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GEOTHERMAL EXPLORATION IN SKARDSMÝRARFJALL, HENGILL AREA, SW-ICELAND

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ABSTRACT

The present study area is a part of the active Hengill central volcano. It is categorized as a high-temperature area in line with measured and inferred temperature greater than 200°C at less than 1 km. The geothermal manifestations in the area are located above 300-400 m altitude. A boiling reservoir at some depth causes geothermal manifestations like hot ground. The distribution of geothermal manifestations appears to be controlled by faults/fractures almost in a NE-SW direction. In part of the area the bedrock is altered whereas the overlying glacial sediment is fresh, thus indicating declining activity since the area became ice free. Most of the geothermal manifestations lack native sulfur. The extinct hydrothermal alteration has probably reduced the porosity and permeability. This affects the present surface geothermal activity, most of which appears to be related to structural features like faults.

Two types of geothermal activity are observed: a) Extinct alteration which is evidenced by greenish- reddish altered hyaloclastites, the alteration minerals are smectite and iron oxides. b) Present geothermal activity, represented by areas of hot geothermal manifestations are characterized by grey or dark brown to reddish brown smectitic clays.

1. INTRODUCTION

Vietnam, which is the home country of the author, has experienced a shortage of electricity in recent years. This shortage is prominent especially during the summer season. In order to find ways to improve the electrical supply, Geological Survey of Vietnam and Research Institute of Geology and Mineral Resources have cooperated to study the geothermal resources in the country. Training of specialists in the different geothermal science fields is an important part of that.

The author participated in the Geothermal Training Programme of the United Nations University in Iceland in 2001, in the specialised field of geological exploration. The training duration was six months beginning in April. The first month covered general lectures in the various fields of geothermal sciences, and the next two were used for specialised lectures, field excursions and training in geological exploration. The last 3 months were used for practical training in geothermal exploration, carrying out a geothermal mapping project under supervision, results of which are described in this report. In the exploration of a geothermal prospect, geological mapping of surface geothermal manifestations, shallow temperature surveys and measurement of the flowrate of springs are among the first steps to define possible geothermal resources. The objective of the study presented here, was to give the author practical training in geothermal exploration, including geological mapping with analysing of geological structures, mapping of surface geothermal manifestations and use of shallow temperature measurements for mapping the distribution of the geothermal output.

2. THE HENGILL AREA

2.1 General aspects of the geology of Iceland

Iceland is situated at about latitude 65°N in the North Atlantic Ocean, just south of the Arctic circle. It is located at the intersection of two major structures, namely the Mid-Atlantic Ridge and the Greenland-Iceland-Faeroes Ridge. The Mid-Atlantic Ridge defines the constructive plate boundary between the American and the Eurasian plates. From magnetic anomalies to the north and south of Iceland, the spreading rate has been estimated as 2 cm/year. The Greenland-Iceland-Faeroes Ridge is thought to be the trail of the Icelandic hot spot, which has been active from the time of opening of the North Atlantic Ocean 60 million years ago to the present. The hot spot is thought to be located below Central East Iceland, close to the volcanic rift zone which crosses Iceland from southwest to northeast in a complicated manner. The volcanic rift zone is the surface expression of the Mid-Atlantic Ridge in Iceland. It is divided into two parallel branches in South Iceland. In South Iceland and north of Iceland, the Mid-Atlantic Ridge has been displaced to the east by transform faults, which are defined as fracture zones. The southern fracture zone is called the South Iceland seismic zone while the northern one is called the Tjörnes fracture zone. These fracture zones are very active seismically and earthquakes are experienced regularly. The largest known earthquakes have been of a magnitude that can exceed 7 on the Richter scale.

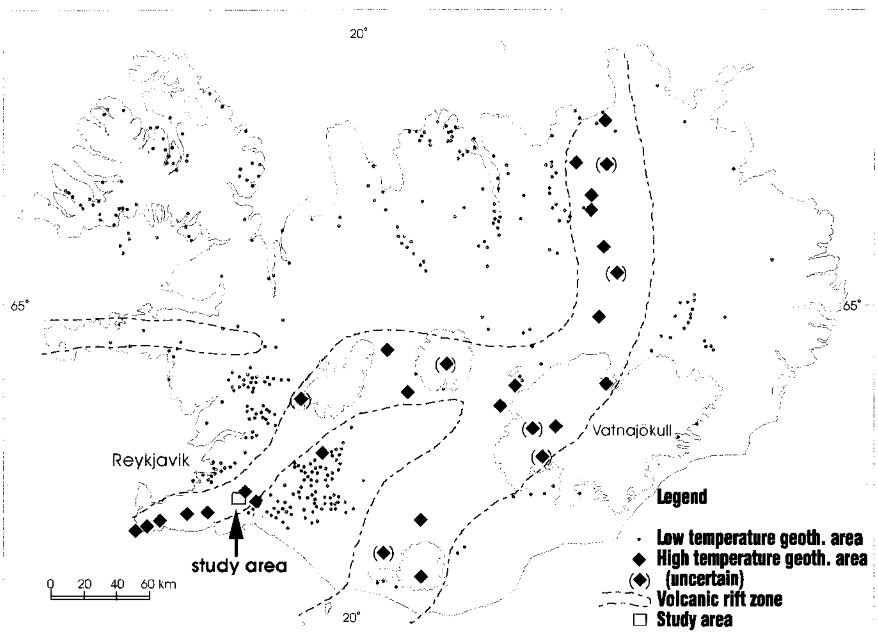

FIGURE 1: Map of Iceland showing the volcanic rift zone passing through Iceland and its division in S-Iceland; also shown is the location of high- and low- temperature area and the location of the study area

The geothermal areas in Iceland are divided into two main groups, low-temperature and high- temperature geothermal areas (Figure 1). Low-temperature areas are mainly found outside the volcanic rift zones and involve geothermal systems of temperatures lower than 150°C. They are found in the Plio-Pleistocene and Tertiary formations. The low-temperature areas are often fracture-dominated systems, which derive their heat from the hot crust by active and localised convection in nearvertical fractures. Away from the fractures, the bedrock is less permeable and heat transfer is dominated by conduction.

The high-temperature areas are found only within the active volcanic rift zones. They are characterised by active volcanoes and fissure swarms. The uppermost 1000 m of this zone are made up of highly porous and permeable basaltic lavas or hyaloclastite. Due to an abundance of cold ground water, low temperature gradients are expected in the uppermost kilometre, but below that depth relatively high gradients are observed. The high-temperature areas are localized features. The temperature within the high-temperature geothermal systems is typically >200°C at 1 km depth. They are usually located within central volcanoes, but occasionally along their fissure swarms. The geothermal activity of the high-temperature fields is attributed to intrusive activity at high levels in the upper crust (Flóvenz and Saemundsson, 1993).

2.2 Tectonics of the Hengill area

The Mt. Hengill central volcano lies about 45 km east of Reykjavík. The high-temperature area that accompanies it is one of the biggest in Iceland. The Hengill central volcano developed on the western branch of the active rift zone in SW-Iceland, which is characterized by tensional stress parallel to the spreading direction. The Hengill central volcano (Figure 2) is intersected by a fracture system or fissure swarm trending N30-35°W, which extends for 60-80 km from southwest to northeast. The main geothermal activity like fumaroles and hot springs, is found in the central part. Besides the major fissure swarm there are some faults and eruptive fissures transsecting the centre of Hengill in a NW-SE direction toward the Hveragerdi system, i.e. perpendicular to the main tectonic trend.

The relationship between the fissures/faults and geothermal activity is often quite obvious, especially in relation to the seismic activity. During earthquakes, which are related to the S-Iceland seismic zone, changes have been observed in the surface geothermal activity. Major earthquakes of magnitude around

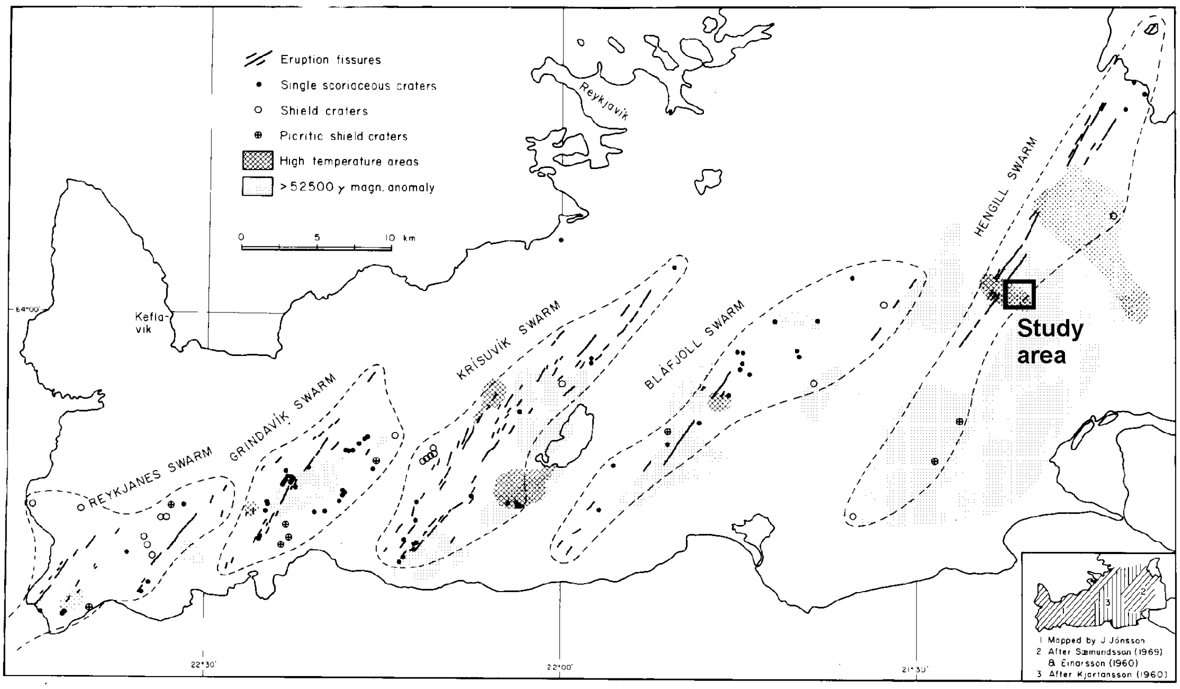

FIGURE 2: The volcanic systems and fissure swarms in SW-Iceland with eruptive fissures and different types of crater; also shown is the location of the study area (modified after Jakobsson et al., 1978)

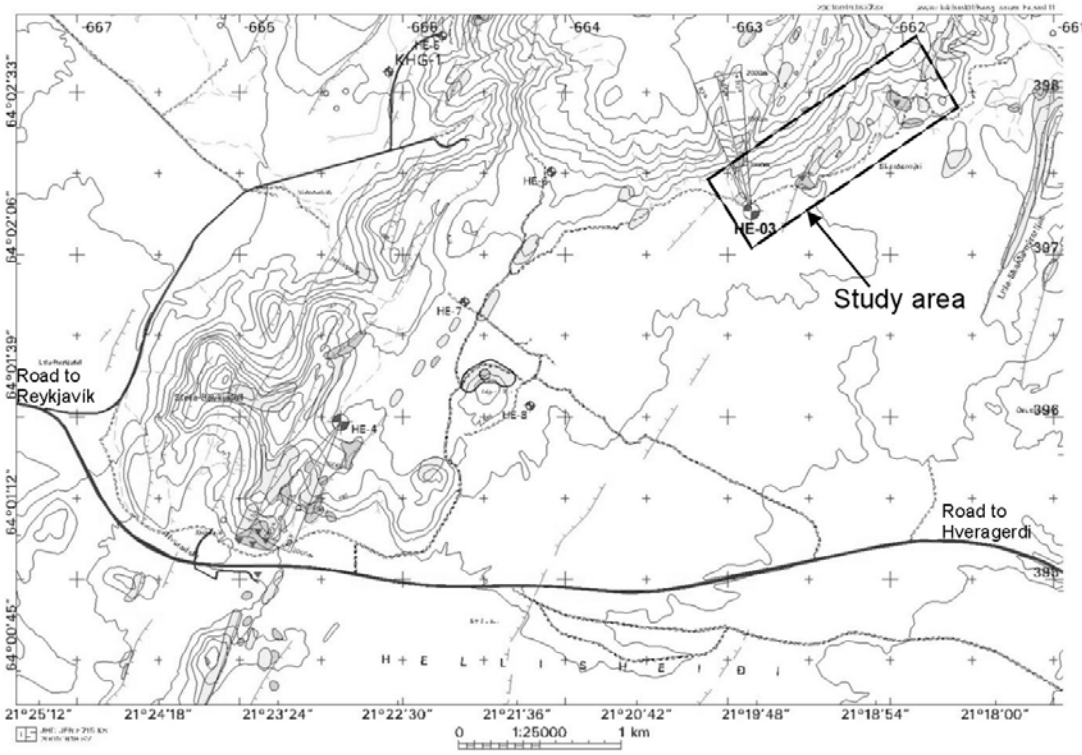

FIGURE 3: Location of the study area and drillhole HE-03

6-7 shake the area east of the Hengill region severely about once a century. Such earthquakes were last experienced in 2000, 1896, 1912 and 1784. A rifting episode occurred on the Hengill system in 1789. Fault trends of the seismic zone occur in the eastern part of the Hengill fissure swarm. Two major volcanic systems are found within the Hengill area. They are the presently active Hengill system near the crest of the axial rift zone and the extinct Hveragerdi volcanic system which has drifted about 5 km to the east away from the rift axis during the last 500 thousand years.

2.3 Location, topography and climate in the study area

The study area lies just south of the mountain Hengill and 8 km west-northwest of the town of Hveragerdi (Figure 3). Mt. Skardsmýrarfjall, where the study area is located, lies in the southern part of the active Hengill central volcano and lies to the northeast of well HE-3 drilled by the Reykjavík Energy Company in the summer 2001. The topography of the study area comprises a barren mountain slope of volcanic rocks and a lava plain partly covered by moss. The altitude is between 400 and 500 m. The slope is drained by small perennial streams, which disappear on the porous lava plain.

The climate of the study area is characterized by a cold winter and a moderate summer. The weather is highly unpredictable and rainfall can be quite high.

2.4 Previous work

Reconnaissance geological mapping of the Hengill area was carried out in the mid sixties by Saemundsson (1967). Twenty years later the Hengill area was remapped in connection with drilling activity. Many of the lithological formations of the active Hengill central volcano were then established. Later, Saemundsson and Fridleifsson completed the geological mapping with an emphasis on lithostratigraphy, tectonics and geothermal alteration and activities of the Hveragerdi volcano (Saemundsson and Fridleifsson 1992 and 1996; Saemundsson, 1995a and 1995b).

Jónsson (1989) has undertaken some research in the area, mostly on upper Pleistocene and Holocene lavas. Walker (1992) mapped the adjacent Grensdalur (Hveragerdi) volcano with respect to eruptive units and their petrology in relation to her Ph.D. studies at Durham University.

2.5 The Hengill high-temperature geothermal area

The Hengill high-temperature geothermal area is located within the volcanic rift zone zone in SW-Iceland, 40 km east of Reykjavík. The geology is characterized by the active Hengill central volcano, and its fissure swarm. This is an extensive high- temperature area containing several economically promising geothermal prospects. An extensive regional reconnaissance study was made of the whole Hengill area in the late seventies and early eighties. A short review and preliminary analysis of some of the data was presented by Björnsson and Hersir (1981).

Deep exploratory drillholes have been drilled in three sub fields of Hengill area and many production wells drilled at the Nesjavellir geothermal field, in the northeast Hengill area. There, Reykjavik Energy Co. has constructed a power plant, here cold groundwater is heated with steam. The hot water is piped to Reykjavík and used for heating in the city. The power plant also produces electricity.

The main heat sources of the Hengill area are thought to be magmatic intrusions in the upper crust and/or the transport of heat by deep circulation of groundwater in highly fractured rocks, tapping heat from the deeper crustal layers.

3. GEOLOGICAL MAPPING OF THE STUDY AREA

The study area is located on the southern side of the Hengill mountain. The area is about 1.2 km long and 600 m wide, including flat ground and slope. The bedrock of lava and pillow lava is partly covered by scree, glacial sediment and stream deposits.

The geological map of the Hengill area in 1:50,000 and a geothermal map in 1:25,000 show a number of geothermal features in the southeast of Skardsmýrarfjall. This area was selected for a close study because of a major drilling operation just being in that area.

3.1 The geological features

The rocks in the surroundings of the study area at Skardsmýrarfjall mountain are volcanic, mainly composed of various lithofacies of subglacially formed hyaloclastites and pillow lava and postglacial lava. Figure 4 shows a geological map of the study area.

The pillow lava is of basaltic composition, being a plagioclase porphyritic olivine tholeiite. Petrographically, the rocks range from glassy tuff, through pillow lava to holo-crystalline basalts. The pillow lava formation forms a square mountain, which probably reflects a thick pillow lava flow that spread from a single vent to form Skardsmýrarfjall. No dykes are found on the surface. The postglacial lava is 2000 year old aa lava flow. It was erupted from NE-SW trending fissures. It is characterized of Skardsmýrarfjall by a rubbly surface and is basaltic in composition. Figures 5 and 6 show geological cross-sections through the area with the locations shown on the geological map in Figure 4. The section was compiled on the basis of the surface geological survey and the drilling documents from wells close by, recently completed by the Reykjavík Energy Company.

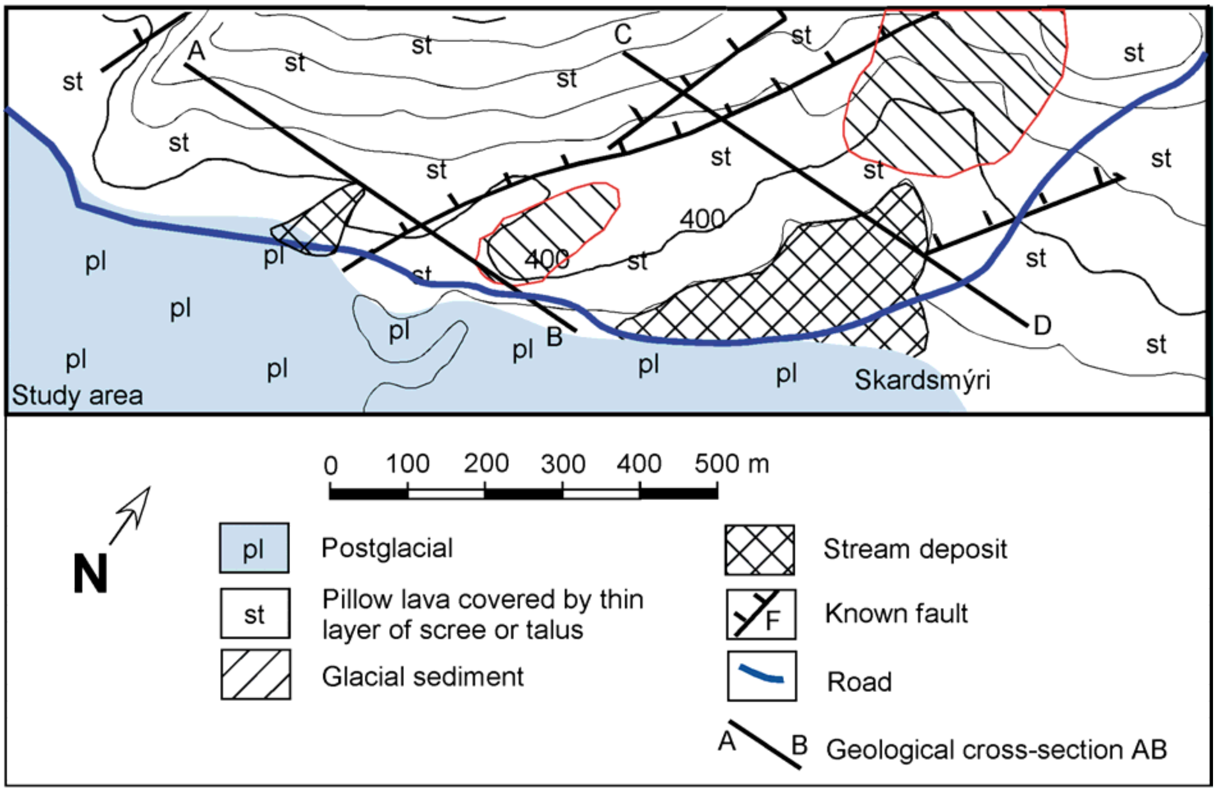

FIGURE 4: Geological map of the Skardsmýrarfjall area (extracted from geological map of the Hengill area of Saemundsson (1995a))

3.2 Surface deposits

The surficial geologic formations are very important as some of the geothermal manifestations occur among these. They include the following:

Scree or talus, is usually deposited on the pillow lava slopes and at their foot. It is composed of angular to subangular debris of the older underlying rocks mixed with loose soil and gravel transported by streams, grading to a nearly plain area of stream deposits. In some cases, at the foot of slope, these are quite thick and some of the geothermal manifestations are related to these.

Fluvial sediment. These are unconsolidated to poorly consolidated sediments. The fragments are subrounded to subangular and form along most stream beds, even those often without water. They are mainly found in the lower parts of the slope, with increasing thickness towards the bottom of the slope, disappearing in the higher slopes and out on the flat plain. Several geothermal manifestations are found in these sediments.

Rock slides are a less common surface feature in the study area. They date from Holocene and may have been caused by large earthquakes. Due to the gravity force they are mainly found along and at the bottom of steep slopes and cliffs. In the study area, the largest rock slide is found just west of the study area. No geothermal manifestations were discovered there.

Soil. Below the mountain slope, the Skardsmýri plain or valley-bottom is covered by a patchy layer of brown soil, which is silty in nature. The soil is usually 0.3-1m in thickness but might be used for cultivation, even though the climate that high would probably make it difficult. In the study area the soil is usually covered by vegetation (grass). The effect of geothermal activity on vegetation can be observed by comparing the vegetation colour and growth in several places.

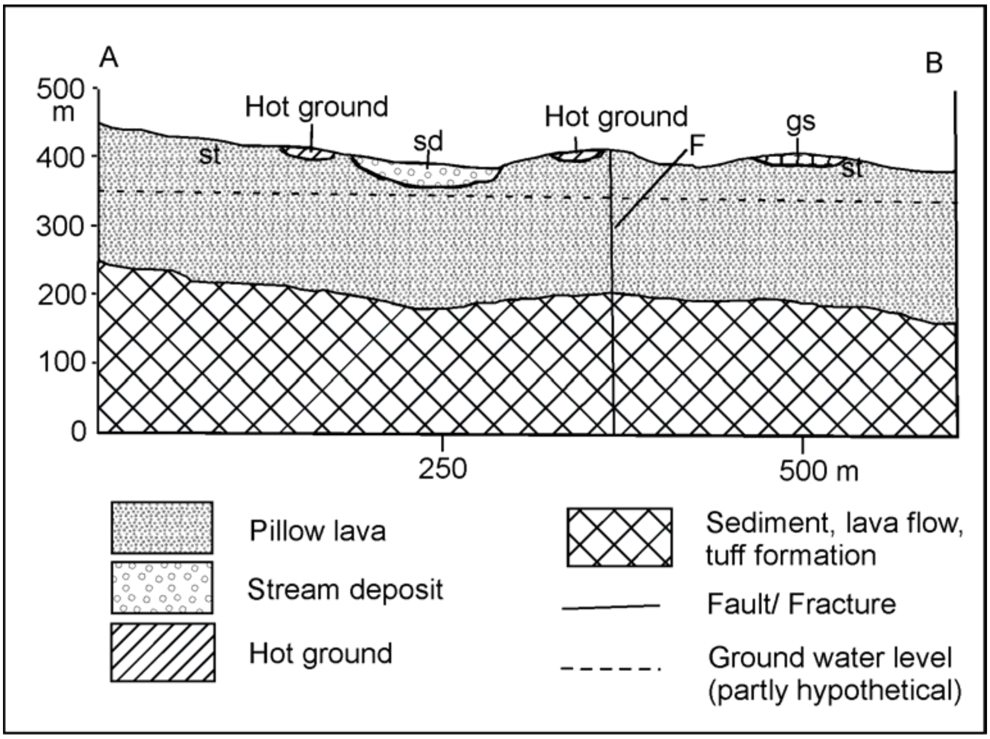

FIGURE 5: Geological cross- section AB (location shown in Figure 4)

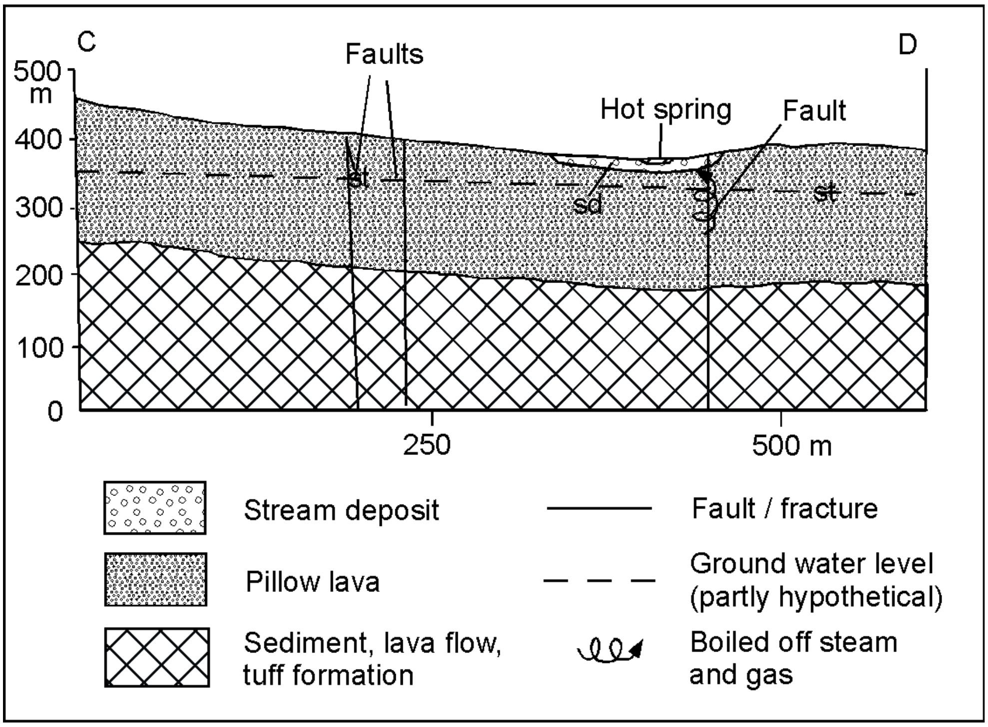

FIGURE 6: Geological cross-section C-D (location shown in Figure 4); the subsurface lithology of Figures 5 and 6 is based on analysis of borehole cuttings from the recently completed well HE-3 (see Figure 3); and the groundwater situation is also inferred from borehole information

3.3 Surface manifestations of geothermal activity

For further clarification of the thermal activity of the area a sub-division was made in two units. The pillow lava occurs on the mountain slope and at the foot of the slope. It includes rocks that have been affected by strong surface hydrothermal alteration. The alteration degree reaches brownish smectite - alteration. Multicoloured soft clay around fumeroles is iron-stained kaolinite (Saemundsson and Fridleifsson, 1992).

The postglacial lava that occurs at Skardsmýrarfjall is unaffected by hydrothermal alteration. The main difference between the two bed rock units pertaining to the hydrology and geothermal activity in the area is their different permeability. The more altered unit is characterized by the occurrence of hot ground, warm ground and hot springs, whose upflow of steam seems to be related to fractures and faults. The relatively fresh lava unit is highly permeable and for the most part lying above the groundwater table. Holocene lava flows erupted in the fissure swarm are found south of the study area.

3.4 Groundwater situation

From the recently drilled wells in the lava just west of the study area, it appears that the groundwater level lies some 50 m below the surface. The groundwater is hot and must be boiling below the eastern part of Skardsmýrarfjall as shown by the fumeroles and steaming ground.

3.5 Tectonics

From earlier geological mapping in the region, tectonic movements within the study area are chiefly of three types:

1. *Tilting towards northwest.* Tilting of the lava pile towards the northwest is regional and in particular it tilts into the axis of the graben cutting through the Hengill volcano. It is caused progressively by the load of increased eruption material of younger volcanics in the Hengill central volcano.

2. *Faulting and fracturing of the rocks with or without displacement.* Faulting and fracturing is quite common in all rock types in the Hengill central volcano. The main trend is NE-SW, associated with the Hengill fissure swarm, which is 4-5 km broad and passes through the Hengill central volcano. Several areas of hydrothermal alterations and geothermal manifestations are associated with it.

3. *Formation of open fissures.* Open fissures are quite common in the Hengill area but due to scree and soil creep they are difficult to ascertain. The existing geological map 1:50,000 shows a fault or fissure in the lava southwest of the study area. This could not be confirmed in the present study.

In the study area three large faults were observed. They are normal faults with throw to the northwest, running parallel with the axis of graben cutting through the Hengill central volcano. The main trend of these faults is NE-SW. A fourth large fault runs parallel to the others some 150 m west of the study area. No thermal activity is associated with that, contrary to the eastern ones.

4. GEOTHERMAL EXPLORATION

4.1 Purpose

The following studies were carried out:

- Mapping of geothermal manifestations (springs, steam vents, hot ground, hydrothermal alteration, vegetation, surface conditions etc.) found in the study area;
- Preparation of an isothermal map for the most interesting parts of the study area based on temperature measurements at regular intervals at shallow depth (0.6 m).

The purpose of these studies was to correlate the findings of the geothermal mapping to the geology, hydrology and the structures of the area to acquire a basic knowledge of the geothermal field. All of these are usually amongst the first exploration steps in geothermal prospecting (Flóvenz, 1985).

4.2 Procedure and equipment

The assessment of all the geothermal manifestations occurring in an area has been considered a first step in geothermal prospecting. This has been done by mapping in detail hot springs, steam vents, hot ground and mud pools and measuring their temperature. In addition, information about the rock type, rock alteration, soil and vegetation must be taken into account, as it affects the interpretation. The exact location of alteration should also be marked, as it may help in understanding the nature of the thermal manifestations and assist in locating hot ground in the area. Where necessary, sketches should be made to describe the manifestations in detail and these should be correlated with the possible structures.

Measurement of temperature at a convenient depth in the soil can give important structural information related to the geothermal prospect (Flóvenz, 1985). For making an isothermal map, one must measure the temperature distribution in the ground at a convenient depth at regular intervals. A narrow hole of the required depth is made by a steel rod. A rod with a thermistor at the end is then pushed down the hole and the temperature at the bottom is registered with accuracy. Because of the annual variation in temperature it is important to carry out the survey in as short a time as possible, and to do it when temperature changes are slow. Then the data has to be plotted in an appropriate scale for making the isothermal map according to the requirements. During the survey, other information is also collected, such as about the rock/soil type, alteration, topography, hot and cold water springs, streams, steaming ground, vegetation etc. This is very important for the interpretation of measured thermal anomalies and their behaviour with respect to other structures.

Prior to the ground temperature measurements a base line with exact length and direction is marked on the ground related to some reference points/localities. This line is transferred to the map and a millimetre paper. With reference to this base line all locations are given. All other reference points/localities like houses, roads, paths, drill hole, trenches etc., are also noted and drawn on the map with reference to the same base line.

The equipment used for the temperature survey includes: A measuring string and tape marked at regular intervals in metre lengths according to requirements. In the present work, a measuring string of 300 m length and a tape measure of 50 m length were used. A compass and right angle instrument is necessary to mark the base line and reference points and their direction on each side of the base line or measured profile. A clinometer was used to define the angle of slope in survey area 2. A digital thermometer consisting of a 1 m long rod with an electrical thermometer or sensor at one end and an electrical cable connected to the handle on the other end; the signal being conducted from the sensor to a box. This box runs on a small 9 V battery, and contains a circuit that transforms the signal to a temperature value. A T-shape steel/iron rod about 1 m long with a pointed end for making holes in the ground according to

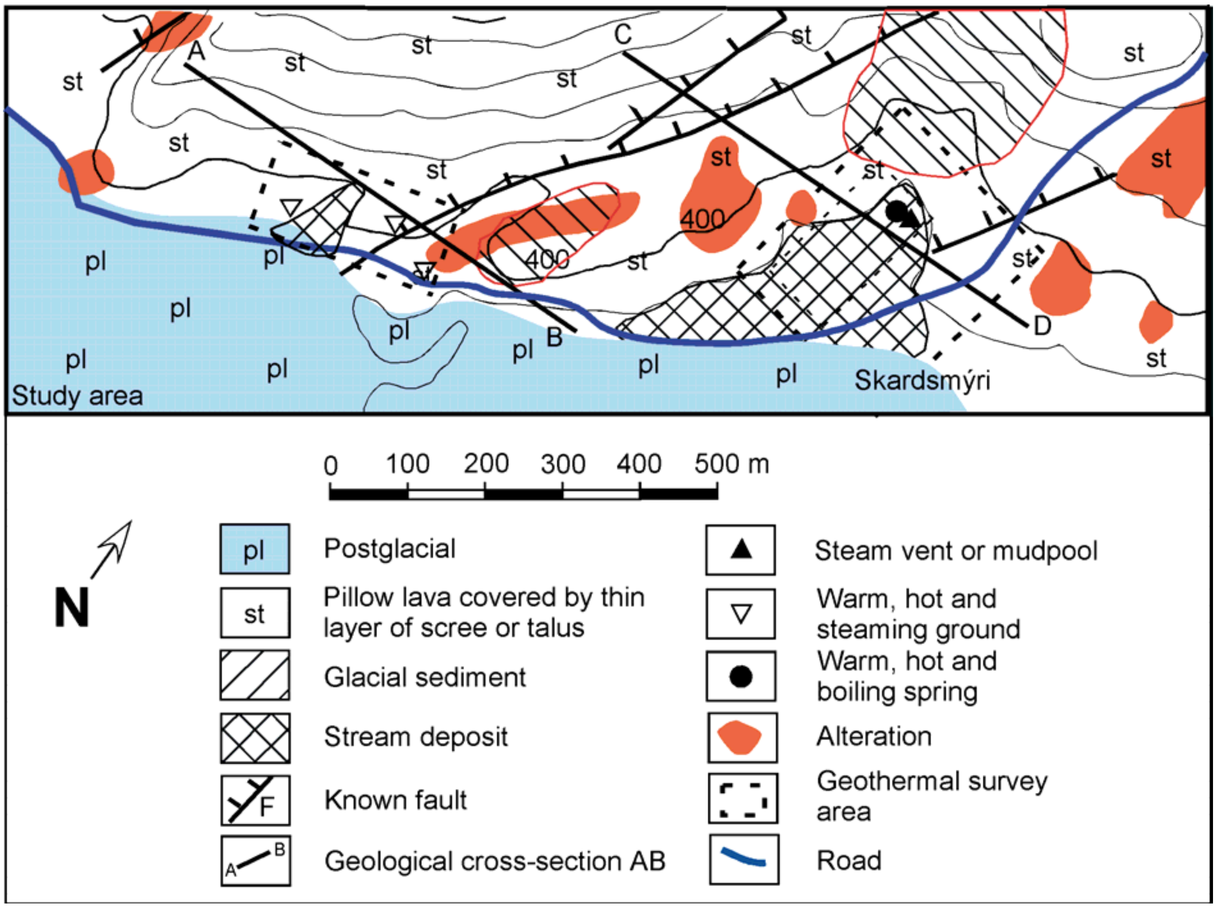

FIGURE 7: Geothermal map of the Skardsmýrarfjall area; the alteration shown on this map is from the published geothermal map 1: 25,000 (Saemundsson, 1995b)

required depth for temperature measurements. To drive it into the ground one often has to use a heavy hammer. A base map of the area in an appropriate scale is necessary and for plotting mm-graph paper. Other tools include range poles, mercury thermometer and common field tools.

4.3 The geothermal manifestations

Figure 7 shows the main geothermal manifestations in the area superimposed onto the geological map. It also shows the selected areas for thermal mapping. The various forms of geothermal manifestations are grouped together since in many cases they are found not only to be interlinked, but often close to each other. This was found to be more of a rule rather than the exception. They were located and plotted onto the base map. For the fumaroles or steamvents it was noted if the steam was being ejected under pressure or not. The temperatures of mudpools were measured and note taken of the presence or absence of gas bubbles. Finally, the water discharged from these manifestations was noted.

Hydrothermally altered ground is a direct manifestation of active or extinct transfer of geothermal energy. However, only active alteration, i.e. altering ground, was mapped in the vicinity of hot or warm grounds. Where possible a note was also taken of the relative abundance of sulfur or mineral deposition. Effort was made to determine the extent of the hot ground around the larger of these. Special notice was given to the surrounding ground to determine whether there was any current shifting, relatively, in the heat, and effort was made to determine the temperature distribution within the hot ground and/or active alteration. Special notice was given to the colour of the altered ground and its form. The form of the precipitates and taste was noted to try to distinguish between silica and some forms of mineral salt.

4.4 Detailed geothermal mapping

Two areas were selected for this survey, where the most intense geothermal activity in the study area occurs (location see Figure 7). One is relatively rough and dry, the other smooth and covered by alluvial gravel. During the survey all the geothermal manifestations occurring in the area were plotted in detail. Other information, such as soil type etc., was also noted. The bigger area was in the western part of the study area (Figure 8). Here the base line was marked nearly parallel to a road. The direction of the base line was N100ºE and the length was 250 m. For the second area (Figure 9), in the east study area, the base line was marked on the SW side of a house, used by skiers in the winter. The direction of the base line is N110ºE, and the length was 95 m. All other lines were taken parallel to the base lines with an interval of 10 m. Along the lines the temperature was measured at 5-10 m intervals and at a depth of 60 cm. All the data was plotted on the map of appropriate scale and isotherms drawn at 10˚C intervals.

4.5 Results of detailed geothermal mapping

Figures 8 and 9 show the isothermal maps constructed by using results from the temperature measurements. The figures show that at a depth of 60 cm the temperature varies from 10-98˚C in the area. Four significant hot spots had temperatures above 50˚C. All extra hot areas are related to the faults/fractures cutting through the study area. Thus, it can be stated that the faults and fractures play an important role in transmitting the heat to the surface. The fault directions trend NE-SW parallel with the axis of the graben cutting through the Hengill central volcano.

Looking first at Figure 8, three main areas of warm ground are shown. The warmest ground is found under scree in the central northern part of the measured area, with no cover of vegetation. The highest temperature measured is 98˚C and this is associated with a northeasterly trending fault. Another warm area is located in a road cut, 50 m southeast of it in a area of clayey alteration and a little scree. The highest measured temperature found was 72˚C. The third area is in the western part of the map. The main hot upflow is located in a scree or talus which is partly vegetated. The highest measured temperature is 50˚C and it lies near a big fault.

Figure 9 shows a linear thermal anomaly. The hottest part lies at the foot of a slope with a flat vegetated gravel plain extending south from it. The flat is in places wet and boggy and it is drained by a small stream. The main hot spring is a pan, some 10-15 m in diameter, where many steam holes and mud pools occur. The highest temperature measured is 98˚C. The feature is obviously related to a fault with a NE-SW direction. This fault is exposed northeast of the hot spring and trends directly towards it.

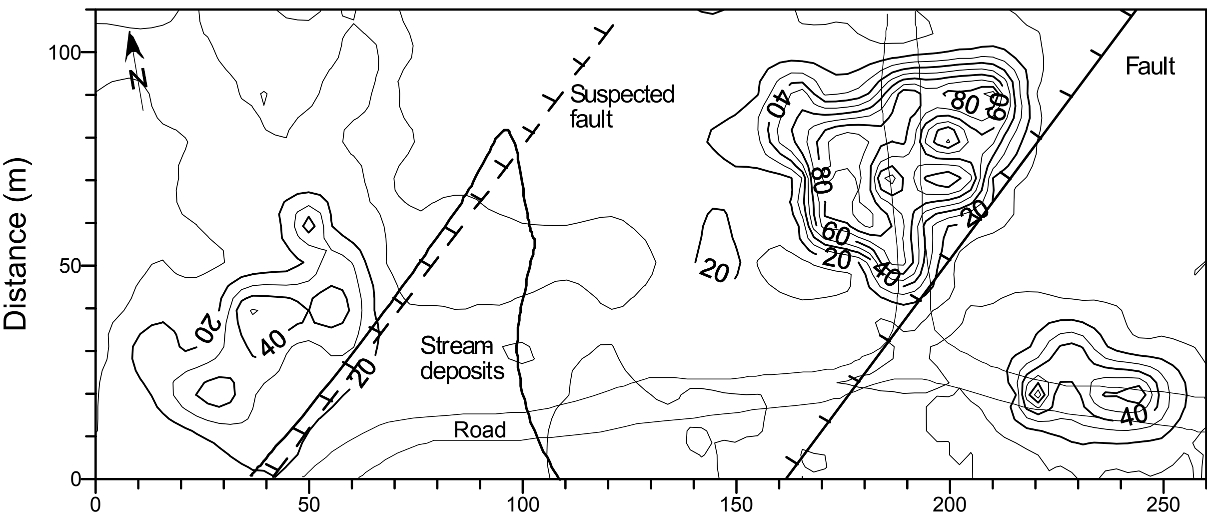

FIGURE 8: Isothermal map of the western survey area (area 1) (location see Figure 7)

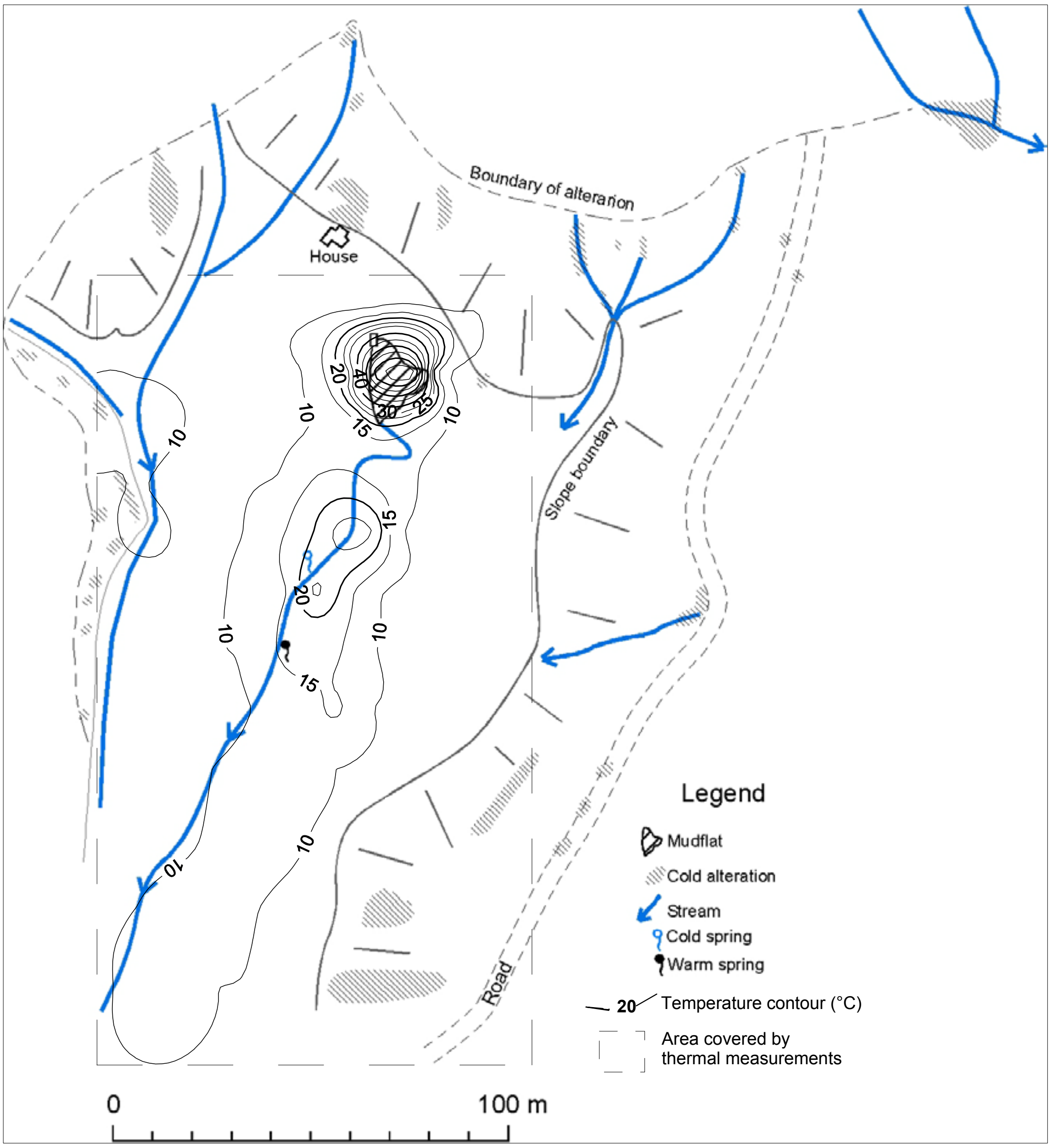

FIGURE 9: Isothermal map of the eastern survey area (area 2) (location see Figure 7)

4.6 Interpretation of the geothermal exploration

The results of the ground survey have shown two main geothermal areas: Area 1 shown in Figure 8 and area 2 in Figure 9. In area 1 there were three active hot ground spots with temperature varying from 10-98ºC. No extinct alteration was observed around these. Area 2 lies on the floor and slopes of a shallow depression and covers three thermal anomalies. One is almost extinct, the others are active with a hot spring and warm ground.

The study area is cut by three main faults. The faults lie in all cases east of the surface manifestations. In area 2 there occurs a number of cold alteration spots on the slopes surrounding the hot spring. Unaltered glacial sediment overlies altered pillow lava in area 2. The age of this alteration therefore must be older than Holocene.

Based on extinct alteration around the hot spring in area 2 and the generally small content of native sulfur, we conclude that the geothermal activities in the study area are decreasing.

5. CONCLUSION AND RECOMMENDATIONS

5.1 Conclusions

1. Most of the geothermal manifestations are related to structural features like faults indicating that the upflow in the area is mostly controlled by them.

2. Geothermal manifestations and temperature distribution indicate fractures trending approx. NE-SW. These are probably faults controlling the movement of the geothermal water of the area. Heat sources are believed to be cooling instrusions underneath (Hengill central volcano).

3. Extensive hydrothermal alteration has probably decreased the porosity and permeability of the rocks in the core of the volcano.

4. Much of the alteration around the hot spring of area 2 predates a moraine which overlies the primary bedrock. This indicates a decline in activity since glacial times.

5. The low presence of low native sulfur in the geothermal manifestations of the study area suggests that the geothermal activity is on the decline. It is also quite obvious in presently active geothermal activity compared with regional alteration.

6. The presence of most of the cold water springs above the geothermal alteration zone at about 300-400 m altitude indicates that the ground water level is quite low and is controlled by faults/fractures.

5.2 Recommendations

1. Before drilling new exploratory wells in the area, one needs to study structures like faults and fractures. It is recommended the drillholes be drilled directly on the faults and fractures, and especially where faults and fractures cross, because of good aquifers.

2. Based on the results of the first exploratory drilling in the study area in 2001, a good aquifer is known to be at a depth of 800 m. A detailed map of geothermal manifestations and, in particular, young structural features would be a useful first step to further successful drilling.

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