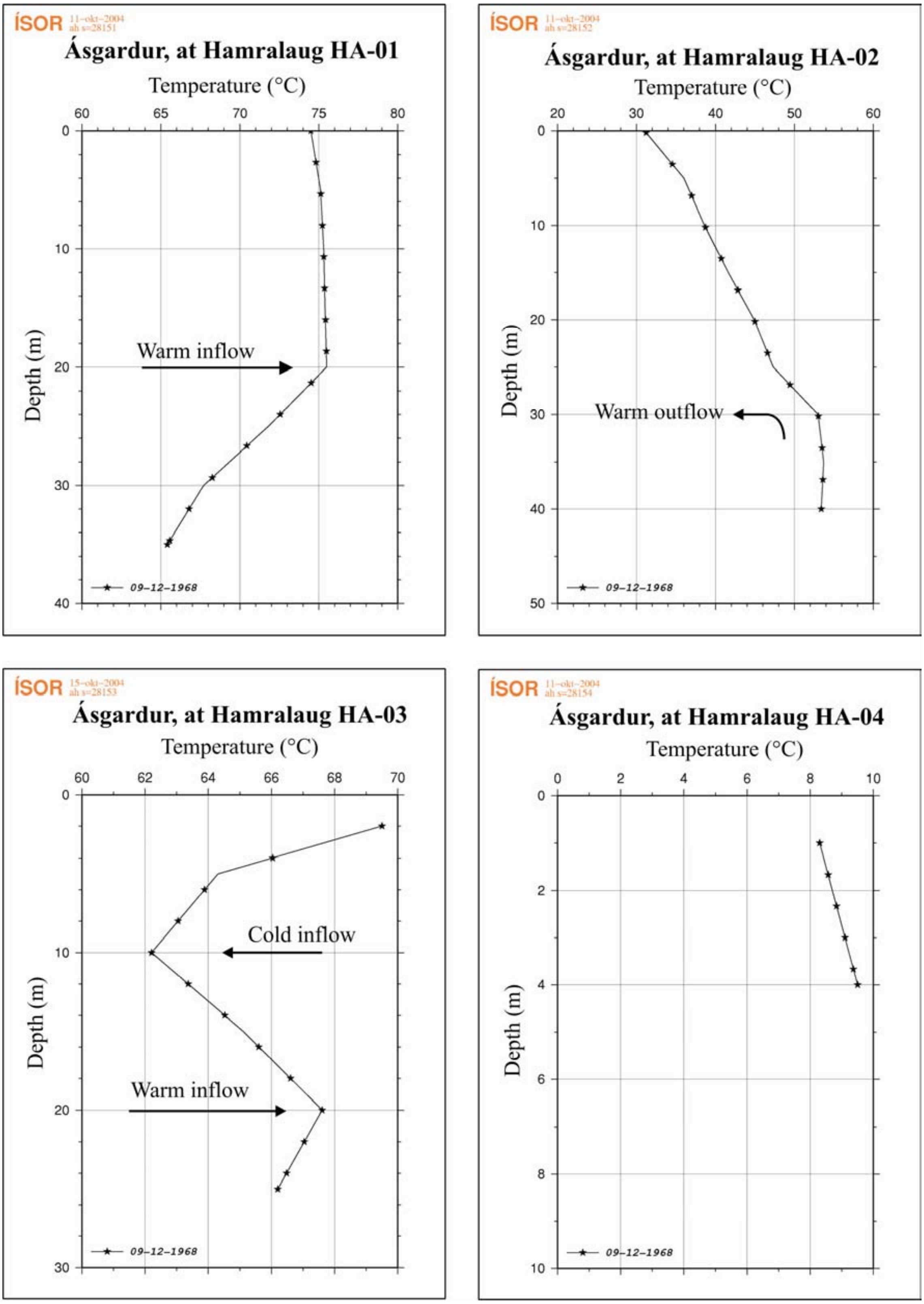

FIGURE 6: Temperature logs from the wells around Hamralaug hot spring

Figure 7 shows geological sections through wells HA01-04. They show glacial sediment or silt in the uppermost 23-27 m, but basaltic basement below that.

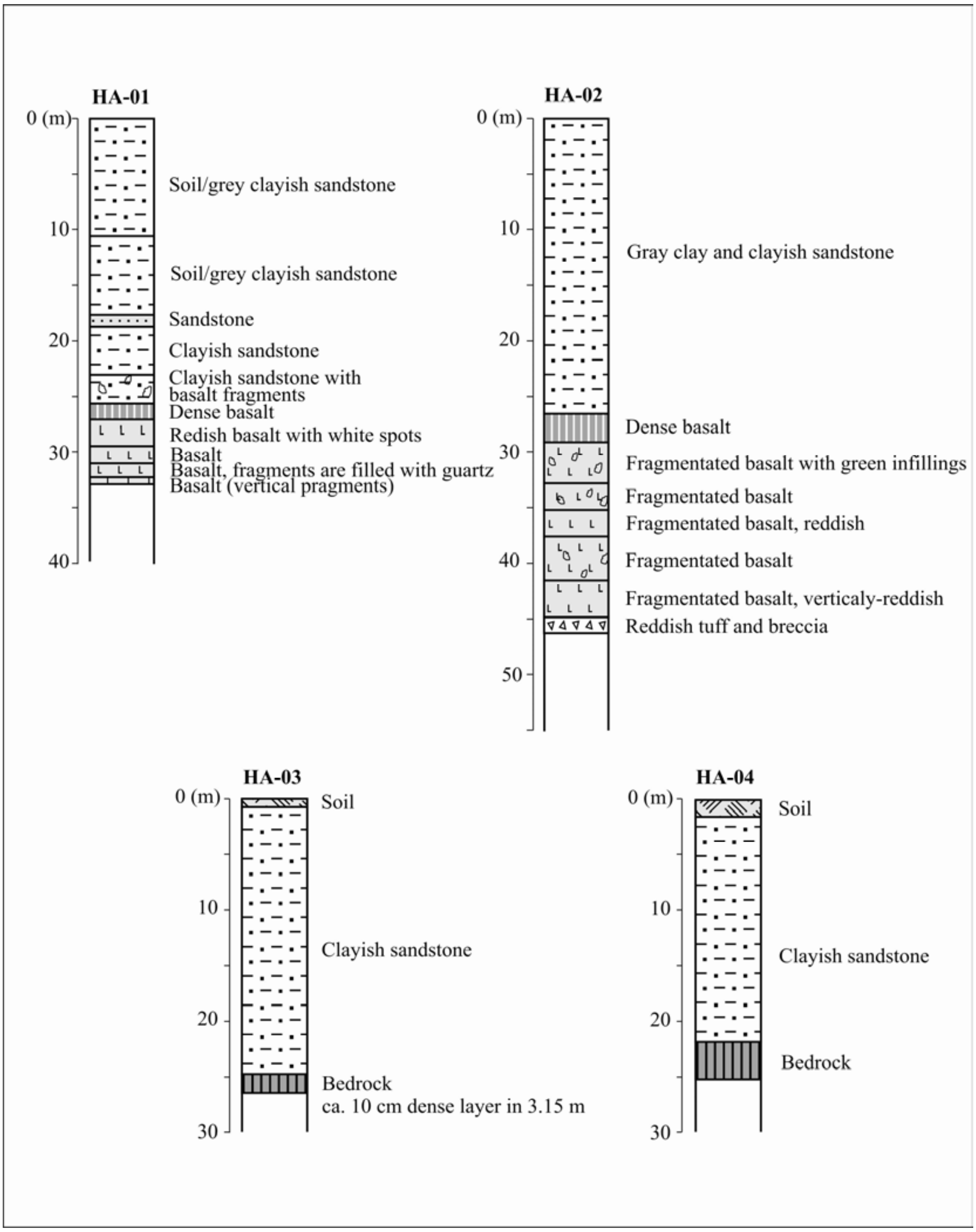

FIGURE 7: Geological sections through the Ásgardur wells, based on descriptions in the drillers report (Icelandic Drilling Co. 1965)

5. SOIL TEMPERATURE SURVEY

The purpose of the work was:

- To map in detail the soil temperatures around the Hamralaug warm spring and the occurrence of hot ground in the Ásgardur area;
- To correlate the soil temperatures to the geological structure of the area and;
- To acquire, in this way, a basic knowledge of the geothermal field that might be useful for planning for more sophisticated and more expensive research methods.

For making a geothermal map based on shallow measurements, one must measure the temperature in the ground at a convenient depth, and at regular intervals, and plot the data on a map of sufficiently large scale for tracing isolines. The intervals between measuring points are not fixed in advance. When the values recorded are relatively high, one has to reduce these intervals in order to delimit and to follow more precisely their distribution. In the present work, the temperatures were taken at 0.6 m depth and the intervals were chosen as 10 m and 5 m for values higher than 8°C. The surveyed area was 400×200 m^2. The measurements were made in August 2004.

The data acquired during this survey were analysed and contoured. A contour map of the study area is shown in Figure 8. The normal soil temperature was 8-10°C. Temperature above that indicates a geothermal influence. As expected, an anomaly appeared around Hamralaug. It had two maxima, the larger one (36.7°C) was close to the spring itself but the smaller one (24.0°C) was 40-50 m north-northwest of it. The anomaly was elongated to north-northwest in a similar direction as the suggested continuation of the Hamragil fracture that is thought to cross the area.

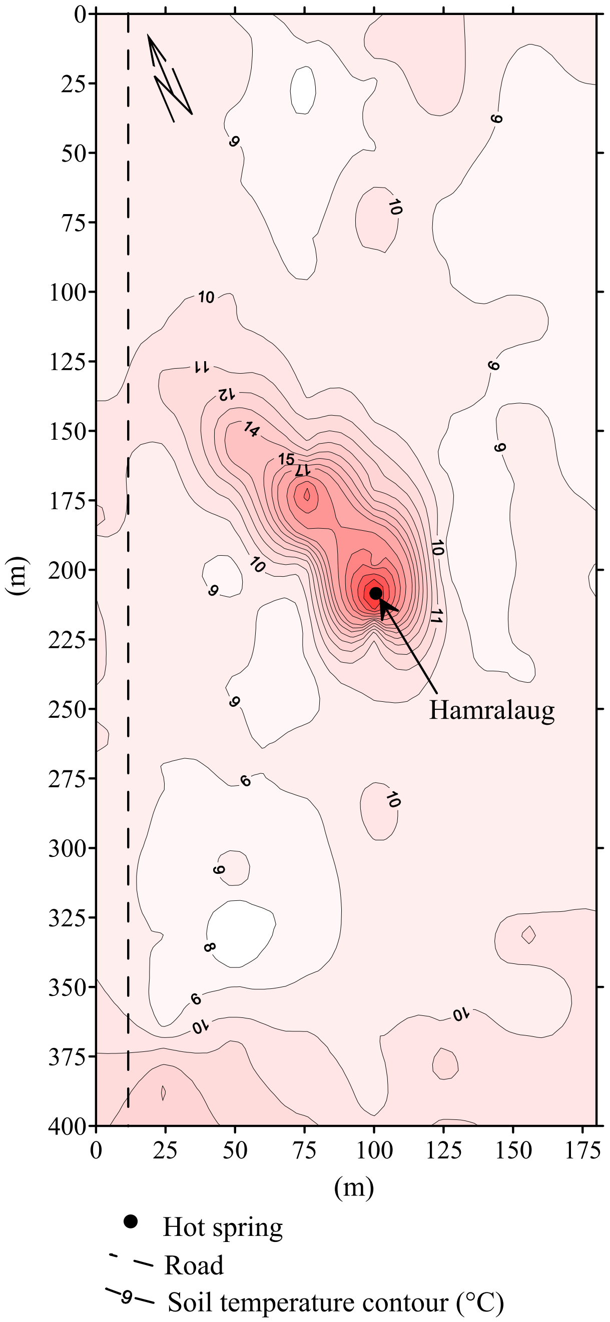

FIGURE 8: Soil temperature contour map around the Hamralaug hot spring. The geothermal map is based on measurements at 60 cm depth

6. GROUND MAGNETIC SURVEY

6.1 Introduction

The aim of the ground magnetic survey at Ásgardur was to reveal near-vertical structural features of the basement, around the Hamralaug hot spring. The method is powerful in locating dykes, faults or other linear near-vertical structures when the basement is covered with relatively thin soil or sediments. Usually, results of magnetic surveys are easy to interpret without any special processing, but in some cases computer processing is necessary, such as filtering or removal of topographic effects, or enhancements of anomalies with vertical gradient (Flóvenz and Georgsson, 1982).

The hot spring at Ásgardur is located only about 150 m from the foot of the hill on the south side of Reykholtsdalur Valley. Sediments could be expected to be around 20-30 m thick at this site as confirmed through the drilling of shallow wells. Thus, magnetic measurements could be expected to be effective for prospecting there.

The survey was carried out on September 26th. The survey was done with a proton precession magnetometer measuring the total magnetic field at 2.5 m height above ground level. Eleven parallel lines were measured with 5 m between measuring points and an interval of 20 m between the profiles. The length of the lines was 300 or 400 m, and the total measured area 0.068 km^2. The Hamralaug hot spring was located centrally in the measured area. Minor irregularities in the data mainly caused by an electric power line were filtered out.

6.2 Results

Figure 9 shows the magnetic map of the measured area. A strong linear anomaly runs through the area trending NE-SW (exact direction N43-51°E), running close by the hot spring. With low magnetic values on the northwestern side, and high magnetic values on the southeastern side, the shape of the anomaly reflects clearly a fault, possibly also associated with a dyke in the most southwestern part. Figure 10a shows a 3-dimensional surface map of the area, and shows very clearly the anomaly associated with this fault.

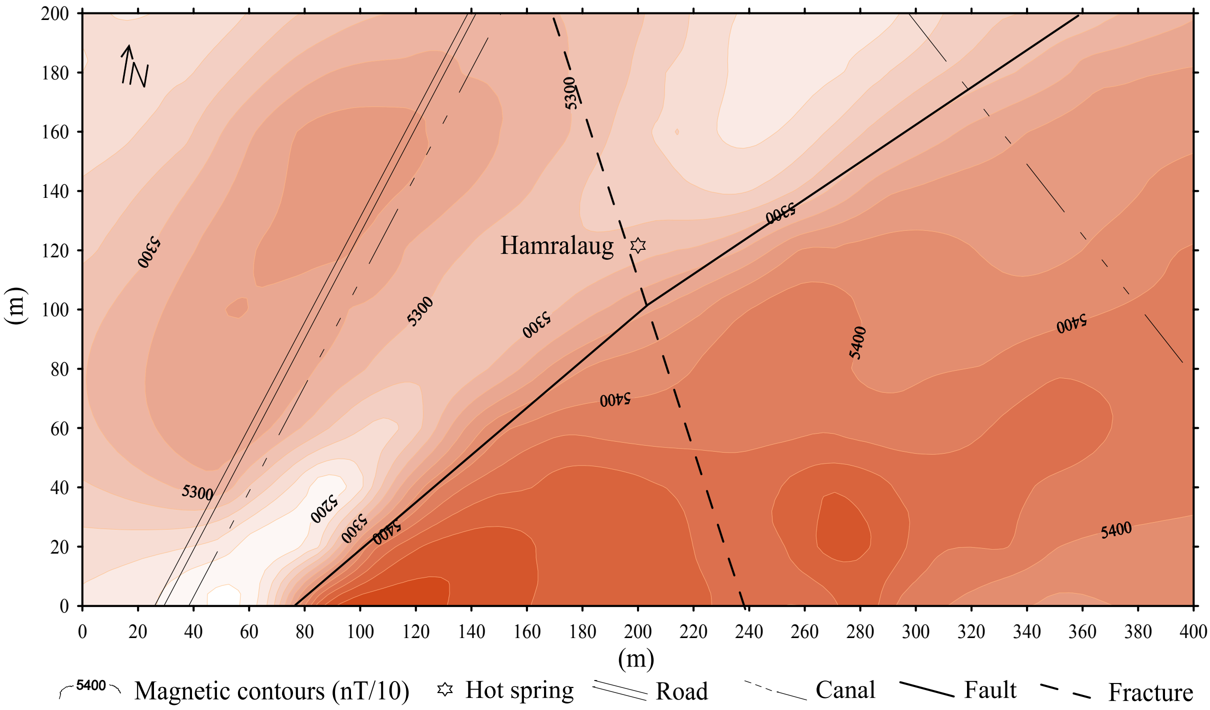

FIGURE 9: Geomagnetic contour map based on a ground magnetic survey

The N37°W trending fracture exposed in the hill above Ásgardur, with a trend pointing to the hot spring and the Bali well, is not seen clearly in the magnetic map. However, irregularities seen in the magnetic profiles support its existence and that it appears to cross through the site of the hot spring.

In early October, some additional measurements were made to find the southwestern continuation of the fault. The measurements showed that it could easily be traced further towards the southwest. At the same time, a new line was measured across the small hot spring east of Ásgardur farm (Figure 3). The magnetic values there were very constant along the line showing no anomaly. This is most probably due to much thicker sediments covering the bedrock on this site than near the Hamralaug spring. Figure 10b shows the magnetic values along this line and a line measured across the fault west of Hamralaug, where the surface sediments are relatively thin.

Based on the geological and magnetic data, it is probable that the ascent of hot water in the Ásgardur thermal field is controlled by a combination of a fracture and a fault, with the hot spring found at their intersection. It is probable that the northeasterly fault is the main aquifer towards the field, but where it is intersected by the active N37°W trending tectonic fracture, the water flows to the surface. This may be considered as typical for the Reykholt thermal system. It is also interesting to note that the

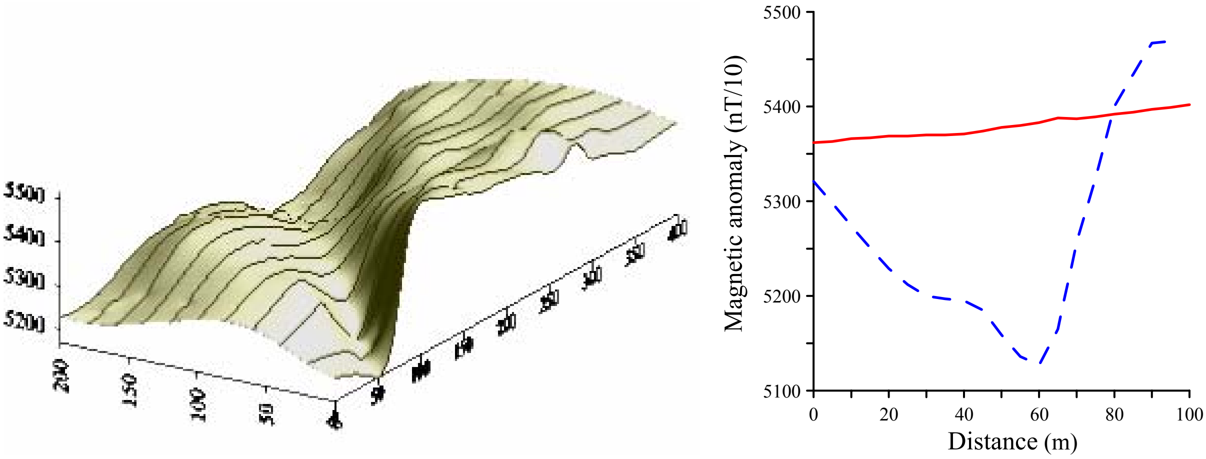

FIGURE 10: a) Three dimensional representation of the geomagnetic measurement; b) Graphs showing the difference between magnetic measurements made on a thick and thin sedimentary cover. The solid line is across the small warm spring east of Ásgardur farm, where sedimentary cover is thick. The dashed line is across the fault west of Hamralaug

trend of the northeasterly fault indicates that it may run very close to the Deildartunga hot spring, and thus it may possibly be the same fault (Georgsson et al., 1978), as is believed to supply the water to the Deildartunga hot spring.

7. BEDROCK INVESTIGATION

7.1 Stratigraphic profile

A strata profile was measured along the Hamragil gully in the slope of the hill north of Ásgardur. The 200 m thick strata pile in Hamragil is made of 4.8-4.9 million year old basalt layers (McDougall et al., 1977). The rock types were identified, the thickness of each layer was measured, secondary minerals were studied and the paleomagnetic polarities of the lava layers were measured using a fluxgate magnetometer. The pile is predominantly made of Tertiary basalt lavas with occasional thin interbeds. Three lava types were identified, tholeiite basalt, olivine basalt, and porphyritic basalt. One basalt dyke was found. The Hamragil gully has a straight N35°W direction (see Figure 3), and is thought to indicate a tectonic fault or fracture. No fault was found, and therefore it will be interpreted as a fracture. The profile is shown in Figure 11. The profile was used to complete the geological map in Figure 3.

The lowermost 110 m of the profile are made of 10-12 m thick fine-grained lava layers of tholeiite basalt. Then there is a single layer of olivine tholeiite, 7 m thick, which is comprised of secondary minerals, mainly chabasite (Figure 12, see also Section 7.3).

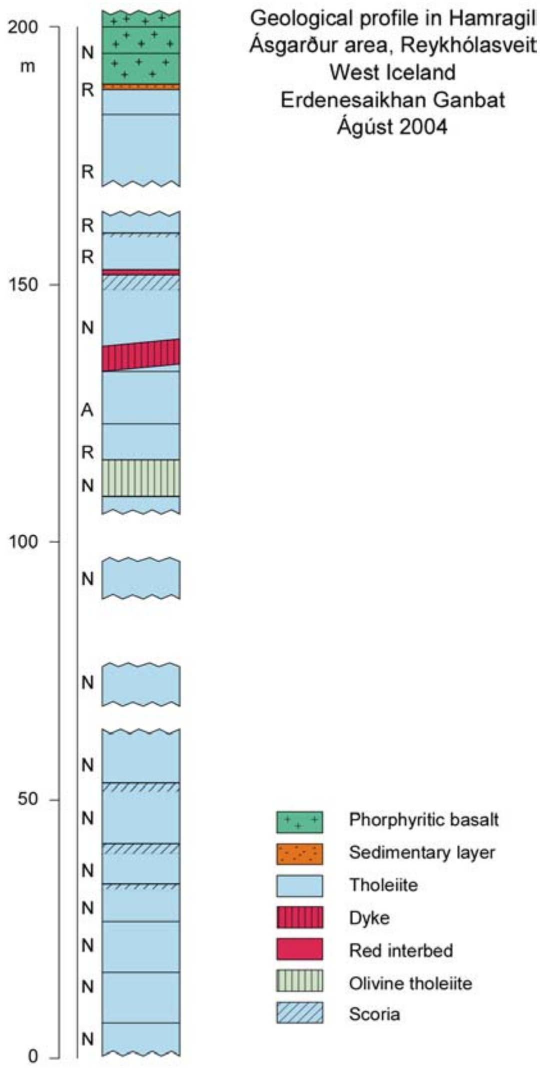

FIGURE 11: Detailed stratigraphy of the geological profiles, showing lava types and thicknesses, sediments, and magnetic polarity

Above it is an 80 m thick pile of tholeiite basalt composed of six layers with one thin sedimentary horizon of red coloured interbed. The topmost part of the pile is made of porphyritic basalt layers, comprised of up to 25% light coloured plagioclase phenochrysts. These layers are separated from the others by a 1 m thick sedimentary horizon.

The paleomagnetism of the lower part of the profile is normal (N). A polarity reversal takes place near its central part with some irregularity in the magnetic field. A new reversal seems to take place at the top of the profile. According to McDougall et al. (1977), this is the bottom of the Sídufjall geomagnetic subchron, 4.9 million years old.

7.2 Dykes

Relatively few dykes have been found in the research area (Figures 11 and 3). On the southern side of the study area, an olivine tholeiite dyke strikes N45°E that is subvertical and 5 m wide. The dyke continues towards the Kleppjárnsreykir hot springs. The dyke is shown on the geological profile in Figure 11.

7.3 Alteration

Chabazite is hydrous sodium calcium aluminium silicate that commonly occurs as a secondary mineral in cavities of olivine basalt (Pough, 1960). It is typical for the uppermost zeolite zone, and is most often found in olivine tholeiite. The chabazite is indicating a mild alteration of the rock. The formation of zeolites is strongly temperature dependent, and because of this, they are a useful guide to their deposition temperature. Figure 12 shows chabazite alteration in olivine basalt.

FIGURE 12: Chabazite in olivine basalt

8. CONCLUSIONS

The Hamralaug hot spring seems to be connected to an intersection of a fault having a northeasterly direction, and a fracture with north-northwesterly direction (Figure 13). The fracture is a continuation of the Hamragil gully towards the north-northwest. The production well at Bali is utilizing the fracture. The fracture therefore seems to be the near-surface aquifer, but the fault might act as a deeper geothermal aquifer diverting the hot water flow from the highlands.

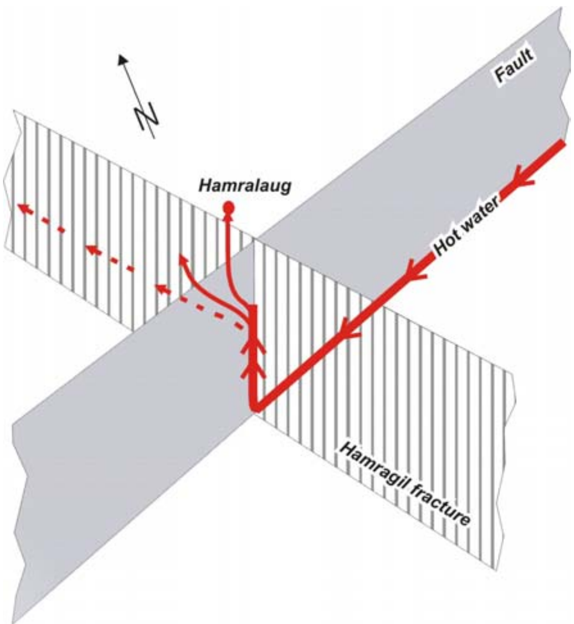

FIGURE 13: Geothermal model of the Ásgardur farm

The hot water upflow in the bedrock is not located directly below the Hamralaug spring, and the wells around it do not cut the water bearing fracture.

The water seems to flow horizontally for 20-30 m away from the fracture to the spring at the bottom of

25 m thick surface sediment layers.

The probability for a good production well near Hamralaug hot spring seems to be good.

This new production well should be located about 50 m southeast of the spring. It should be inclined 10°NW in order to cut the junction of the fracture and the fault at around 200 m depth.

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