UNITED NATIONS UNIVERSITY

GEOTHERMAL TRAINING PROGRAMME
Orkustofnun, Grensasvegur 9,
IS-108 Reykjavik, Iceland

Reports 2012
Number 34

GEOLOGICAL AND STRUCTURAL MAPPING OF THE MIDFELL-FLÚDIR LOW-TEMPERATURE GEOTHERMAL FIELD, S-ICELAND

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ABSTRACT

Geological, structural and surface alteration mapping was carried out in the Flúdir-Midfell low-temperature geothermal field in South Iceland. A Plio-Pleistocene interglacial and glacial bedrock succession is made of three units of hyaloclastite, and two units of basaltic lava flows, with intercalated sandstone and tillite. Fluvial silt and gravel was deposited during a marine transgression in early Holocene time.

Structurally, the bedrock of the area is steeply tilted to the northwest and strikes about N 40° E. It is intersected by a number of normal faults of mostly NE-SW trend with downthrows of several tens of metres, most of them to the southeast in a step fault pattern. Fractures of similar strike control most of the geothermal manifestations at Flúdir and Grafarbakki.

The low-temperature zeolitization of the bedrock indicates that at least 300-400 metres have been stripped off by erosion from the original surface of rock pile. From palaeomagnetic dating and available radiometric age dating in the area, the age of the rock is estimated to be about 2 m.y. old.

A soil temperature survey was carried out in a sedimentary covered geothermal field at Grafarbakki garden. The geothermal mapping indicated lateral flow from a NE-SW fracture underneath a 20 m high river bank of sediment. The geothermal model of the drilled area is consistent with the existence of a structurally controlled low-temperature geothermal reservoir at about 400 m depth.

1. INTRODUCTION

1.1 General geology of Iceland

Iceland is located on the divergent plate boundary of the Mid-Atlantic ridge. The rate of spreading is 2 cm per year. The formation of Iceland is believed to be due to its location on a mantle plume. The existence of a plume leads to dynamic uplift of the Iceland plateau and an increase in melting of the

mantle and volcanic activity relative to the submarine ridge. New crust is generated within the spreading zone. It includes volcanic systems which form a number of elongated en echelon segments across the country from southwest to northeast. The formation of the country is suggested to have started about 24 million years ago though the oldest rocks are dated about 16 million years old (Thórdarson and Larsen, 2007). Iceland holds a unique geological feature in the Mid-Atlantic oceanic plate boundary being seen on dry land.

The exposed volcanic pile of Iceland is predominantly of basaltic composition (80-85%), while acidic and intermediate rocks constitute about 10%. The basalts have been classified into three main types: compound flows of olivine tholeiite, simple flows of olivine tholeiite and quartz tholeiite and porphyritic flows in plagioclase. Olivine tholeiite morphologically gives pahoehoe lava fields, while olivine poor tholeiite gives primarily rise to aa lava fields. Sediments, mostly of volcanic origin, constitute about 5% of a typical Tertiary lava pile, but a much higher percentage in Quaternary rocks due to glacial erosion and deposition. The active periods of volcanic systems have been established to vary from 300,000 years to over 1 million years. They are preserved as entities in the volcanic pile, indicating that they grew within, drifted off towards the margin of the active spreading zone and then became extinct (Saemundsson, 1979).

The oldest exposed rocks in Iceland occur in the north-western and eastern parts as is obvious from their regional dips, super-positioning and the present configuration of the axial rift zones.

1.2 Geothermal aspect of Iceland

Iceland is characterised by high heat flow due to its geological location on a divergent plate boundary. The regional heat flow ranges from 80 to 200 mW/m^2, furthest away from and near the spreading zone, respectively. Geothermal activity in Iceland is categorised as low- and high-temperature fields. The latter are found in the active volcanic zones and are associated with central volcanoes which form the foci of the volcanic systems. By definition, the high-temperature areas are over 200°C at 1 km depth.

The low-temperature fields occur on the flanks of spreading zones and draw their heat from the regional heat flow of the crust. The geology in these areas is composed of mainly subaerial lava in the Tertiary part of the country and an increasingly higher percentage of subglacial volcanics in the lower and middle Quaternary areas (Fridleifsson, 1979). The current study area is located in that type of geology in South-Iceland about 25 km east of an active spreading zone.

1.3 Scope of the current study

Geological, structural and hydrothermal mapping are the earliest important investigations to be undertaken when evaluating any geothermal field for exploitation. The information obtained in these studies is vital in determining the upflow zone of the geothermal reservoir. With the complement of geochemical and geophysical exploration, the information can be used to build a geothermal model. Hence, the aim of the study was to map the lithologies and structures that might control the Midfell-Flúdir low-temperature geothermal field. The main objective of the study was to construct a geothermal model for the field. In order to realise this, the following objectives were set up:

- To establish the structure (strike and dip) of the bedrock in the Midfell-Flúdir geothermal field;
- To trace visible faults in the bedrock and search for fractures in the sediment covered geothermal field;
- To establish the relative age of rocks in the Midfell-Flúdir geothermal field;
- To establish current soil temperatures of Grafarbakki farm for comparison with an earlier survey;
- To define the siting of production boreholes drilled south and north of Midfell, relative to the faults and fractures found in this study.

In order to attain these objectives, the following activities were undertaken:

- Detailed geological and structural mapping of Midfell-Flúdir geothermal field, in order to understand the structure of the bedrock;
- Measure the palaeomagnetic signature of the rock, for comparison with the Matuyama part of the palaeomagnetic time scale, in order to establish the approximate age of the rocks;
- Measure soil temperature profiles to define the thermal pattern of a sedimentary-covered geothermal field and to delineate its extent.

1.4 Geological position of the study area

The study area is located on a microplate (Hreppar plate) between active spreading zones to the west and east. The Hreppar plate was generated on the western spreading zone and the regional dip of its rocks is to the northwest. The geology of the area is characterised by rocks called the Hreppar series of tilted plateau basalt with intercalations of hyaloclastite, and sediments including tillite. The rocks of the Hreppar series occupy the whole gap between the two limbs of the active volcanic zone in Southern Iceland (Saemundsson, 1970).

1.5 Location and accessibility of Midfell-Flúdir

Midfell-Flúdir is located in Hrunamannahreppur municipality in Southern Iceland. The field is located within latitude of 64°6'- 64°8'North and longitude 20°21'-20°18'30"West. The area can be accessed from Reykjavík to Selfoss using the main Sudurland road and from Selfoss to Midfell-Flúdir area using the Skeidar and Hrunamanna road. Figure 1 shows the location of the study area and the volcanic zone. Midfell mountain is found to the northeast of Midfell farm village while Flúdir is located to the northeast of the mountain.

FIGURE 1: Location of the study area in S-Iceland and in relation to the volcanic zones (inset map)

There is no thermal spring in the Midfell field but a hot water borehole was drilled there in 1969. It intersected a hot aquifer at 120-140 m depth. The borehole is still producing hot water of about 63°C. The Flúdir geothermal area is one of the largest low-temperature fields in South Iceland. It has a production capacity of well over 100 l/s of boiling water. The natural flow before drilling was about 25 l/s of 90-100°C water from a 1.5 km line of hot springs.

The study area has a population of about 250 people. The main economic activity is agriculture including greenhouse farming. The geothermal resource of the area is mainly utilised directly, including district heating, swimming pool and greenhouse farming.

2. PREVIOUS WORK IN THE MIDFELL-FLÚDIR AREA

2.1 Geology and hydrothermal alteration mapping

The geology of this area was first described by Kjartansson about 50-70 years ago. He named the plateau basalts, with their abundant intercalations of hyaloclastites and tillite rocks, the Hreppar series. In his writings, the Hreppar series included rhyolites, and intrusive bodies. Saemundsson (1970) described the main structural features of the Hreppar series and the interglacial lavas overlying it discordantly. Aronson and Saemundsson (1975) published radiometric datings of the Hreppar series.

2.2 Geothermal model

Björnsson and Saemundsson (2006) presented a model of the wider geothermal area of Hreppar (Figure 2) based on borehole data, structure and a resistivity survey and map by Georgsson et al. (1988). It shows the Flúdir-Midfell area as part of a 3-5 km broad tongue extending over 20 km NE-SW with a main upflow zone 10 km northeast of Flúdir.

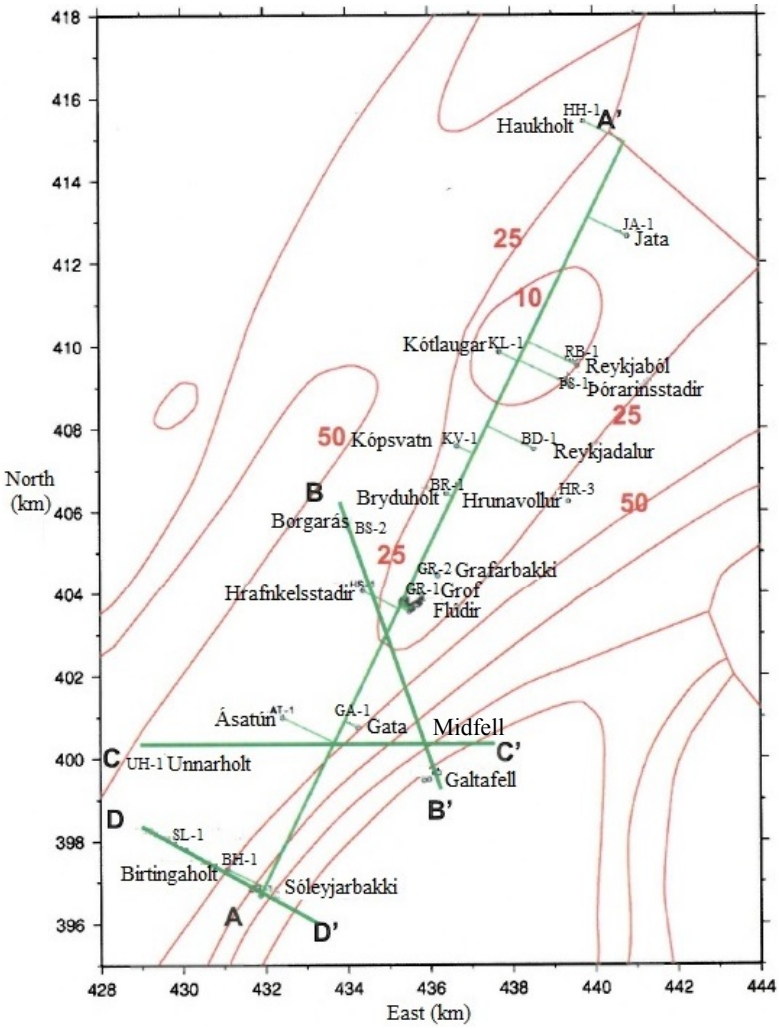

FIGURE 2: Iso-resistivity contours (Ωm) and boreholes in the area of the Hrunamannahreppur geothermal anomaly (Björnsson and Saemundsson, 2006)

3. GEOLOGICAL AND STRUCTURAL MAPPING

3.1 Methodology

Geological and structural mapping was carried out in August, 2012, covering the Midfell mountain and Flúdir geothermal field. During the survey, several rock formations of hyaloclastite, basalt, tillite and sandstone were identified. Many structural features were mapped, including faults and fractures. Most of these structures were tracked in the field using a GPS where accessible. Where not accessible, the features were delineated from the base map and aerial photo. A topographical map of 1:10,000 was used as a base map for the drafting of the geological map. Short notes were also taken. Map-Source and ArcGIS software were used to process the data. Figure 3 shows a geological map of Midfell mountain, while Figure 4 shows two geological cross-sections, locations are shown on Figure 3.

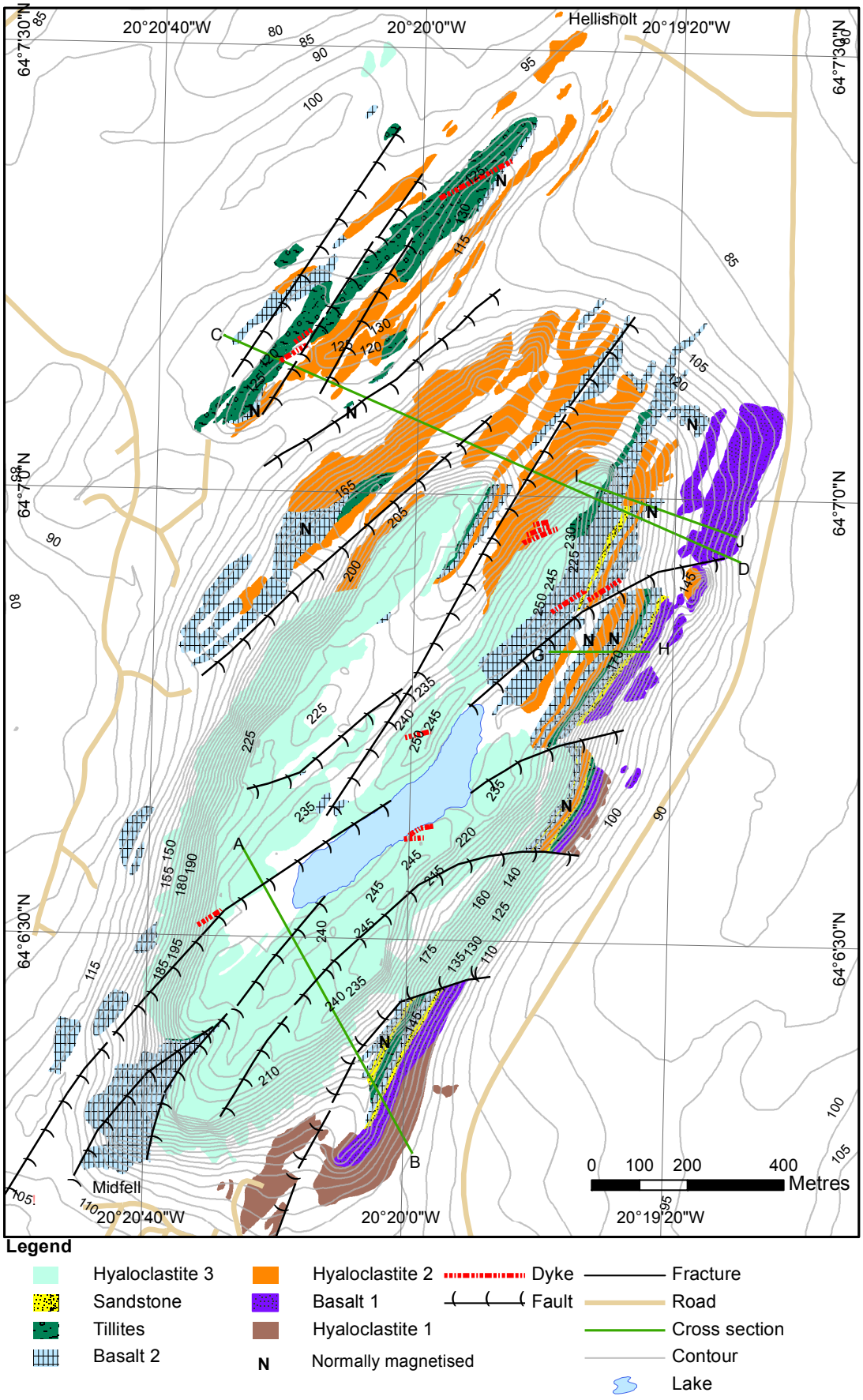

FIGURE 3: Geological map of Midfell mountain

3.1.1 Palaeomagnetism

Palaeomagnetism is the dating method that uses ancient remnant magnetization in rocks. The principle is that during rock formation, igneous rocks acquire the earth's magnetic polarity of that time. This magnetic sign is kept in the rocks' magnetic minerals. Rock which was formed when the earth's magnetic polarity was in the opposite direction to the current one will show a reversed magnetic sign and rocks formed during similar earth magnetic fields to the current one will show normal magnetisation.

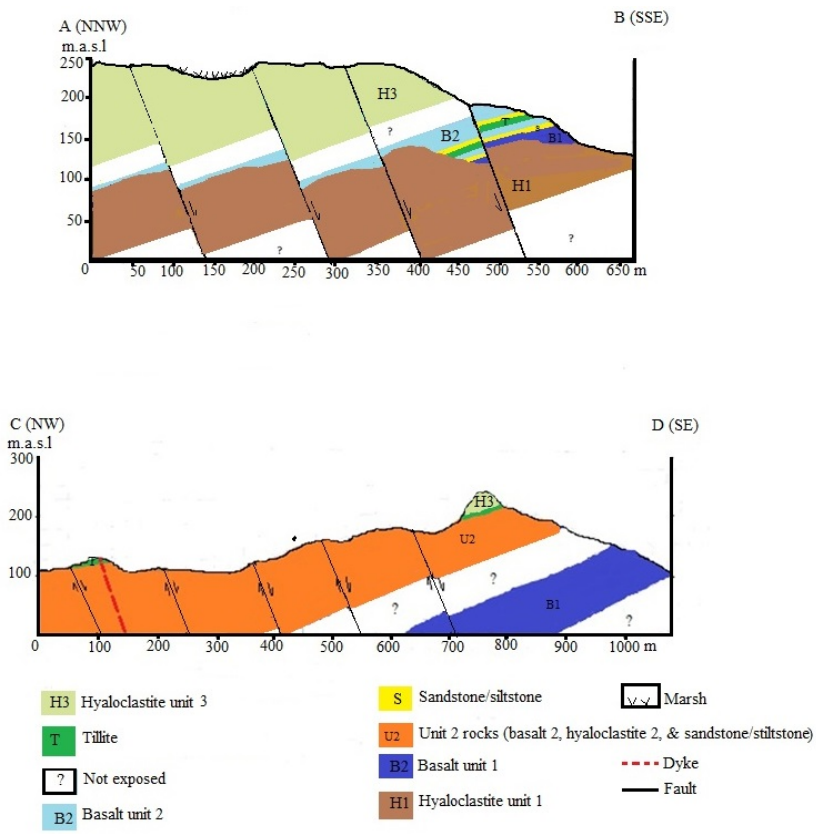

FIGURE 4: Two geological cross-sections from the study area, trending NNW-SSE and NW-SE; locations are found in Figure 3

Using this principle, the palaeomagnetism of the rock sequence of Midfell was determined using a portable magnetometer. The thickness of each stratum within the profile was measured and recorded. Then a profile was constructed and compared with the Matuyama part of the palaeomagnetic time scale.

3.2 Rock types of the Midfell-Flúdir area

Three main rock types were identified: volcanic, intrusive and sedimentary. The volcanic rocks of the area are made of hyaloclastite and basalt flows. The sedimentary rocks are composed of four varieties namely tillite, sandstone, siltstone and conglomerate. The intrusive rocks of the area are composed of dykes and sheets.

3.2.1 Hyaloclastite

Hyaloclastite rock consists of tuff, breccia and pillow lava:

Hyaloclastite tuff is partially glassy and palagonite. It is black in colour where glass dominates or brown in colour where palagonitized. Secondary zeolite minerals were observed in the hyaloclastite other than the tuff.

Breccia. It is made of lithic fragments of basalt in a matrix of granular glass. The low-temperature zeolites, thomsonite and chabazite, are the most abundant secondary minerals. It is dark in colour.

Pillow lava. It consists of densely packed pillows. The size of the pillows ranges from a few centimetres to two metres. Figure 5 shows pillow lava within hyaloclastite unit 1 at Mt. Midfell. The outer surface of the pillows consists of a black glassy rind, while inside it is densely jointed and fractured. Secondary zeolite minerals were observed in the pillow lava.

The hyaloclastites occur as layers and were also observed as piles of rocks buried by basalts, southeast and northeast of the mountain. In most cases, hyaloclastites (other than the tuff) are not layered.

FIGURE 5: Pillow lava within hyaloclastite unit 1 at Mt. Midfell

3.2.2 Lavas

There are two types of basalt lava flows:

Tholeiite basalt. It shows flow banding and is greyish in colour. The tholeiite is more porous and has a thick upper part of somewhat rough scoria. It contains low-temperature zeolites, mainly chabazite and occasionally thomsonite. In most cases the tholeiite has been broken into slabs, a characteristic that comes from banding. Two tiered columnar jointing occurs as well.

Olivine basalt. It is composed of a fine-grained matrix with some olivine crystals visible to the unaided eye. The flows have no flow banding and are dark in colour. Zeolites and opal are most abundant in this type of flow.

3.2.3 Tillite

The tillite layers of Midfell are composed of heterogonous conglomerates of large to small sized boulders cemented in a grey matrix. The matrix consists of a fine-grained, weathered volcanic glass of hyaloclastite origin. The clasts consist of basalt, roundish and subangular. The tillite forms layers of variable thickness, a few tens of metres up to many metres. There is no stratification in the tillite. It is dense and no secondary minerals were observed.

3.2.4 Other bedrock sediments

At Midfell mountain thin sandstone and siltstone layers were observed. They consist of coarse- to fine-grained sandstone and siltstone. The siltstone is greyish in colour, while the sandstone is brownish. Both sandstone and siltstone are bedded and consist of regular stacked layers. Occasionally the direction of the transporting agent can be seen acting from northeast to southwest. Soil remnants were observed between some of the lavas. They are reddish in colour. The thickness seen was in the range from traces to 30 cm. Such layers are best seen in the steep side of southeast Midfell. Elsewhere the inter-lava contacts are usually covered and often only the dense middle part of the flows is exposed.

3.2.5 Post-erosional silt and conglomerate of Early Holocene age

A sedimentary stratum of about 20 m thickness was identified along the banks of Litla Laxá river and Hellisholtalaekur brook close to the Flúdir swimming pool. It seems to extend across the level country around Midfell mountain but is not exposed because of vegetation cover, settlements and farms. This is a post erosion marine to fluvial deposit. The lower silt part of it is horizontally bedded and forms the base of the conglomerate. The conglomerate consists of a lower foreset bedded unit and an upper topset unit. The post erosion silt was formed offshore. A stream transgressed over it, depositing the foresets in shallow waters and the topset on land. At the end of Pleistocene there was a transgression event where the sea level rose high, relative to the land, and the shoreline moved toward higher ground about 90-100 m in our area. The origin of the sediment was due to rapid melting of the Pleistocene ice sheet and ample loose deposits left over by glacial erosion. The conglomerate indicates that the deposition was near shore with high energy water levels. The conglomerate is mainly basaltic.

3.3 Stratigraphy of the Flúdir-Midfell area

3.3.1 Stratigraphic layers

Hyaloclastite unit 1 is the oldest rock in the area and forms the basement of the Midfell mountain. The unit is well exposed on the southeast part of the mountain. It consists of mainly hyaloclastite breccia and tuff. The tuff is fine-grained and palagonitized. An isolated pillow lava outcrop occurs northeast of the main exposure. It belongs probably to this unit. The pillow lava is about 7 m thick at the outcrop. Secondary minerals of zeolites like chabazite and thomsonite were observed.

Basalt unit 1. Overlying the hyaloclastite are basalt lava flows. The presence of lava flows tells that there was an interglacial period where volcanic eruptions were not affected by glacial cover. The unit consists of flow banded tholeiite basalt. In some localities the tholeiite forms two tiered columnar jointing. This means that the lava was flowing in a depression which resulted in water flowing over it while still hot. This resulted in the formation of the irregular columns at the top of regular columns (Saemundsson, 1975). The thickness of this unit ranges from a few metres to tens of metres.

Hyaloclastite unit 2 consists of pillow breccia in a matrix of porous shards. The size of the pillows ranges from a few centimetres to about two metres; highly fractured and broken pillows with filled fractures were considered largely as in situ pillows. This unit is widespread, meaning that at the time of the formation the whole area was covered by a glacier. The thickness of the unit east of Midfell is about 10 m. In the northeast it forms a pile of up to 50 m thickness. This unit is overlain by tillite.

Basalt unit 2. Overlaying hyaloclastite unit 2 is basalt unit 2. It consists of tholeiite and olivine basalt. In some cases, the scoria part of the lavas has been oxidised to a reddish brown, probably due to the heat from the overlying flow. The basalt flows are generally massive, but the top is scoreaceous and vesicular.

Tillite and other sediments. Tillite overlies basalt unit 2. It consists of roundish and subangular basalt pieces set in a grey matrix. This material was transported for a long distance by glacial action which compacted the till. The thickness of the layer is about 12 m.

A coarse- and fine-grained layer of stratified conglomerate and sand-stone was observed overlying the tillite. It suggests fluvial deposition after the ice melted. The direction of the transporting agent was from northeast to southwest. The thick-ness of the sandstone is a few cm.

Hyaloclastite unit 3 is found at the top of the Midfell mountain. It forms the largest part of the Midfell bedrock sequence by area and thickness. It is mainly composed of breccia with pillow lava and basalt sheets near the base. Bedding with shallow southeast dip was seen in the south of Midfell mountain. It suggests deposition from the east or northeast. The maximum thickness observed in the south of Midfell was over 50 m.

3.3.2 Relative age of Midfell rock sequence

Profiles (GH and IJ in Figure 6) show the position of a few normally magnetised flows within a sequence of reverse magnetisation. The profiles only show a part of the basalt's magnetism, but all of the hyaloclastite, i.e. the pillow lava, was measured and was found to be reversed. All the sheets and dyke that were measured showed also reverse magnetisation. This shows that the Midfell rocks are reverse normal reverse (RNR). The normally magnetised flows occurred near the middle of the section. The very thin normal group and radiometric dating of a few samples within the Hreppar district indicate a most likely correlation with the Reunion event of the Matuyama epoch and, thus, an age of about 2.2 Ma (Saemundsson, 1970). Therefore, the Midfell rock sequence is estimated to be 2.2 Ma old.

3.4 Tectonics

The early Pleistocene rock sequence of Midfell mountain and its surroundings is tilted to the northwest and cut by numerous normal faults trending NE-SW. Dykes cutting the sequence have been tilted with it. The structural trend of the area is approximately parallel to the axis of the spreading zone to the northwest (Western Volcanic Zone).

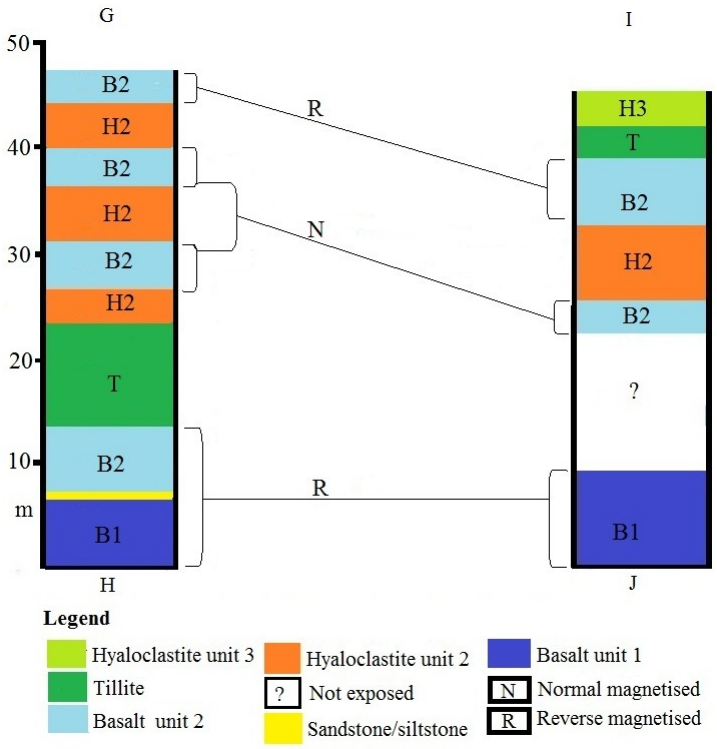

FIGURE 6: Palaeomagnetic profiles GH and IJ; for location see Figure 3

3.4.1 Strike and dip

The rocks of Midfell mountain strike northeast at about 40°. The dip is to the northwest at about 25°. Such steep dips occur in Iceland only as a result of regional flexing or locally due to a volcano-tectonic process within a central volcano (Saemundsson, pers. comm.). One such is immediately east of Midfell (Fridleifsson, 1970). In southern Midfell the breccia of hyaloclastite unit 3 dips to the southeast at a few degrees (about 5°). This dip is depositional, i.e. foresets that were originally dipping some 30°SE were tilted back tectonically.

3.4.2 Tilting

The northwest dip of Midfell rocks was caused by tectonic tilting. The area experienced tilting after the build-up of the entire volcanic sequence and its faulting. As the result of tilting, the faults which originally were nearly perpendicular have now been reduced to about 65° dip. This characteristic is prominent in most of the faults. It was suggested that the change in dip of the Hreppar rocks (which are part of the current study area) was caused by the accumulation of volcanic materials in the western limb of the active volcanic zone to the west (Saemundsson, 1967). However, as the very steep dips are local rather than regional, other agencies must have contributed. Excessive volcanic production in the area to the northwest may have been the main reason.

3.4.3 Faults and lineaments

All the faults trend almost NE-SW, at about 45° and the fault planes dip 65° and 70° southeast. The study estimated that the initial dip of most faults was almost vertical. A fault with an opposite throw to the northwest was identified in the southeast of Midfell mountain. A splay fault west of it dips about 80° southeast. This characteristic would at first suggest a reverse fault. It is suggested that this fault was initially nearly vertical like the others but, because of the northwest tilting of the area, it acquired a tilt of about 65° to the southeast, resembling a reverse fault. Figure 4 with the geological cross-sections AB and CD displays the inclination of the faults.

At Flúdir, fractures of similar strike were observed in Holocene conglomerate connecting two old boreholes. Such fractures were also noted in Holocene silt at the hot spring field northeast of the main green house complex at Grafarbakki. In all localities, hot springs are associated with fractures. Thus,

at several places along Litla Laxá river, fractures were observed in the Holocene overburden in the survey area, producing hot water of about 90°C.

3.5 Intrusive rocks

Two types of intrusive rocks were observed in Mt. Midfell: Dykes and sheets that are part of hyaloclastite unit 3; and such sheets and dykes that cut all the other rock units.

3.5.1 Dykes and sheets co-genetic with hyaloclastite unit 3

The first type of intrusive rocks is composed of sheets that form the base of hyaloclastite unit 3. Dykes that cut into the hyaloclastite of this unit are also found within it as irregular lenses. Plugs of dense basalt occur near the base of it in the southwest of the mountain. All these are characterised by columnar jointing and there are chilled margins. In this category of intrusive rock, the sheets predominate over dykes. The size of both sheets and dykes ranges from a few centimetres to one metre. The plugs measure tens of metres across. In some localities it is difficult to differentiate the sheets and dykes from the main body of the hyaloclastite. Of alteration minerals, only opal was identified in these rocks. The texture is aphyric like the main body of hyaloclastite unit 3.

3.5.2 Other dykes and sheets

A few dykes cut several units of Midfell mountain. The dykes stand almost perpendicular to the lavas where they intersect them. The sheets are inclined at less than 30°. The composition of both is that of fine-grained basalt without phenocrysts and they are dark in colour. They trend NE-SW and dip southeast, but a few trend E-W. The thickness of both dykes and sheets ranges from less than 1 to 5 m. Figure 7 shows a dyke northwest of Midfell mountain.

FIGURE 7: A dyke northwest of Midfell mountain

3.6 Secondary alteration of the Midfell sequence

The rocks of Midfell usually contain secondary minerals such as zeolite, and opal. The zeolites were identified as chabazite and thomsonite; opal was the only silica mineral. In the olivine basalt the secondary minerals are mostly abundant. Hyaloclastite amygdales in some localities contain chabazite and thomsonite. Chalcedony and quartz were not found in any of these localities. The secondary mineralisation intensity is low, indicating a low pre-erosion temperature of 50-60°C. This would indicate that about 300-400 m may have been stripped off by erosion from the original surface of the rock pile (Saemundsson and Gunnlaugsson, 2002).

4. GEOTHERMAL MAPPING

Mapping of geothermal surface manifestations was carried out in order to understand the Midfell-Flúdir geothermal field while preparing for a preliminary geothermal model.

4.1 Methodology

Geothermal mapping in this study included a ground temperature survey, locating of thermal springs and deposition of them and hot water boreholes. The temperature of the springs and whether they were boiling or sported geyser action was noted as well. Hot grounds were mapped by tracking around them. Both new and old boreholes were located by GPS. The data was then downloaded into a computer using Map-Source software. Then ArcGIS software was used to analyse the data. Figure 8 presents a map of the geothermal manifestations of Flúdir and Grafarbakki.

4.2 Hot springs and hot water boreholes

Flúdir geothermal area has boiling springs in an area which is about 1.5 km long, oriented NE-SW. There are three main groups of springs. The largest is at Hvammur in the northeast of the hot spring group. The natural flow was about 25 l/s of boiling water. Most of the hot springs with temperatures above 90°, both at Hvammur and Grafarbakki, are surrounded by minor silica sinter. Old abandoned boreholes were seen to be coated with silica sinter as well. In some samples, calcite was found to be a secondary mineral, seemingly filling the fractures of rocks at the bottom of the river Litla Laxá. Silica sinter was the most common deposit in the hottest area. Most of the area enclosed by the 50°C isotherm had some silica sinter. Within it were found mostly boiling springs. The highest temperature measured in the hot springs was 99°C. The vegetation gives a rough picture of the temperature within the hot ground, being yellowish to brown in areas with temperatures higher than 40°C.

Steam from hot water seepage was observed southwest of Grafarbakki on the Litla Laxá river bank. Most of these thermal springs and hot grounds are aligned with fractures trending 45° northeast. Figure 9 shows a geyser hot spring at Grafarbakki in action. Similar fractures were observed at Flúdir connecting two old boreholes.

The main borefield is located at the southwest group of hot springs, at Flúdir. There are five production boreholes with a total yield of about 100 l/s free flow. The maximum borehole temperature ranges from 101°C in the borehole farthest to the southwest, to 105°C in the borehole farthest to the northeast, over a distance of about 150 m. The boreholes are shallow, most of them about 300 m. One borehole in the northeast Grafarbakki group is 190 m deep. It yields about 100 l/s of free flow boiling water when fully open. The inflow at depth measures 108°C. Free flow from it interfers with flow of the Flúdir wells.

There are no geothermal manifestations at Midfell farm village, but the hill between Flúdir and Midfell (Mt. Midfell and the area west of it) is split by normal faults which trend towards Flúdir. In 1968 a hot water borehole was drilled at Midfell. It struck a 63°C aquifer at 120-140 m depth. Below it, there was an inversion in temperature to 36°C at 350 m depth. This borehole struck one of the old faults which seem permeable to hot water which is suggested to be coming from the northeast.

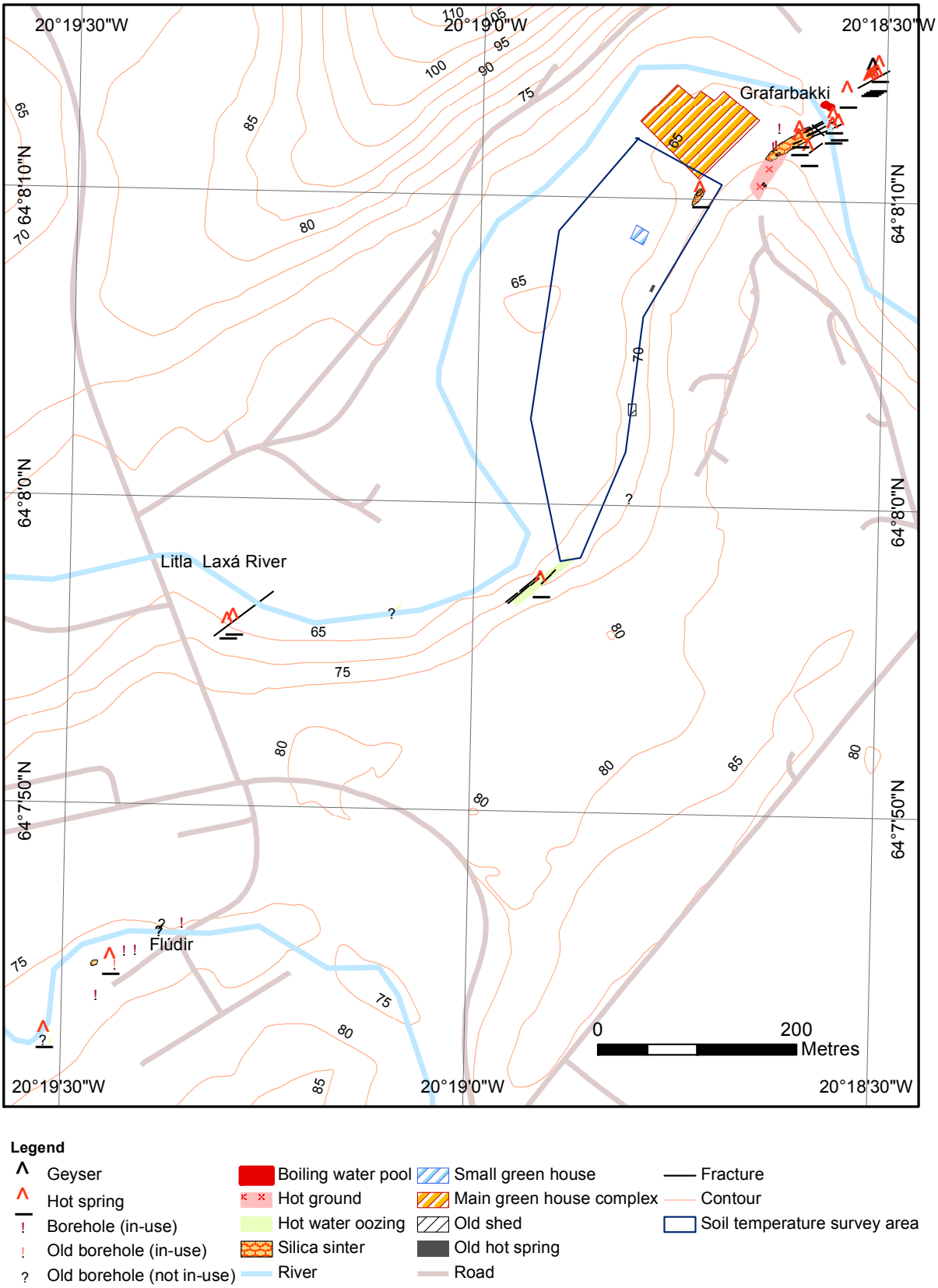

FIGURE 8: Geothermal manifestation map of Flúdir and Grafarbakki

4.3 Ground temperature survey

FIGURE 9: Geyser hot spring in action at Grafarbakki

As part of the study, soil temperature measurements were done at Litla Laxá at Grafarbakki. The measurements were done from 2nd to 6th August, 2012. The aim of the survey was to define the thermal pattern of a sediment covered geothermal field and to delineate its extent. In addition, the survey was done to establish data for comparison with an earlier study done by Fridleifsson in 1997. The weather during these days was mild, about 12-14°C air temperature, cloudy with occasional showers. The wet conditions did not have any effect on the measurements. The garden that was measured was mostly bare. This was during harvesting time and the measurement lines crossed through a whole garden and pathways.

To start with, a straight line was laid down with the accuracy of the measuring tape. The length of the lines ranged from 50 to 70 m, except for the first and second lines which were 10 m and 30 m, respectively. A steel rod was hammered into the ground before the thermometer was inserted; the temperature was read and recorded after a few minutes. Measurements were made at 5 m intervals at 60 cm depth. The temperature readings were recorded with respect to GPS waypoints. The waypoint data was downloaded into the computer using Map-Source software. The manually recorded data was entered into an Excel worksheet. These two data sets were then combined and processed using ArcGIS software. The uncertainty factor in the measurements is about ± 0.5°C. A one degree (°C) discrepancy from these measurements is within error limits (Fridleifsson, 1997), but weather factors and the condition of the gardens also have to be accounted for if similar measurements are done in the future. The current study field was larger than the earlier study area. The comparison of the two fields should take this into account.

Figure 10 shows an isotherm map of Grafarbakki farmland from the current study (2012), plotted in 10 step isotherms. The highest measured temperature was 87.4 °C at 60 cm depth at the most northeasterly line of the surveyed area. The minimum temperature recorded was 15.3 °C. There is an increase in the temperature when compared with the previous study. Figure 11 shows the isotherm map of Grafarbakki farmland which was done 15 years ago by Fridleifsson (1997) in late June. It recorded 10°C as the minimum and 42.2°C as the maximum temperature. This was the opposite of what was feared, that the drilling of a new well might cause lowering in the temperature of the farm land. However, the high-temperature anomaly that was previously recorded near a hot spring in the southernmost tip of the survey area had decreased from 72.6°C to 36.8°C and shifted westward in the current findings, relative to the earlier survey. The different measurement dates, (late June in 1997 with temperatures of 10-12°C vs. early August in 2012 with temperatures of 12-14°C) may influence the difference between the results of the surveys to some extent. However, it is unlikely that this is the only reason.

The soil temperature map shows temperature anomalies trending NE-SW with a maximum near the 20 m high bank of Litla Laxá. The hot water that heats the soil seems to come from underneath there. This

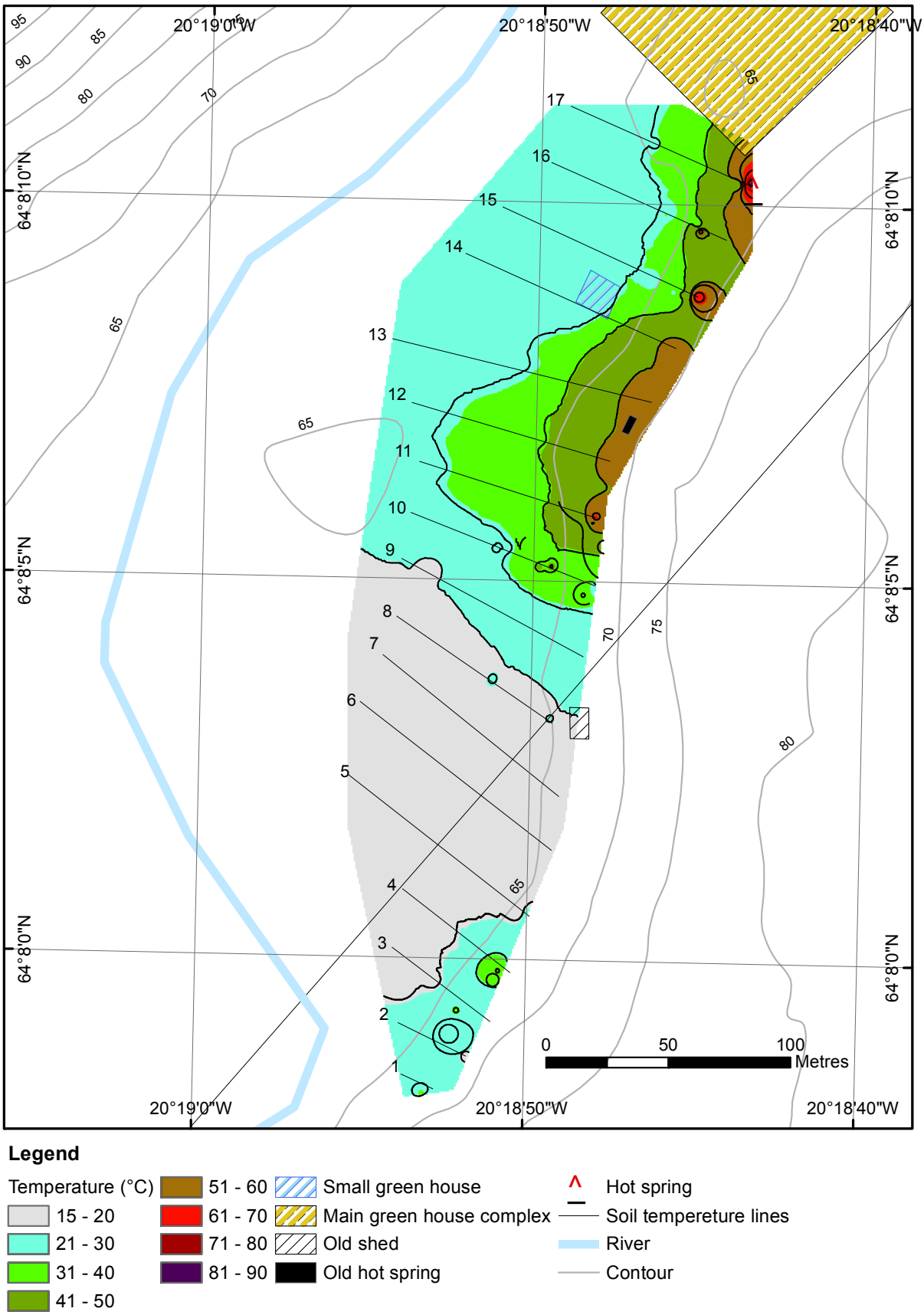

FIGURE 10: An isotherm map of the Grafarbakki farmland from the current study (2012)

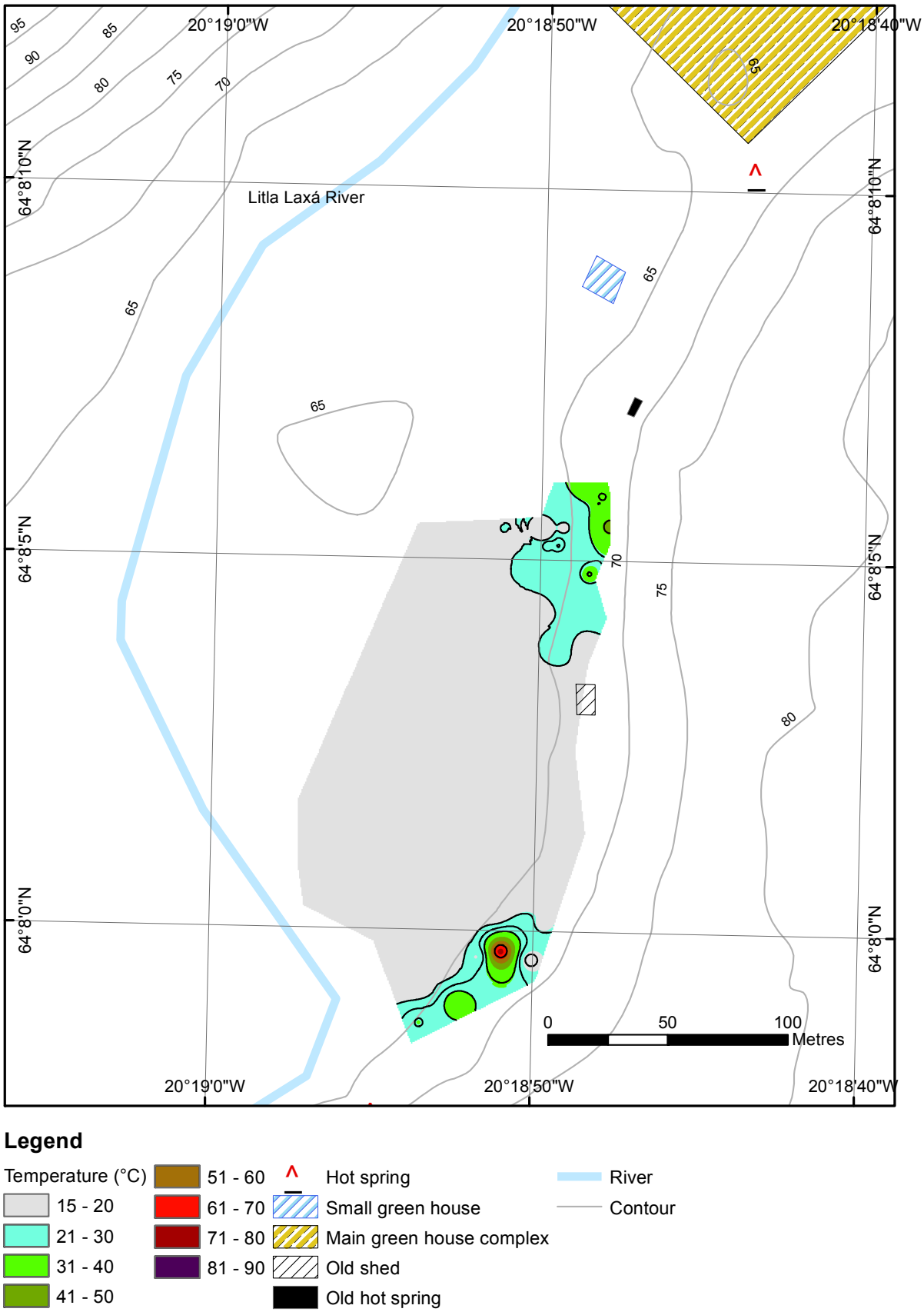

FIGURE 11: An isotherm map of the Grafarbakki farmland from the previous study by Fridleifsson (1997)

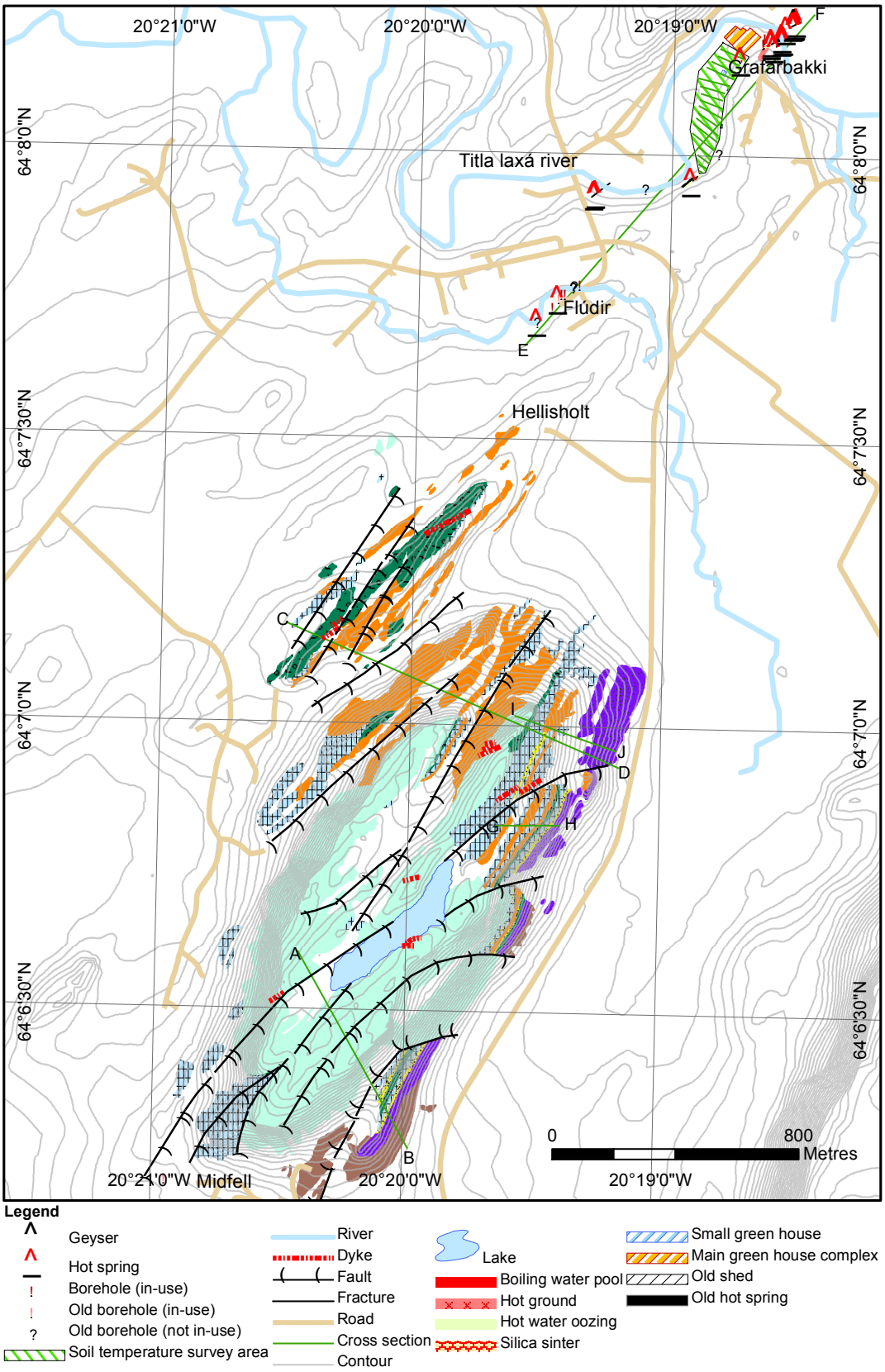

FIGURE 12: Structural and geothermal manifestation map

is also indicated by hot springs half way up the bank at the contact between the silt and foresets. The hot spring area of Flúdir-Grafarbakki-Hvammur is in line with a proposed fault west of Midfell mountain (Figure 12).

Figure 12 shows the hot springs of the Flúdir area and structures. The hot springs are in line with a fault in the northwest part of the mapped area. Fractures of the same strike were noticed at the Flúdir hot springs (about 90°C) and in the river bed of Litla Laxá northeast of Grafarbakki. Similar fractures were identified at the bottom of Litla Laxá river near the bridge, producing a thermal spring of about 78°C. Almost all the hot springs in the area have a NE-SW trend and are in line with the Midfell fault system. For this reason, it is concluded that faults are contributing to or controlling the geothermal manifestations of the area.

5. GEOTHERMAL MODEL

A geothermal model of the general Hreppar area by Björnsson and Saemundsson (2006), shown earlier as Figure 2, was built using data from geological and geothermal mapping, borehole data and a resistivity survey. The model shows a major geothermal flow zone extending from the northeast across Flúdir-Midfell. The Flúdir-Midfell area forms the middle part of this geothermal anomaly. Figure 13 shows the geothermal model of that section. Retrieved data from boreholes revealed information about subsurface temperatures. These data show decreasing temperature from Grafarbakki across Flúdir to Midfell. Grafarbakki borehole GB-02 shows a temperature of about 108°C below 60 m depth and 105°C at 180 m depth. Flúdir borehole FL-08 shows a temperature of 104°C at 200 m depth. Borehole FL-06 shows a temperature of about 101°C at 200-300 m depth and there was an inversion below 300 m. Midfell borehole GA-01 (Figure 14) shows a temperature of about 63°C at 140 m depth, while there was an inversion to 36°C at 350 m depth.

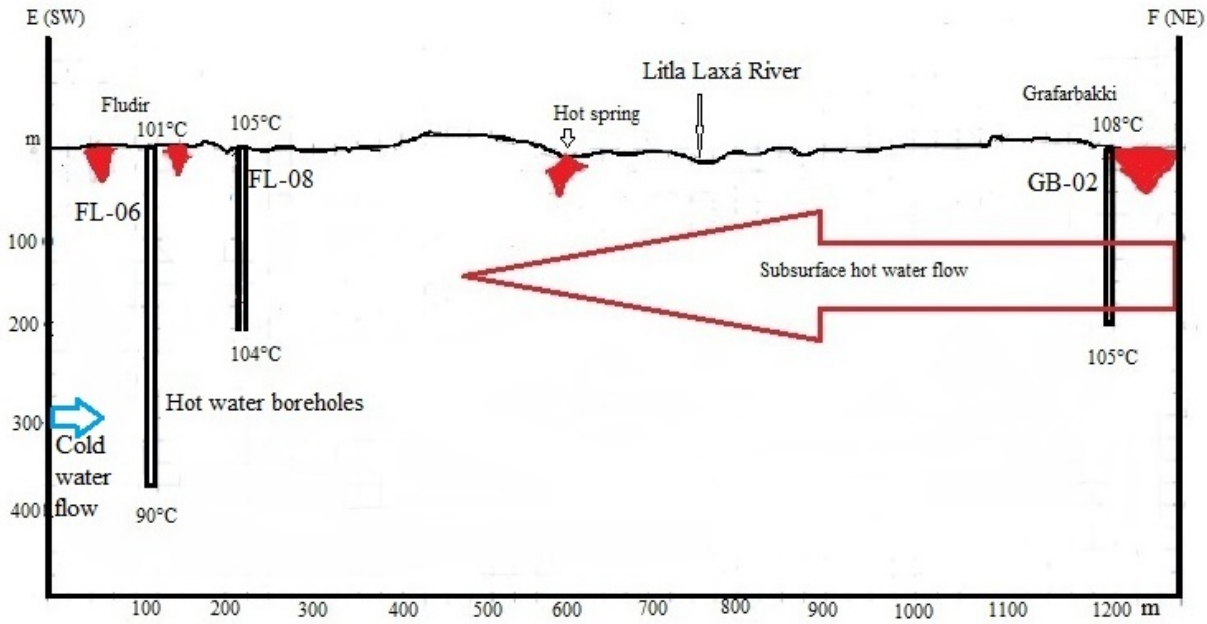

FIGURE 13: Geothermal model; for location see Figure 12

The temperature inversion in all the boreholes indicates hot water upflow north of Grafarbakki with flow to the southwest. The mapped NE-SW faults are permeable and provide conditions for the development of local convection systems.

6. CONCLUSIONS AND RECOMMENDATIONS

The Midfell-Flúdir area is located within a microplate called the Hreppar plate between active spreading zones to the west and east. The bedrock of the study area is composed of Early-Pleistocene rocks which consist of three cycles of interglacial-glacial sequences. The inter-glacial periods are characterised by the formation of basalt lavas, conglomerates, sandstone and siltstone while the glacial periods are characterised by tillites and hyaloclastite units that consist of different lithofacies, such as pillow lava, breccia and tuff. The low lands of Flúdir and Grafarbakki are completely covered by early Holocene siltstone and conglomerate. The bedrock of the study area is tilted by 25° to the northwest and cut by several normal faults trending NE-SW.

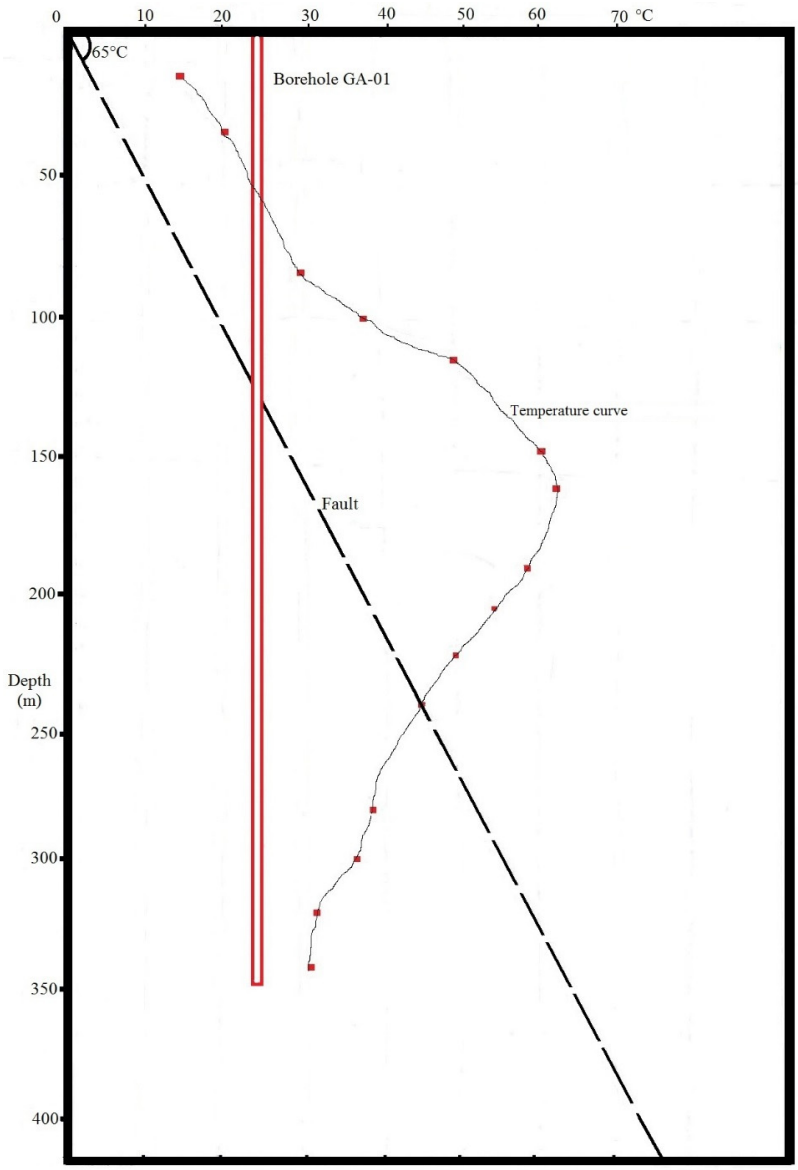

FIGURE 14: Borehole at Midfell farm village in relation to a normal fault west of it

Geological and geothermal mapping show geothermal water welling up from fractures. At depth, faults are channels for geothermal water. Most hot springs and hot ground are aligned within the fracture and fault areas. This indicates that the tectonic structures of the area control the distribution of the geothermal manifestations.

There were no geothermal manifestations south of Mt. Midfell. But 63°C hot water was struck at 120-140 m depth in a borehole. This together with data from several other boreholes in the area southwest of Midfell-Flúdir, showed that old basement faults should be targets for hot water drilling. Further mapping of basement faults is recommended for future drilling.

ACKNOWLEDGEMENTS

My warmest gratitude should go to the Director, the Deputy Director and all staff members of UNU-GTP. Supervisors, Dr. Kristjan Saemundsson and Dr. Gudmundur Ómar Fridleifsson, and lecturers and staff members at ISOR, you all deserve credit. Knowledge is power; you have empowered me.

REFERENCES

Aronson, J.L., and Saemundsson, K., 1975: Relatively old basalts from structurally high areas in Central Iceland. *Earth & Planet. Sci. Letters, 28,* 83-97.

Björnsson, G., and Saemundsson, K., 2006: *Temperature model of Hrunamannahreppur*. Orkustofnun, Reykjavík, report ISOR-06004 (in Icelandic), 17 pp.

Fridleifsson, G.Ó., 1997: *Temperature measurements of soil at Litla Laxá in the land of Grafarbakki 2, Hrunamannahreppur*. Orkustofnun, Reykjavík, report GÓF-97-04 (in Icelandic), 4 pp.

Fridleifsson, I.B., 1970: *The Stóra-Laxá igneous complex.* University of St. Andrews, Edinburgh, MSc. thesis, 88 pp.

Fridleifsson, I.B., 1979: Geothermal activity in Iceland. *Jökull, 29*, 47-56.

Georgsson, L.S., Hjartarson, Á., Hardarson, B.A., Sigurdsson, F., Torfason, H., and Saemundsson, K., 1987: *Natural conditions for fish farming in the upper counties of Árnessýsla and Rangárvallasýsla.* Orkustofnun, report OS-88045/JHS-08 (in Icelandic), 39 pp + maps.

Saemundsson, K., 1967: An outline of structure of SW-Iceland. In: Björnsson, S. (ed.*), Iceland and Mid-Oceanic Ridges.* Soc. Sci. Islandica, 38, 151-161.

Saemundsson, K., 1970: Interglacial lava flow in the lowlands of southern Iceland and the problem of two-tiered columnar jointing. *Jökull, 20,* 62-77.

Saemundsson, K., 1979: Outline of the geology of Iceland. *Jökull, 29*, 7-28.

Saemundsson, K., and Gunnlaugsson, E., 2002: *Icelandic rocks and minerals*. Edda and Media Publishing, Reykjavík, 233 pp.

Thórdarson, Th., and Larsen, G., 2007: Volcanism in Iceland in historical time: Volcano types, eruption styles and eruptive history. *J. Geodyn., 43,* 118-152.