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Orkustofnun, Grensásvegur 9,
IS-108 Reykjavík, Iceland

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GEOTHERMAL EXPLORATION OF SAUDÁ VALLEY NORTH OF HVERAGERDI, SW-ICELAND

Abdul Hafeez Malik
Geological Survey of Pakistan,
P.O. Box 15, Sariab Road, Quetta,
PAKISTAN

ABSTRACT

The present study area is a part of the extinct Hveragerdi 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 depth. Cold water springs in the area are located above the geothermal alteration zone at 300-400 m altitude. In many cases it is observed that cold ground/surface water passes through geothermal manifestations like hot ground and steaming ground and is heated up. The distribution of geothermal manifestations shows normally two sets of faults/fractures almost in NE-SW and NW-SE strike direction. In the areas covered by rock slides and alluvium, the linear arrangement of the manifestations has been obscured. Most of the geothermal manifestations lack native sulphur but silica sinter could be observed in the shape of platforms, particularly in the southern part of the study area near Reykir, and is related to outflow of high-temperature water. The extinct hydrothermal alteration has probably reduced the porosity and permeability of the rocks in the core of the volcano. This affects the present surface geothermal activity, most of which appears to be related to structural features like faults and dykes. Deep reservoir silica-rich water emerges only at low elevations in the south.

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

1. INTRODUCTION

1.1 General aspects

Iceland is situated at about 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-Faeroes Ridge. The Mid Atlantic Ridge defines the divergent plate boundary of the American and the Eurasian

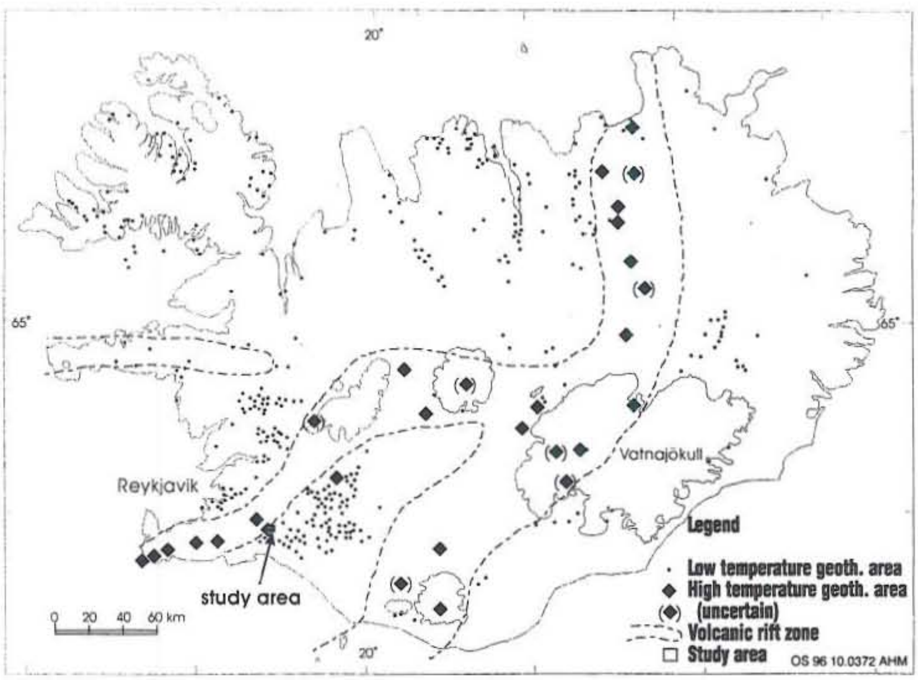


FIGURE 1: Map of Iceland showing the volcanic rift zone passing through Iceland and its division in SW-Iceland; also shown is the location of high- and low-temperature areas and the location of the present study area

plates. The spreading direction is N10°E. 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 Iceland hot spot, which has been active from the time of opening of the North Atlantic ~60 million years ago to the present. The hot spot is thought to be situated below Central East Iceland, close to the neovolcanic zone, which crosses Iceland from southwest to northeast in a complicated manner. It is divided into two parallel branches in South Iceland. The Mid Atlantic Ridge in the south and north of Iceland 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 seismically active and regularly involve earthquakes which may exceed magnitude 7 on Richter scale.

The neovolcanic zones of Iceland have been divided into axial rift zones and flank zones. The axial rift zones are under tensional stress parallel to the spreading direction. The flank zones are isolated volcanic zones outside the main axial rift zones.

The geothermal areas are divided into two main groups, low-temperature geothermal areas and high-temperature 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 volcanics. The low-temperature areas are often fracture dominated systems, which derive their heat from the hot crust by active and localised convection in near vertical 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 volcanic rift zones. These are characterized by active volcanoes and fissure swarms. The uppermost 1000 m of this zone are made up of highly porous and permeable basaltic lavas and hyaloclastites, with heavy flow of ground water. Very small temperature gradients are expected to prevail in the uppermost 500-700 m, but below that depth high gradients are observed. The high-temperature areas are localized features. The temperature within the high-temperature fields is typically above 200°C at 1 km depth. They are usually located within the central volcanoes and rarely on 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).

1.2 Background and objective

Pakistan, 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, resulting in frequent power shut downs. In order to improve the electrical supply, the Geological Survey of Pakistan (GSP) initiated a study programme of possible geothermal resources in the country (Todaka, et al., 1989). In the exploration of a geothermal prospect, geological mapping of surface geothermal manifestations, shallow temperature surveys and measurement of flow rates of springs are amongst the first steps to define possible geothermal resources. Therefore, on the request of GSP the government of Pakistan approved the present author's to attendancd at the Geothermal Training Programme in the specialized field of geological exploration at the United Nations University in Iceland in 1996. The training duration was six months beginning in April. 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.

The objective of this study was to give the author practical training in geothermal exploration, including geological mapping with analysing of geological structures, mapping of surface geothermal manifestations, shallow temperature surveys and flow rate measurement of springs.

1.3 Location, topography and climate in the study area

The study area *"valley of Saudá"* lies just north of the town of Hveragerdi, which is located 45 km east of Reykjavik (Figure 2). This town has a population of about 1500 and was developed solely because of easy access to geothermal resources. The people have utilized geothermal energy for space heating, greenhouse farming, industries, swimming pools and other domestic purposes since 1929. The study area ranges from Hveragerdi in the south to the water dividing lines on the mountains in the north, east and west. The topography comprises mountains of volcanic rocks and a valley mostly covered by alluvium and vegetation. The altitude is between 50 m and 500 m a.s.l. The area is drained by Sauda river with streams emanating from mountain slopes. The climate of the area is characterized by a cold winter and a moderate summer. The mean monthly temperature ranges between -5 and 5°C in winter and 5 to 15°C in summer. The weather is highly unpredictable since rainfall may occur at any time, and snowfall can prevail in the winter.

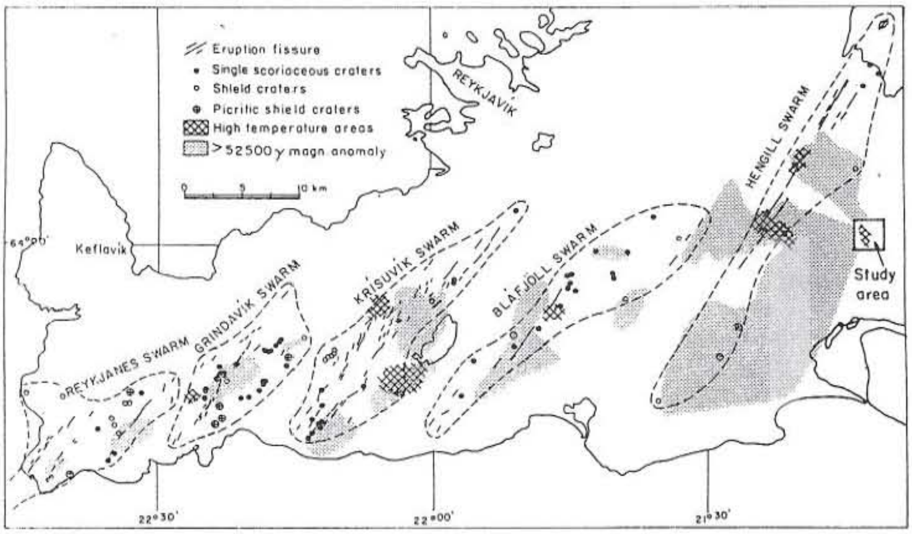


FIGURE 2: The volcanic systems and fissures swarms in SW-Iceland with eruptive fissuers and different types of craters; also shown is the location of the study area (modified after Jakobsson et al., 1978)

1.4 Previous work

The study area is within the central volcano of Hveragerdi, which is hydrothermally altered and eroded. It is about 5 km east of the presently active Hengill central volcano, which is in the main rift zone. Reconnaissance geological mapping of the area was carried out by Saemundsson in 1967. A few years later, around 1970, he remapped the southern part of the area in connection with drilling activity at Hveragerdi and Sogn. Many of the lithological formations of the Hveragerdi central volcano were then established. In 1987 an UNU-fellow (Wangombe, 1987) made a geological profile across the volcano. Later, Saemundsson compiled the existing knowledge in 1987, and in the following two summers he and G.Ó. Fridleifsson completed the geological mapping with an emphasis on lithostratigraphy, tectonics and geothermal alteration and activity (Saemundsson and Fridleifsson, 1992 and 1996; Saemundsson, 1995a and 1995b).

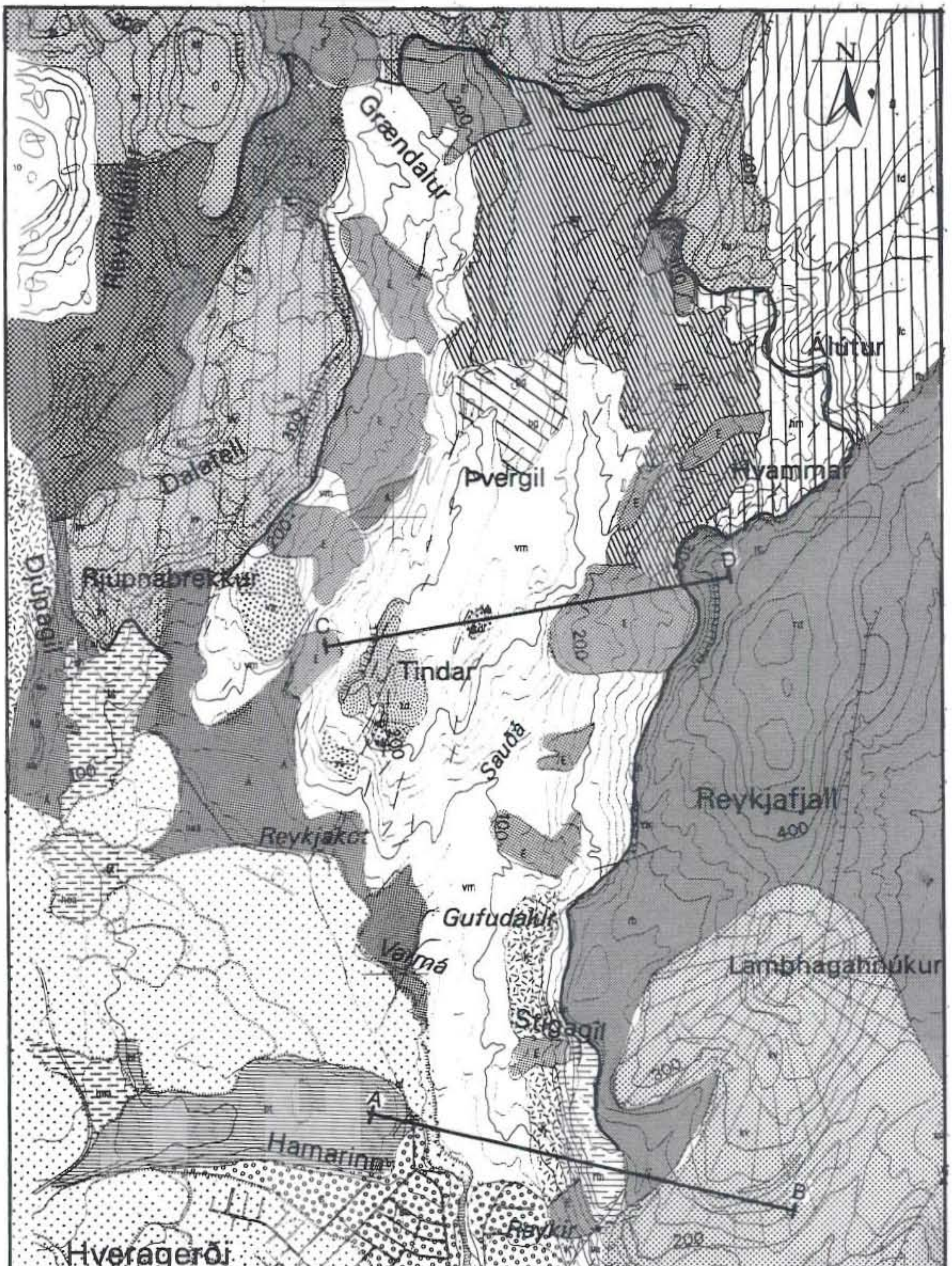
Jónsson (1989) has undertaken some research in the area, mostly on Upper Pleistocene and Holocene lavas. C. L. Walker (1992) mapped the volcano with respect to eruptive units and their petrology in relation to her Ph.D studies at Durham University. In 1990 an UNU-fellow (Bazaale-Dolo, 1990) undertook geothermal mapping at Reykjakot and in 1991 another UNU-fellow (Pullinger, 1991) mapped the Núpafjall area further south, both partly supervised by Dr. Saemundsson.

1.5 Geology of the area

The study area lies in the extinct Hveragerdi volcano, which has drifted about 5 km to the east away from the rift axis during the last 500,000 to 1 million years. The extinct Hveragerdi volcano and the presently active Hengill volcanic system developed on the western branch of the neovolcanic zone in SW-Iceland, which is characterized by tensional stress parallel to the spreading direction. The Hengill central volcano is intersected by a fracture system trending N 30-35°W. Geothermal manifestation like fumaroles and hot springs, are distributed on a zone from Hveragerdi centre to the Hengill centre transecting the main fissure swarms (Fridleifsson, 1979). This indicates that the Hveragerdi system is still connected to the main heat source of Hengill central volcano and hence with the neovolcanic zone through these faults and fissure swarms. The relationship between the fissures/faults and the hydrothermal activity is quite obvious especially in relation to the seismic activity. During earthquakes, which are related to the South Iceland seismic zone, many changes have been observed in the surface hydrothermal activity and presumably some of the numerous rock slides in the region were set off by seismic activity in Holocene time. Major earthquakes of magnitude around 6 shake the Hveragerdi region severely about once in a century. Such earthquakes were last experienced in 1896 and 1784-89.

The rocks in the area are volcanic, composed of various lithofacies of subglacially formed hyaloclastites and interglacial lava flows (Figure 3). The rock is mostly of basaltic composition, ranging from olivine tholeiite to tholeiite, while basaltic andesite also occurs. Petrographically the rocks range from glassy tuff, through hyalocrystalline tuffs to porphyritic tuffs and from aphyric fine to coarse-grained basalts, to porphyritic basalts. The hyaloclastites in the volcano form NE-SW striking ridges, the younger ones additionally showing N-S strike. The rocks are slightly tilted towards WNW or NW, the maximum tilt reaches up to 8° in Dalaskard in the northwest. The tilt is much less in the south and east. Numerous dykes are found in the centre, some of these form dyke swarms, and most of them are of the same composition as the extrusive rocks. Figures 4 and 5 show geological cross-sections through the area, the locations are shown on the geological map in Figure 3.

For the purpose of this work a sub-division has been made into two main rock series. An older series includes rocks that have been affected by strong hydrothermal alteration. The main units of that series are hyaloclastite of quartz tholeiite composition termed Varmá formation (Saemundsson and Fridleifsson, 1992) and of olivine tholeiite composition termed Tindar and Saudá formations. The



THE ROCK UNITS SHOWN ARE:

Varmá formation (vm),	Tholeiite lavas (va),	Reykir formation (rm),
Tindar formation (td),	Saudá formation (sm),	Graendalur formation (dg),
Djúpagil formation (ah),	Hvammar formation (hm),	Thvergil formation (pg),
Reykjafjall a/b (rb),	Reykjafjall c (rc),	Reykjafjall d (rd),
Kvíar basalt (kv),	Klóarfjall formation a (ka),	Dalaskardshnúkur formation (kh),
Bitra lavas (bt),	Postglacial lavas (hvh),	Terrace deposits (C),
Stream deposits (A),	Rock slides (E),	Talus (K).

FIGURE 3: Geologicial map of the study area and its surroundings, which includes the valleys of Saudá and Graendalur (after Saemundsson, 1995a); the bold line shows the division between strongly and weakly altered rock units with the weakly altered ones surrounding the core area of the Hveragerdi central volcano at higher altitudes

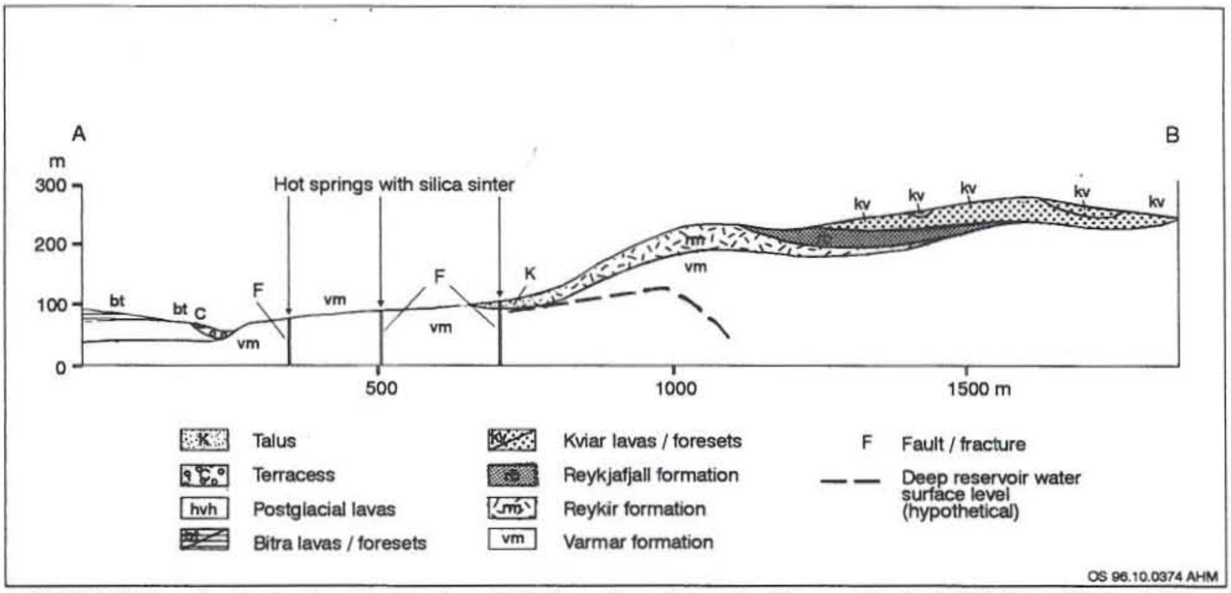


FIGURE 4: Geological cross-section A-B (location shown in Figure 3), the bold dotted line shows a hypothetical deep reservoir water surface level; the lower contact of the Varmá formation (vm), the oldest in the area is unknown, therefore it is not shown in the cross-section

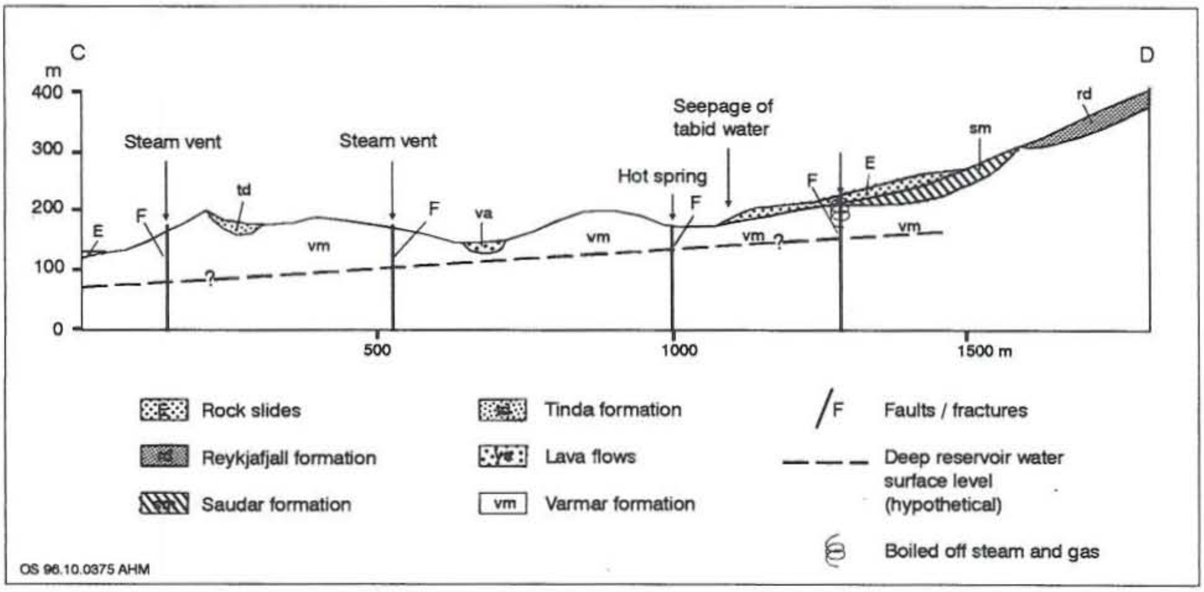


FIGURE 5: Geological cross-section C-D (location shown in Figure 3), for explanations see Figure 4

alteration degree reaches into the smectite/chlorite-alteration zone locally (indicated by pale green colour of the rocks) in the stratigraphically lower Varmá formation. The regional blackish to brownish colouring of the Tindar and Saudá units suggests a smectite alteration-zone (Saemundsson and Fridleifsson, 1992).

A younger rock series including units that have been less affected by hydrothermal alteration, occur at higher level in the hills north and east of the Saudá valley. The main units involved are a group of lavas termed Kvíar basalts (Saemundsson and Fridleifsson, 1992) and a group of hyaloclastites above those, extending to Reykjafjall east of Saudá. The main difference between the two main series pertaining to the hydrology and geothermal activity in the area is their different degree of primary permeability. The lower altered series are characterized by the occurrence of warm and hot springs, whose upflow seems to be related to fractures or faults. The relatively fresh upper series is characterized by cold and cool springs which in soe cases seem to emerge at stratigraphic discontinuities.

Holocene lava flows erupted in the Hengill fissure swarm are found south of Varmá and in the river bed south of the area of detailed geothermal mapping.

Surface deposits are very important as most of the geothermal manifestations are related to these in some way or another. The surficial deposits include:

Terrace deposits. These are unconsolidated to poorly consolidated. The fragments are subrounded to subangular and form low to moderate slopes along most of the high ridges and banks of main streams. In the southern part of the study area the terrace deposits are present along the banks of the Varmá river and several famous geothermal manifestations like those of Reykir and Hveragerdi occur there.

Rock slides are a prominent surface feature in the study area. They are from Holocene and were probably caused by large earthquakes related to the South Iceland seismic zone. They also occur due to the gravity force along the steep slopes of high ridges. Sometime the rock slides are quite thick, with over 10 m high edges. The largest may act as aquifers. In the study area the largest rock slide is found on the western slope of the Reykjafjall. It contains several geothermal manifestations.

Scree or talus, is usually deposited below high cliffs. It is composed of angular to subangular debris of the older rocks mixed with loose silt, clay and gravel transported by streams and grading to nearly plain areas of steam deposits. Sometimes in the lowland areas these are quite thick and several geothermal manifestations are related to these.

The Saudá valley is covered by a patchy layer of brown **soil**, which is silty in nature. The soil is usually thin but can be used for cultivation. In the study area the soil is usually covered by vegetation (grass). The effects of geothermal activity on vegetation can be observed by comparing the vegetation colour and growth in several places.

2. GEOTHERMAL EXPLORATION

2.1 Purpose

The following studies were carried out:

a) Mapping of geothermal manifestations (springs, steam vents, temperature alteration, vegetation, surface conditions etc.) occurring in the study area;
b) Preparation of a isothermal map for a part of the study area based on temperature measurement at regular intervals at shallow depth;
c) Flow measurement of selected hot springs;
d) Measuring of cold springs in the hills surrounding the geothermal area.

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

2.2 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 the hot springs, steam vents, mud pools and hot grounds 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 cold water springs and their temperature should also be marked, as it may help in understanding the nature of the thermal manifestations and also give the ground water position of the area. Wherever necessary, sketches should be made to describe the manifestation in detail and should be correlated with the possible structures.

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 required depth is made by a steel/iron rod. A rod with thermistor is then pushed down the hole and the temperature 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 do it when temperature changes are slow. Then the data has to be plotted on an appropriate scale for making the isothermal map of different temperatures, according to requirement. In this survey, other information about the rock/soil type, alteration, depth of temperature measured, topography, hot and cold water springs/streams, steaming ground, vegetation etc., are also very important for the interpretation of anomalies and their behaviour with respect to other structures. Prior to the ground temperature measurement a base line with exact length and direction is marked on the ground related to some reference points/localities and then this line is transferred to the map and a millimetre paper. With reference to this base line all the locations will be taken and marked for temperature measurement. All other reference points/localities like houses, roads, paths, drill holes, trenches etc. are also drawn on the map, which is helpful for transferring the data on to a proper map.

Flow measurements in a geothermal field indicate the natural heat loss of the field, and they help in designing utilisation schemes, and future management. There are several methods for flow measurements, but the "timing method" is probably the oldest and easiest to apply. This method is mainly used when dealing with relatively low flow rates.

The equipment used for the temperature survey includes: A measuring string tape marked at regular intervals in metres of length according to requirements; in the present work, 3 string tapes of 50 m length were used all marked in metres; a compass and right angle lens to mark base line and reference points and their direction on each side of the base line or measured profiles; 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 is conducted from the sensor to a box, running on a small 9 V battery, containing a circuit that transforms it to a temperature value; a T-shaped steel/iron rod about 1 m long with a pointed end for making holes in the ground according to 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; in the present survey mm graph paper was used for plotting; other tools include range poles, mercury thermometer, and common field tools.

The equipments needed for flow measurement are a stopwatch and boxes of known volume such as a bucket or a barrel or whatever comes handy. Other tools include a shovel, PVC pipes, and a thermometer for measuring the temperature.

2.3 Geothermal manifestations of the study area

The study area *"Saudá valley"* lies within the Hveragerdi central volcano and comprises basaltic hyaloclastite, pillow lavas and associated sediments of upper Pleistocene age mostly within the Varmá unit. This sequence is a part of an extinct central volcano, which has been eroded and covered by unconformable layers of glacial sediments, talus and soils (Saemundsson, 1995a). Most of the geothermal manifestations in the form of hot springs and steam vents (Figure 6) were observed in the southern part of the area on the banks of Varmá river. In most of these hot springs the water is boiling but the flow of water is small. Steam vents and mud pools are common in higher ground. Warm springs occur mainly among thick surficial deposits. Some of the geothermal manifestations are described separately under the given locality no. which is marked on the geothermal map (Figure 6).

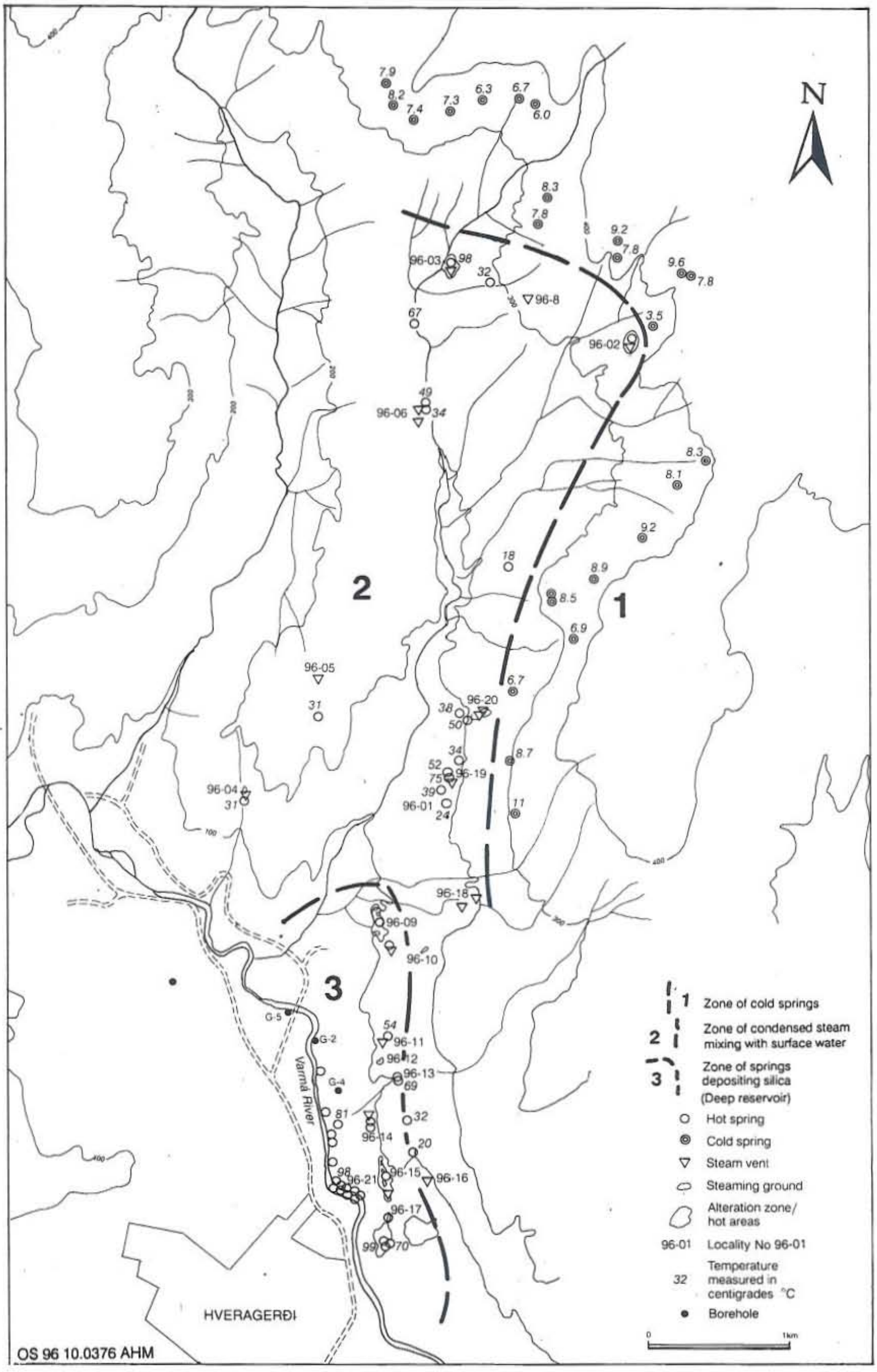


FIGURE 6: Geothermal manifestations and hydrological map of the study area; bold lines show the approximate divisions, 1) zone of cold water springs; 2) zone of condensed steam mixing with surface water and producing mudsprings and steam vents without silica; and 3) zone of deep reservoir hot water springs, which deposit silica sinters and have clear water with substantial flow

Locality No. 96-01: It comprises two hot springs located on the western slope of Reykjafjall (Figure 6). The temperature measured was 39°C and 24°C. The area is covered by alluvium consisting of gravel and silt and also by soil, partly vegetated. The water is running in small separate streams. There is no smell of H_2S. Silica is also not seen. The measured flow from the springs was just about 0.1 l/s in each spring.

Locality No. 96-02: It is located in the northwestern slope of Selfjall (Figure 6 and 7). It consists of steam vents and steaming grounds. The total area is about 70-80 m long and 10-15 m wide. A cold water stream runs through the area. The steam vents are on the upper side of the stream, while only steaming ground is closer to the stream, clearly affected by the cold water. The water is boiling in these locations. The area is highly altered to light brown and reddish brown clays with white patches. It smells of H_2S and opaline silica is seen at a few locations. Most of the steam vents seem to be structurally controlled, as they are distributed in an alignment in N 20°E (Figure 7).

Locality No. 96-03: It is located in the northern part of the valley close to Sauda river (Figures 6 and 8) and consists of steam vents, hot springs, and mud pools. The area can be divided into two parts (Figure 8). The northern area is about 25 m long and 15 m wide. It consists of vivid steam vents, a steaming ground and a boiling hot spring next to the river. The southern area (Figure 8) is about 35 m long and 25 m wide. It consists of steaming vents, a boiling hot spring and a boiling mud pool. The steam from the vents and mud pools can be seen from long distances. A slight smell of H_2S can be found. Native sulphur is not observed, but opaline silica is seen. The area is covered by gravel and silt of alluvium deposits, and is altered to reddish brown and grey to whitish clays. In the southern part the distribution of the geothermal manifestations indicate that it might be structurally controlled, striking N20°W (Figure 8).

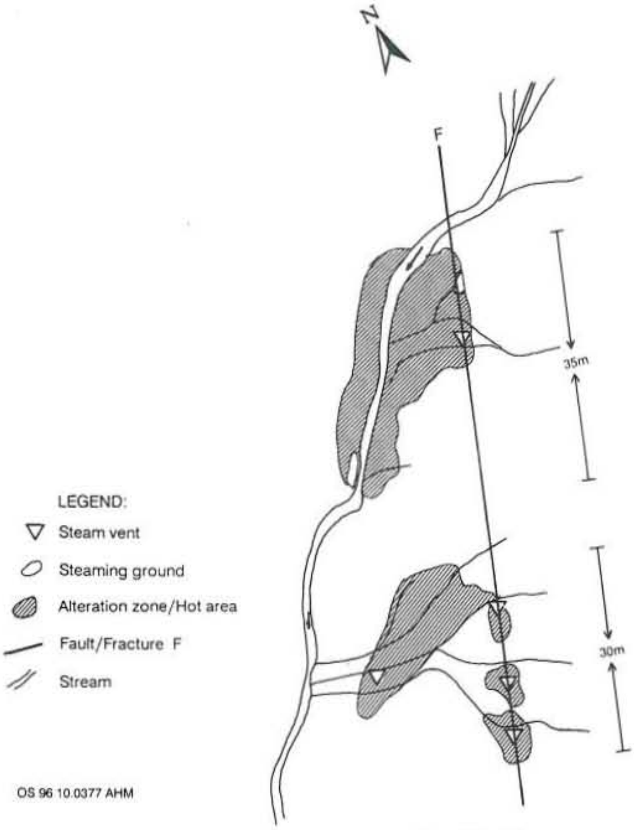


FIGURE 7: Geothermal locality 96-02

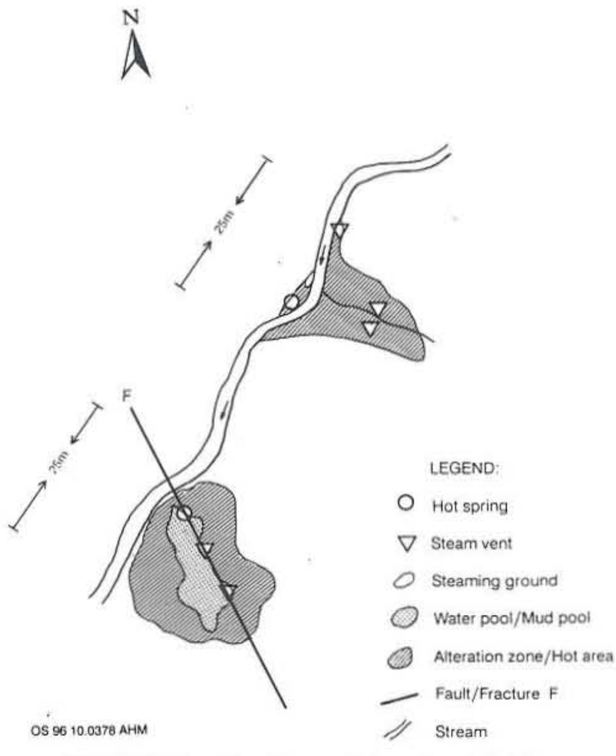


FIGURE 8: Geothermal locality 96-03

Locality No 96-04: It is located in a gully north of the Reykjakot farm (Figure 6). A small cold water stream runs through the gully past the farm down to Varmá river. The manifestations are spread on an area 15 m long and 10 m wide, consisting of a few steam vents and hot springs. The water in the springs is boiling but outflow is very small. The steam vents are noisy and the column of steam can be seen from long distances. A slight odour of H_2S can be smelt and silica sinter can also be observed. The area below the hyaloclastite rocks is altered to reddish brown and grey clays. All the altered area exposed is warm, ranging in temperature from 15 to 75°C. A dyke is exposed close to the hot springs, which probably controls the upflow.

Locality No. 96-05: It is located on the western side of the river Saudá up in the Tindar hill (Figure 6). The area is about 32 m long and 30 m wide, relatively plain and covered by alluvium silt and gravel. Grass vegetation in the area has recently been spoiled by hydrothermal activity. The manifestations consist of a weak steam vent. H_2S odour is present. The area is altered to grey and white clays and is very hot, having temperatures ranging from 20 to 98°C.

Locality No. 96-06: It is in the northern part of the valley south of Klóarmelur (Figure 6). The area is about 20 m long and a few metres wide on the slope into the strongly altered Varmá formation. The manifestations consist of steam vents, clay ponds and small hot springs. The area is covered by scree deposit and altered to red brown clay. Native sulphur is not found. H_2S odour is apparent. The steam output is low. The water in clay ponds and springs is boiling, but flow is very small.

Locality No. 96-07: It is in the northern end of the valley (Figure 6). It consists of steaming ground and hot springs, at two locations 30 m apart. Both the areas are 6 m long and 3 m wide. The water in the springs is boiling, and the flow is small. The steaming action is low. There is no sulphur nor H_2S smell but silica could be observed. The area is covered by scree and alluvium and is slightly altered to red brown clays.

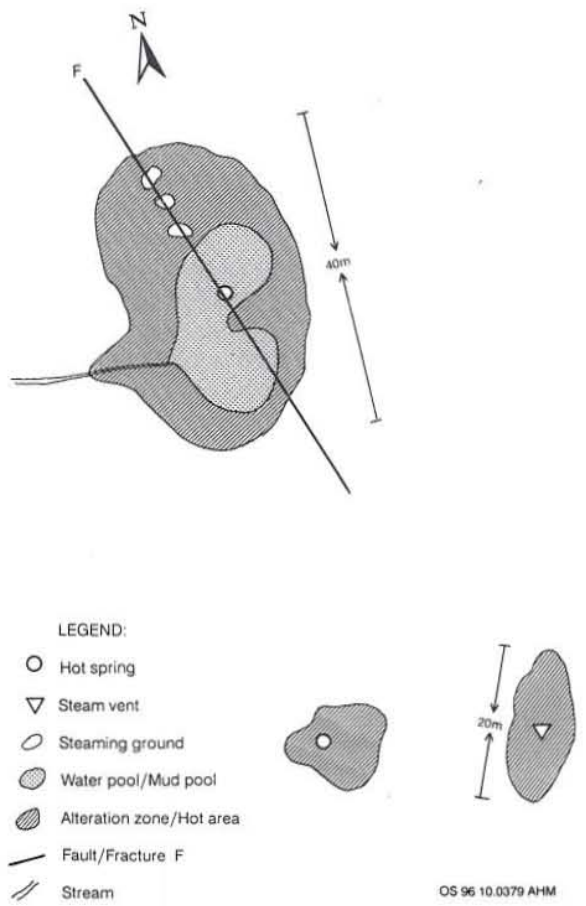


FIGURE 9: Geothermal locality 96-09

Locality No. 96-08: It is located on the slopes of the hill at Klóarmelur area (Figure 6). It consists of steam vents and hot ground. The total area is spread over an area about 35 m long and 10 m wide with three highly altered spots of reddish brown clay. All of the area is very hot, temperatures range from 20 to 98°C. In a few spots the noise of boiling water could be heard. The steam output is very low.

Locality No. 96-09: It is located east of Gufudalur farm consisting of hot springs, mud pools and steam vents (Figures 6 and 9). The area is about 40 m long and 30 m wide and is altered to reddish clays. The flow of water is low. In its northern part a hot water pool has a temperature of 57°C. On one side of this pool, surface water mixes with the hot water and decreases the temperature down to 18°C. Just north of this pool, 3 mud pools are located in a line, boiling noisily. About 40 m south of this area there is a hot spring, which is within a concrete cistern. Some old pipes are still fixed, which show this spring was in use some time ago. This spring erupts every half hour, like a small geyser, and water and steam is ejected up to 3-4 m height. The water is boiling and the steam can be seen for a long distance. About 30 m east of this concrete cistern a steam vent is located in an area about 20 m long and 8 m wide altered to reddish brown clays. The steam content is low. No H_2S smell is observed. Silica deposits occur and can be seen on the old pipes from the hot spring.

Locality No. 96-10: It is found on the western slope of Reykjafjall east of the Gufudalur farm (Figure 6). It is a hot ground having 25-75°C about 8 m long and 4 m wide. The area is altered to reddish brown and grey clays. It is located in hyaloclastite rocks at 175 m altitude.

Locality No. 96-11: It is located in the western foothill of Reykjafjall east of geothermal well G-2 (Figures 6 and 10). It consists of steam vents and hot springs. The total area is about 30 m long and 25 m wide. Surface water mixes within the spring pool. The temperature ranges from 25-54°C. Steam is coming up from 5-6 sites. The area is covered by alluvium and is altered to reddish brown and grey clays. A silica sinter is observed.

Locality No. 96-12: It is east of geothermal well G-4 (Figures 6 and 10). It is a hot ground with temperature ranging from 45-98°C. The area is about 6 m long and 4 m wide and is covered by alluvium. Part of the grass in the area is burnt yellow indicating recent heating. The area is slightly altered to reddish brown clays.

Locality No. 96-13: It comprises two hot springs located on the sides of a stream coming from the western slopes of Reykjafjall (Figure 6). The spring on the northern side of the stream has a temperature of 34°C and very little outflow, while the spring on the southern side is 70°C hot with a little flow of water. The area is slightly altered to reddish brown clays, and covered by alluvium and scree.

Locality No. 96-14: It is located just east of the separator installed for geothermal wells (Figures 6 and 10). It consists of hot springs, steaming ground and a steam vent. The water in the steaming ground is boiling. Just in the south of this steaming ground a hot water spring is located, which has formed a small pool. The water temperature is 30°C, and no flow is observed. The total area is about 20 m long and 7 m wide, covered by alluvium and scree at the foot of a small hyaloclastite ridge. The area is slightly altered to reddish brown and grey clays. Further south a small trench is located probably a former wellhead where water is boiling and emitting steam. On aerial photographs all these manifestations, combined with 96-11 and 96-12, are seen on a fracture/fault line striking N25°E (Figure 10).

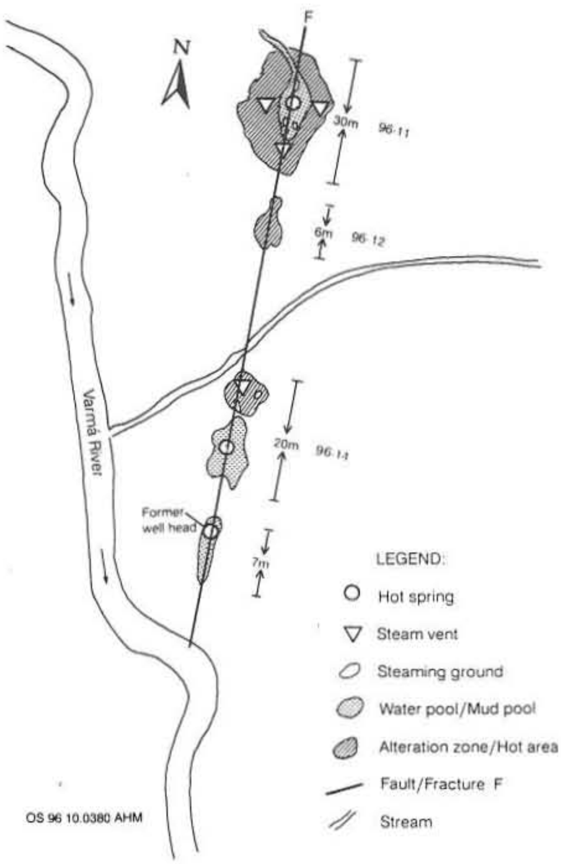


FIGURE 10: Geothermal localities 96-11, 96-12 and 96-14

Locality No. 96-15: It is located in the territory of the Horticultural College (Figure 6), consisting of hot springs, mud pools and steam vents. The hot area is about 110 m long and 60 m wide, all of it highly altered to reddish brown clays. In the mud pools grey boiling clay is observed. The hot spring water is also boiling. Native sulphur is not seen but a light H_2S odour can be smelt. Silica crusts are seen in the whole of the area, which accordingly is marked as a silica sinter. The silica sinter indicates a large outflow of hot water in former times. At present the area is partly covered by alluvium and a small amount of steam is emanating from the vents, indicating boiling water in places below the surface.

Locality No. 96-16: It is also located in the Horticultural College area on the eastern foot hill (Figure 6). It is a small area of 20 m length and 20 m width rounded in outline. It consists of one small and weak steam vent only. The area is covered by alluvium and scree, and is altered to reddish brown clays. All the area is hot, ranging in temperature from 20 to 98°C. No sulphur or H_2S smell is observed, but silica could be seen on a small scale.

Locality No. 96-17: It is located in the Horticultural college and is famous as the Reykir geothermal area (Figure 6). It consists of many hot spring having temperatures ranging from 70-98°C. All the area is altered to reddish brown clays, where crust is observed and hence marked as a silica sinter. Two geothermal wells have been drilled for use in the Horticultural college. No sulphur is found but light smell of H_2S is. In three of the hot springs, water is boiling noisily yielding a lot of steam.

Locality No. 96-18: It is located on the western slopes of Reykjafjall (Figure 6), and consists of several weak steam vents. It is located in a landslide block. The area is very small and altered to reddish brown clays.

Locality No. 96-19: It is further north from the previous locality in the slopes of Reykjafjall (Figure 6). It consists of 2 steam vents, 2 hot springs and hot grounds. Very little steam is emanating from the vents. The water in the springs is almost boiling but not flowing. One of the spring forms a small pool, where water is boiling and coloured by clay but not flowing. Beside these there are several places with hot grounds of 4 m^2 to 60 m^2, which is quite prominent as compared to the surroundings where the vegetation (grass) is not spoiled by the heat. The temperatures in these areas are in the range 35-98°C. All of the area is covered by alluvium, which is altered to reddish brown and gray clays in patches. There is no sulphur nor H_2S smell. Silica is not seen.

Locality No. 96-20: It is located further north from the previous locality on the western foot hill of Reykjafjall (Figure 6). It is an area about 35 m long and 15 m wide consisting of steam vents. All of the area is highly altered to reddish brown clays and a lot of steam rises from the vents, which can be seen from long distances. A cold water stream crosses the area from east to west. There is no sulphur nor silica, but a smell of H_2S is present.

Locality No. 96-21: It is located in the southern part of the area on the bank of the river Varmá just near the small pedestrian bridge crossing the river (Figure 6). There are many springs on both sides of the river. The water in most of the springs is boiling having a temperature of 95-99°C with a small flow of water pouring into the river. Due to the boiling of water a large amount of steam is erupting from this area. The area is covered by alluvium, and is altered to reddish brown and grey clays. Typical H_2S smell is felt, but sulphur is not found. Silica is present. Apparently no structural relationship is observed, except that the locality forms part of a prominent line of hot springs to the NNE and SSW.

2.3.1 Interpretation of geothermal manifestations

The geothermal manifestations are distributed from about 50 m a.s.l. at Hveragerdi to about 350 m a.s.l. northeast of Saudá river (Figure 6). The alignment of surface geothermal manifestations in the study area is shown in Figures. 7, 8, 9 and 10 indicating their relationships with structural trends. Normally two sets of fractures trending NNE-SSW and NNW-SSE are observed. The presence of geothermal manifestations on the banks of the river Varmá in the southern part of the area is probably due to the low topography. In the central part of the valley the area has been affected by landsliding and deposition of alluvial deposits, due to which the linear arrangement of the manifestations is obscured.

Geothermal activity observed in the area is of two types:

1) Extinct regional alteration, which is evidenced by greenish and black to brownish altered hyaloclastites belonging to the oldest rock series. The alteration resulted in primary minerals and glass being replaced by clays of smectite and smectite-chlorite, which are formed at temperatures of 200°C and less.
2) Present geothermal activity, which is represented by active areas of hot springs, steam vents, steaming grounds, boiling mud pools etc., and is characterised by grey or dark brown to reddish brown colours due to smectitic clays, mostly Fe-saponite (Saemundsson and Fridleifsson, 1996).

In some of the soil sections a sequence of episodic geothermal activity during the Holocene period is evident; e.g. about 40 m north of locality No. 96-07 (Figure 6) in the valley, an alteration (red clay bed) was observed below the 2 m thick cover of alluvium. Deposition of silica sinter and clear water with substantial flow in the southern part of the area near Reykir (Figure 6) indicates that the source of the geothermal water is from a very deep reservoir. The geothermal manifestations in the northern and eastern part of the area (Figure 6) show that the condensed steam is mixed with the surface water to produce mud springs and steam vents without silica.

2.4 Cold water springs

Cold water springs in the "Saudá valley" were distributed at an altitude of 300-400 m a.s.l. (Figure 6). The temperature of the springs generally ranges between 6.3 and 11°C. At one location near the geothermal manifestations locality No. 96-02 (Figure 6) a cold water spring is present which has a temperature of about 3.5°C. Most of the cold water springs were located above the geothermal alteration zone, some of them emerging from the bedrock. These cold water springs discharge their water by streams, which ultimately join the Saudá river. The temperature of water in Saudá river ranges between 10-12°C, which is only a slightly higher than the mean temperature in August.

2.4.1 Interpretation of cold water springs

The presence of most of the cold water springs at 300-400 m altitude (Figure 6), indicates that the ground water level is quite high. Worth noting is that almost all the cold water springs are located above the geothermal alteration zone, which also indicates that the geothermal alteration has reduced the permeability of the rocks, and the water cannot percolate freely down below this alteration zone. The presence of a very cold spring (3.5°C) at one locality probably indicates that the source of this spring is from a shallow depth in the bedrock.

2.5 Detailed geothermal mapping

Measurements of temperature at a convenient depth in the soil can give important structural information related to the geothermal prospect (Flóvenz, 1985). The area selected for this survey is relatively flat and has been covered mostly by alluvial gravel and silt (Figure 11). During the survey all the geothermal

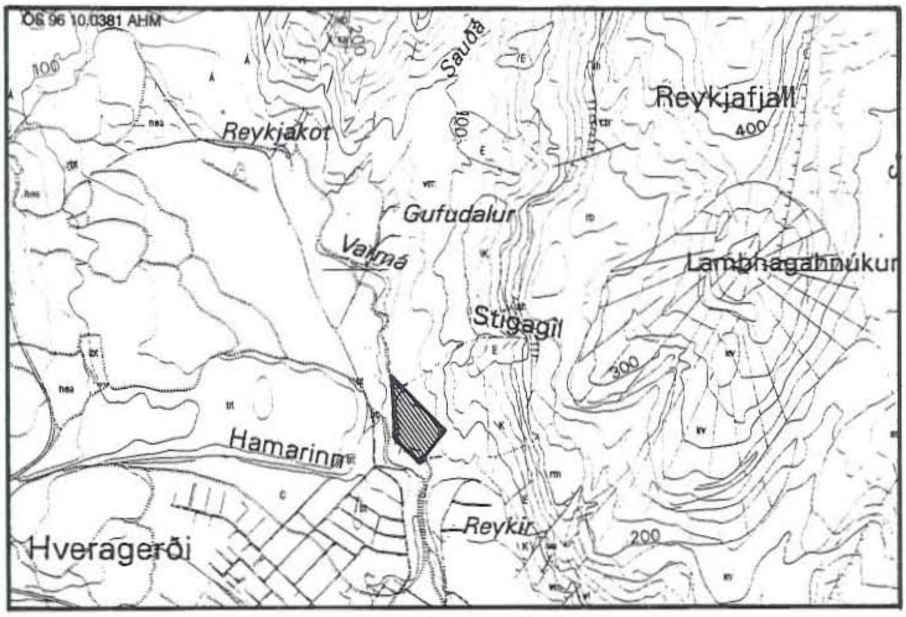


FIGURE 11: Location of the area where soil temperature measurements were carried out

manifestations occurring in the area were plotted on a map. All other information of soil type, alteration, rock type etc were also noted. In the present survey the base line was marked on the southern side of the area with reference to a small bridge (3 m north from bridge) built for pedestrians across the Varmá river. The direction of the base line was N50°W and the length was 95 m. All other lines were taken parallel to this baseline with an interval of 10 m. The first 12 lines were taken at an interval of exactly 10 m to the north from the base line instead of perpendicular. The actual distance was thus 7.7 m. After realizing this mistake, the remaining 12 lines were taken with a 10 m interval perpendicular to base line. Similarly the distances taken on slopes also give small errors, which were taken into account accordingly. Along these lines the temperature was measured at 5 m intervals and at a depth of 60 cm. All the data was plotted on a map of appropriate scale and isotherms of 15, 20, 30 and 50°C temperature were drawn.

2.5.1 Interpretation of detailed geothermal mapping

Figure 12 shows the isothermal lines constructed by using results from the temperature measurements at 15, 20, 30 and 50°C intervals. The figure shows that at a depth of 60 cm the temperature varies from 11-98°C in the area. Three significant hot spots had temperatures above 50°C. One is in the southern part of the area on the banks of the river Varmá, where most of the hot springs with boiling water are located. Apparently there is no relationship with any structure on the banks except that it is a low topography area along the banks of river. From there the thermal area continues south of the river to the centre of Hveragerdi with an almost NE-SW trend. There is, thus, a clear tectonic connection (Thorkelsson 1930) which suggests lateral spread of the hot water from the main fracture in towards the topographic low along Varmá river. The second hot spot is in the central part of the area, having strike direction about NNE-SSW, which is probably a fault/fracture controlling the movement of geothermal water. The third hot spot is located further north from the previous one. It is smaller and has a NW-SE direction indicating a fault/fracture below the alluvium. Beside these, a few other hot spots having a temperature of 20-50°C were found. Most of these are aligned in NNE to SSW direction. This is the most common strike direction of faults/fractures in the mapping area. In the central part of the area an asbestos pipeline has been laid down in the ground in north-south direction for supplying hot water to Hveragerdi. This pipe line has been covered by silt and gravel. Around it the temperature measured shows high values of 20-38°C, even in one instance about 57°C. It indicates that the pipe line is not properly insulated as the whole area close to the pipeline is hot and in one place at least it is leaking.

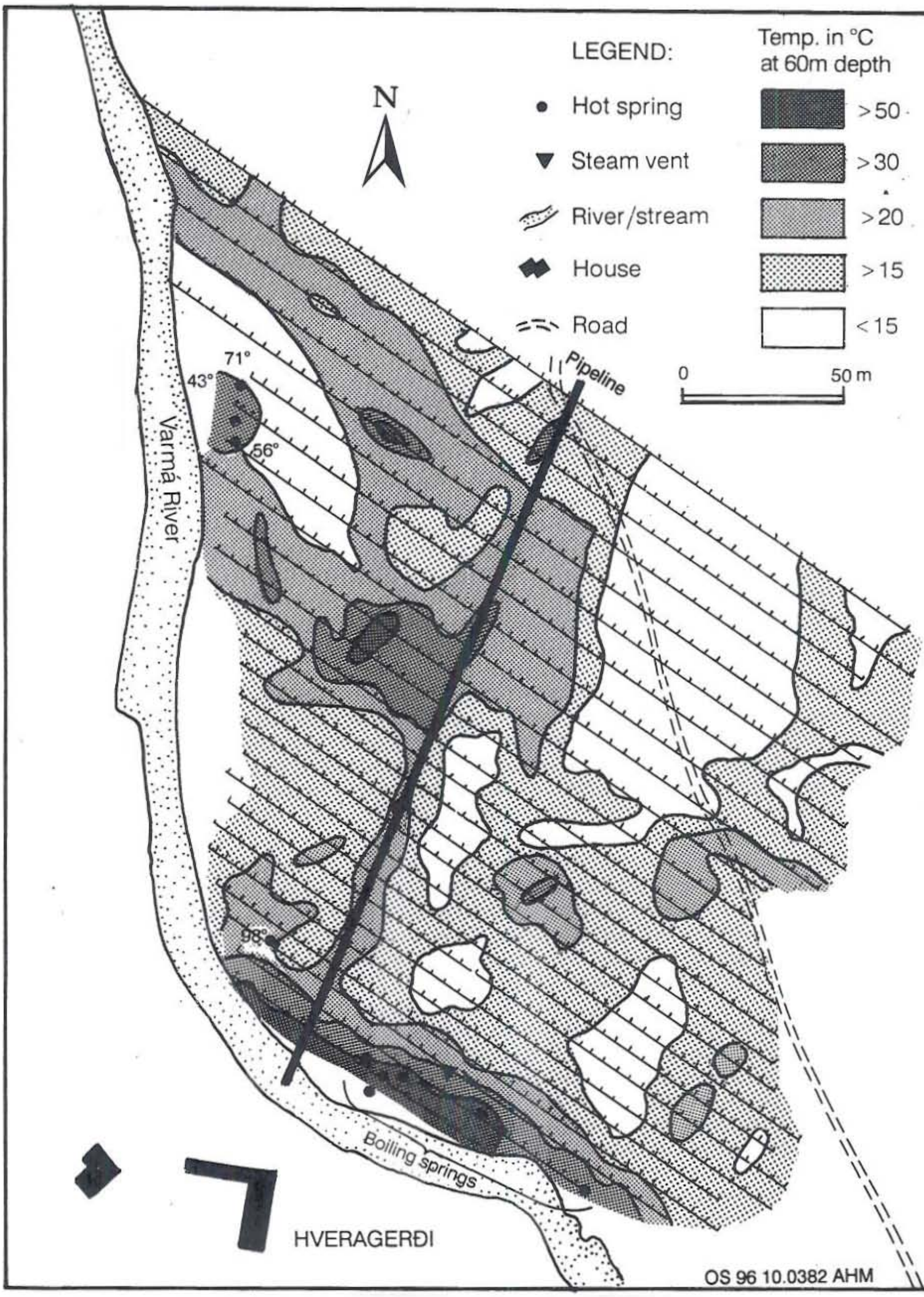


FIGURE 12: Iso-temperature map based on soil temperature survey

In the northwestern part of the area which slopes down to Varmá river temperatures of 20-40°C were reached and a few hot springs are present. This is probably due to seepage from the higher ground to the east rather than to any tectonic significance.

Looking at all the map, the hot spots are on a NNE-SSW line, indicating a fracture below the alluvium.

2.6 Flow measurements

The natural output from a geothermal field may indicate its stored energy. The heat escape is by flow of hot water, steam emanation and conduction in areas of hot ground. In the present survey only the flow of a few selected thermal springs was measured on 25th September 1996 by the timing method. The same locality numbers are used as those in the description of geothermal manifestations (Figure 6). The flow measured is as follows:

1. **Locality No 96-01**: It is located north east of the Gufudalur farm in the valley. It comprises two hot springs, discharging their water into small separate streams. The area is covered by scree and alluvium with vegetation (grass). The flow was measured by using a 5.5 l bucket. The average flow measurement was:
   a. 0.098 l/s of 37.2°C hot water (in August 1996 the temperature of the spring was 39°C).
   b. 0.10 l/s of 32°C hot water (in August 1996 temperature of the spring was 24°C).

2. **Locality No 96-19**: It is located further north of the previous locality. It comprises several small springs and seepages of hot water having temperatures of 30-61°C. Just to the east of these springs, a steam vent and a few hot grounds are located and probably the water coming from uphill is heated up by these hot areas and then the hot water is discharged in the form of small springs and seepages. The flow was measured downslope from a small stream, where several springs and seepages are combined. The average flow measurement by using a 5.5 l bucket was 0.12 l/s of 42.8°C hot water.

3. **Locality No 96-21**: It is located in the southern part of the study area on the bank of the river Varmá near the small bridge built across the river on a footpath. It comprises several hot springs. Two of them were selected for flow measurement. The first spring is about 45 m west of the bridge on the bank of the river. The average flow measurement by using a 1.3 l bucket was 0.30 l/s of 92.8°C. The second location was about 10 m north east of the bridge. It comprises three hot spring, which discharge their water to a small stream, where the flow was measured by using a 5.5 l bucket. The average flow was 0.73 l/s of 98°C hot water.

2.6.1 Interpretation of flow measurements

The flow of hot water to the surface is very low in the area. The ground water recharge is mostly by secondary permeability created by faults/fractures. Over most of the area boiling of the ground water produces steam that is partly condensed and mixed with surface water to produce the turbid springs of low discharge at higher elevations. Clear water boiling springs of significantly higher discharge are only found near Varmá. The alteration of the rock seals small fractures and pores, so surface manifestations are mainly related to secondary fractures. Convection in the geothermal system is regarded as the main mechanism for transferring heat to the surface.

3. RESULTS

3.1 Conclusions

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

2. Geothermal manifestations and temperature distribution indicate two sets of fractures having almost NE-SW and NW-SE strike direction. These are probably faults/fractures controlling the movement of the geothermal water of the area. Heat sources are believed to be cooling intrusions underneath and to the west of the area (Hengill volcano).

3. Though the study area is a part of the extinct Hveragerdi central volcano, which has drifted 5 km to the east away from the axial rift zone, it is still connected with the axial rift zone through fissures or faults /fractures and is categorized as a high-temperature area. Drilling has shown temperatures above 200°C at less than 1 km depth.

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

5. The presence of low native sulphur 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 the 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 high and geothermal alteration has reduced the porosity and permeability of the rocks and percolating of water down below this alteration zone is controlled by fractures/faults.

3.2 Recommendations

1. Before siting a drill hole for geothermal prospect in the area, a thorough study is required of structures like faults, fractures and dykes. This is recommended because the present permeability seems to be of secondary nature.

2. Because of the apparently reduced porosity and primary permeability of the rocks of the area, it is of great importance to locate the most promising upflow zones. A detailed map combining geothermal manifestations and in particular young structural features would be an useful first step.

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