The United Nations
University

GEOTHERMAL TRAINING PROGRAMME
Orkustofnun, Grensásvegur 9,
IS-108 Reykjavík, Iceland

Reports 1996
Number 8

GEOTHERMAL EXPLORATION IN THE HVERAGERDI-GRAENDALUR AREA, SW-ICELAND

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ABSTRACT

Geothermal activity is considerable in the Hveragerdi central volcano, chiefly in the western and southern parts. Geothermal mapping in the scale of 1:10,000 involved the mapping and description of hydrothermal phenomena of this area. A general description of geothermal manifestations in the area is given. The geothermal activity is divided into groups and sub-groups. Geothermal activity is mainly related to fractures and faults and these, together with thick loose sediments and landslides, define the geothermal hydrological features at the surface. The characteristics of the manifestations are very similar throughout the area. Therefore, only two detailed figurative descriptions are presented and one of these is described in detail. A detailed soil temperature survey was done in a selected part of the area to determine the lateral extent of an inferred fracture. Also, the energy content of several hot springs was determined with flow measurements. As a conclusion to this report, a hydro geothermal model of the area is proposed, indicating a recharge to the west of the study area. The steam heats the cold ground water producing hot springs at lower topographical levels and steaming ground and solfataras higher up.

1. INTRODUCTION

1.1 Background

In Uganda, in spite of the presence of respectable geothermal energy manifestations relatively large areas of the country remain undeveloped because of inaccessibility to the national hydroelectric power grid,. Several of these geothermal areas are considered harnessable for certain industrial purposes and geothermal electric power production. Some of these areas have been mapped to a limited extent while others are unmapped.

In line with the current policy of the Ugandan government, the Department of Geological Survey and Mines, under the Ministry of Natural Resources, has decided to carry out geothermal exploration of these areas to the pre-feasibility stage. The goal is to attract investment into the geothermal energy sector.

Geothermal energy, being basically renewable, is increasingly being preferred for use as a source of energy because of the relatively environmental friendliness and cost-effectiveness.

The Icelandic government, in conjunction with the United Nations, is helping train earth scientists from third world countries in the geothermal sciences. This report is a reflection of the ardent desire of the management of the Department of Geological Survey and Mines and the United Nations to develop the capacity of the Department in the fields of geothermal exploration, development and exploitation.

1.2 The Hveragerdi-Graendalur area

The Hveragerdi-Graendalur area is located approximately four kilometres north of the town of Hveragerdi which is itself located about 45 kilometres east of Reykjavik, the capital city of Iceland (see Figure 1). The study area is located within the South Iceland seismic zone which lies on the western flank of the active boundary between the North American and European crustal plates. This area is part of one of the high-temperature areas found exclusively within active volcanic rift zones. The temperatures at 1 km depth are typically above 200°C in the high-temperature areas (Flóvenz and Saemundsson, 1993). Within the Hveragerdi central volcano geothermal activity is prolific, chiefly in the west and south, and the study area is in the southern part.

As the study area is in an active volcanic and seismic region it gives rise to a diversity of hydrothermal phenomena at the surface. The geothermal activity in this area is related to two central volcanoes, the older one being altered and eroded just north of Hveragerdi, but the other presently active in the centre

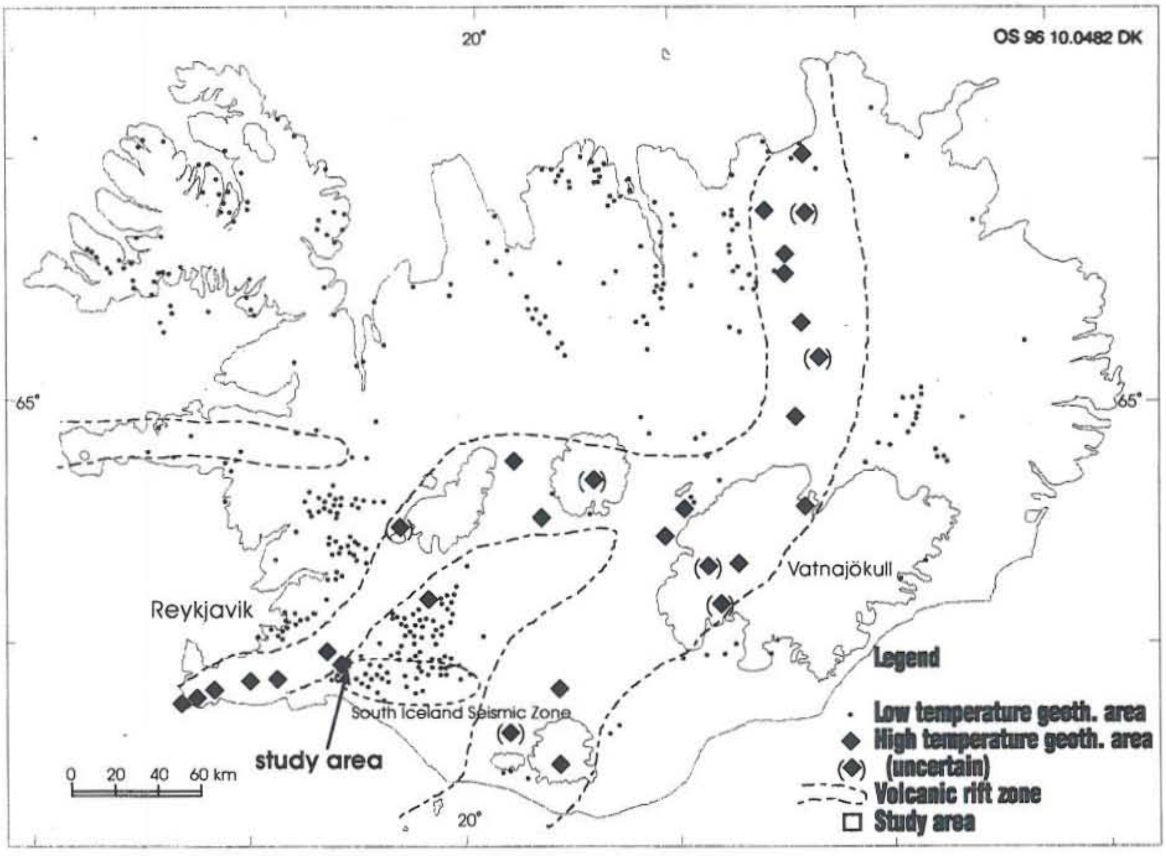

FIGURE 1: Geothermal map of Iceland and the location of the study area

of the rift zone, the Hengill central volcano (Saemundsson and Arnórsson, 1971). The former central volcano was named after the town of Hveragerdi, which is very appropriate, the town being the cradle of geothermal energy usage in Iceland, and in fact owing its establishment 50 years ago to the abundant and sometimes spectacular presence of geothermal phenomena.

Twice in this century considerable changes in the surface hydrothermal activity have been observed in relation to earthquakes in Hveragerdi, at Reykjakot during 1915 or 1916 and at Reykir-Hveragerdi in 1947. During the last decade or so noteworthy changes in surface activity, though on a smaller scale, have been observed in relation to earthquakes in 1982 at Dalaskard and in 1992 at Boli. Presumably some of the rock slides observed in this area are a direct result of major earthquakes which hit the area at least once in a century, the town being located within the South Iceland seismic zone. However, most earthquakes are below 4 on the Richter scale, like those in 1991 and 1995, and occur in swarms.

The study area includes the valley of the Graendalsá river bounded by a topographic high " Dalafell" in the west and a low broad rise which forms the water divide to the Saudá river in the east.

1.3 Previous work

Systematic mapping of the Hengill area, including Hveragerdi-Graendalur began in 1967 (Saemundsson, 1967). A few years later, around 1970, the area was mapped in relation to drilling activities at Hveragerdi (Saemundsson and Arnórsson, 1971). As a result of this work, the Hveragerdi central volcano was outlined and many of the formations of which it is composed were established. Jónsson (1989) undertook some research in the area, mostly on Upper Pleistocene and Holocene lavas. During 1989 and 1990, the geological mapping of this area was completed, the emphasis being on the lithostratigraphy, tectonics, the geothermal activity and alteration of the area (Saemundsson and Fridleifsson, 1992 and 1996). Cherry Walker (1992) mapped the volcano with respect to its eruptive units and their petrology. All this work was combined in a map of the Hengill central volcano in a scale of 1:50,000 (Saemundsson, 1995a).

2. GEOLOGY

2.1 General geology

The Hveragerdi-Graendalur area is basically composed of chiefly hyaloclastites and, to a lesser extent, interglacial lava flows. They have been separated into eruptive units and groups of closely related rocks of given time periods (Saemundsson and Fridleifsson, 1996). Their composition is mostly basaltic, ranging from olivine-tholeiitic to tholeiitic. The hyaloclastites range from glassy/ fine grained tuffs to coarse breccias and pillow lavas. Sometimes these pass into lava flows. The units have textures that range from aphyric, fine or coarse grained to variably porphyritic. These lavas and hyaloclastites form the bedrock in the area and are overlain by surficial deposits. The following lithological description of the units that compose the geology (Figure 2) of the area is extracted from Saemundsson and Fridleifsson (1996).

2.2 Lithologic description

The Varmá formation (**vm** on map) is the oldest and most widely encountered rock group in the study area. It is chiefly a hyaloclastite formation, occurring in the southwestern and central areas of the study area. Two rock types make up this formation: a) hyaloclastite breccias with numerous lava pods and b) hyaloclastite tuffs.

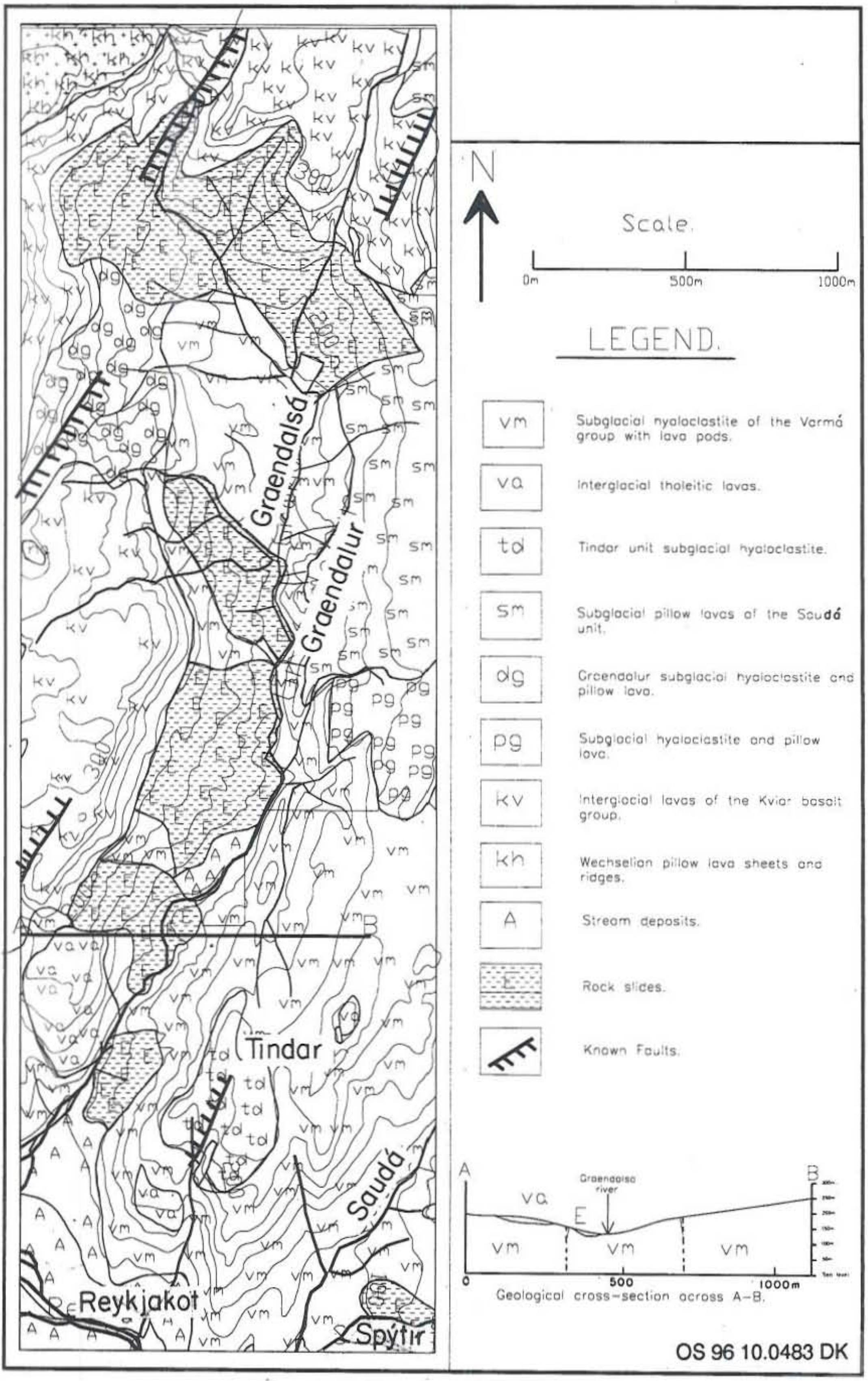

FIGURE 2: Geological map of the Graendalur area (extracted from Saemundsson, 1995a)

a) The breccias and the basalt lava pods form the core of the Varmá formation. The basalt pods and columnar jointed basalt blocks with a tuffaceous matrix, characterize this part of the formation, the pods being up to tens of metres in width. The columnar jointing in these pods is irregular and in the largest ones thick zones with vertical columns similar to sheeted dykes are seen. The lava pods grade into breccias at the margins and are contemporaneous to the hyaloclastite host. The lava pods are composed of intensely jointed, very fine grained, dense olivine-free basalt, apparently of tholeiitic composition.

b) The breccias are overlain by tuffaceous hyaloclastites. In the Graendalur area, further north along the Graendalsá, the hyaloclastite is vesicular and relatively coarse in texture without being brecciated. Above Reykjakot the hyaloclastite is composed of tuff or tuff rich breccias which form thick, layered units which are tilted southwards. The glass is quite altered and is mostly replaced by green chlorite and/or mixed layers of brown smectite in the Graendalur valley. Because of the surficial nature of rock slides and/or stream deposit areas, the most significant geothermal activity occurs in this formation.

Lavas (**va** on the map) are found at two sites at the top of the Varmá formation. They are just west of the Graendalsá river further southwest and in the hills just west of and above Reykjakot. The lavas are fine-grained aphyric tholeiites, dipping 2-3° south.

The **Tindar unit** (**td** on the map) is found in the central southern part of the area of study. Agglomerate basalt lavas and tillite separate this unit from the Varmá formation. This hyaloclastite formation is chiefly composed of pillows in tuff matrix and pillow breccias.

The **Saudá unit** (**sm** on the map), is composed of pillows in tuff and relatively coarse breccias. A hyaloclastite rich sedimentary bed separates it in places from the underlying Varmá formation. No active manifestations were mapped in this formation in the study area.

The **Djúpagil-Graendalur formation** (**dg** on the map) occupying a relatively small part of the study area and lying in the central western part of it, is built of hyaloclastite lavas and pillows which are dark in colour. Geothermal manifestations in this formation in the study area are found in its northernmost contact with the Kvíar basalt group.

The **Thvergil hyaloclastite** (**þg** on the map) is exposed on the rise between the Graendalsá river and the Saudá river to the east of the area of study. It is composed of feldsparphyric pillows and pillow breccias and is resting unconformably on the Varmá formation. No active geothermal manifestations were found in this formation.

The **Kvíar basalt** (**Kh** and **Kv**) lava units and breccias surround the study area at high elevations. Few manifestations were found in these formations.

2.3 Surface deposits

Rock slides (**E** on the map) are one of the most prominent surface features in the study area. Large earthquakes, probably related to the South Iceland seismic zone have caused rock-slide deposits to form and these now cover a substantially large part of the area of study.

Large rock slides are common in the area, some are recently disgorged and lie at higher elevations, having travelled over shorter distances. They show rocks of relatively intense jointing and appear to be weathering quickly and are very permeable. Older deposits which have travelled over longer distances, are at lower elevations near the Graendalur valley, are weathering, fragmented and appear to be slightly consolidated.

Most hot springs are found within these deposits. The soils are locally quite thick within them and consequently relatively thick vegetation abounds in the flatter lying areas. At higher and lower altitudes, attesting to their high susceptibility to weathering, their high porosity and permeability the rock slides store a lot of water. A high amount of surface runoff is evident in these areas in the form of small, apparently seasonal, streams and 'streamlets' and at the lowest elevations these areas are water logged. Most of these rock slide deposits overlie intensive clayey-alteration areas.

Geothermal manifestations in the area are also found within **stream deposits** (**A** on the map).

2.4 Dykes

From the earlier geological mapping done in the area, crosscutting relationships reveal at least 4 major dyke systems (Saemundsson and Fridleifsson, 1996). On the eastern side of the study area furthest south, the olivine tholeiite dykes mostly strike NNE-SSW and are most often subvertical and less than 1 m thick. The dykes are not shown on the geological map in Figure 2.

2.5 Tectonics

From earlier geological mapping in the region, tectonic movements within the area of study are chiefly of three types: 1) tilting towards the northwest; 2) faulting and fracturing of the rocks with or without displacement, and 3) formation of open fissures.

1) **Tilting** towards the northwest is regional, and is only 1-2° in the northernmost part of the Graendalur area. It is caused by progressively increased burial of younger volcanics in the rift zone to the west.

2) **Faulting and fracturing** is quite common in all rock types in the Graendalur area. Sometimes dykes occupy faults or fracture planes with accompanying intensive hydrothermal alteration. The dominant trend is NE-SW.

3) **Open fissures** are quite common in the area but due to erosion they are often difficult to ascertain and those identified by the author are inferred from the consistent alignment of geothermal manifestations along a preferred direction. On the geothermal map known and inferred faults are shown (Figure 3). Like the faults the open fissures generally trend in the NE-SW direction although slightly differing trends are observed.

3. MAPPING OF GEOTHERMAL MANIFESTATIONS

3.1 Methodology

The project involved the mapping of surface geothermal manifestations in the Graendalur area northwest of the town of Hveragerdi. The mapping of surface manifestations involves determining the surface characteristics of the manifestations and plotting their locations on a map (Figure 3).

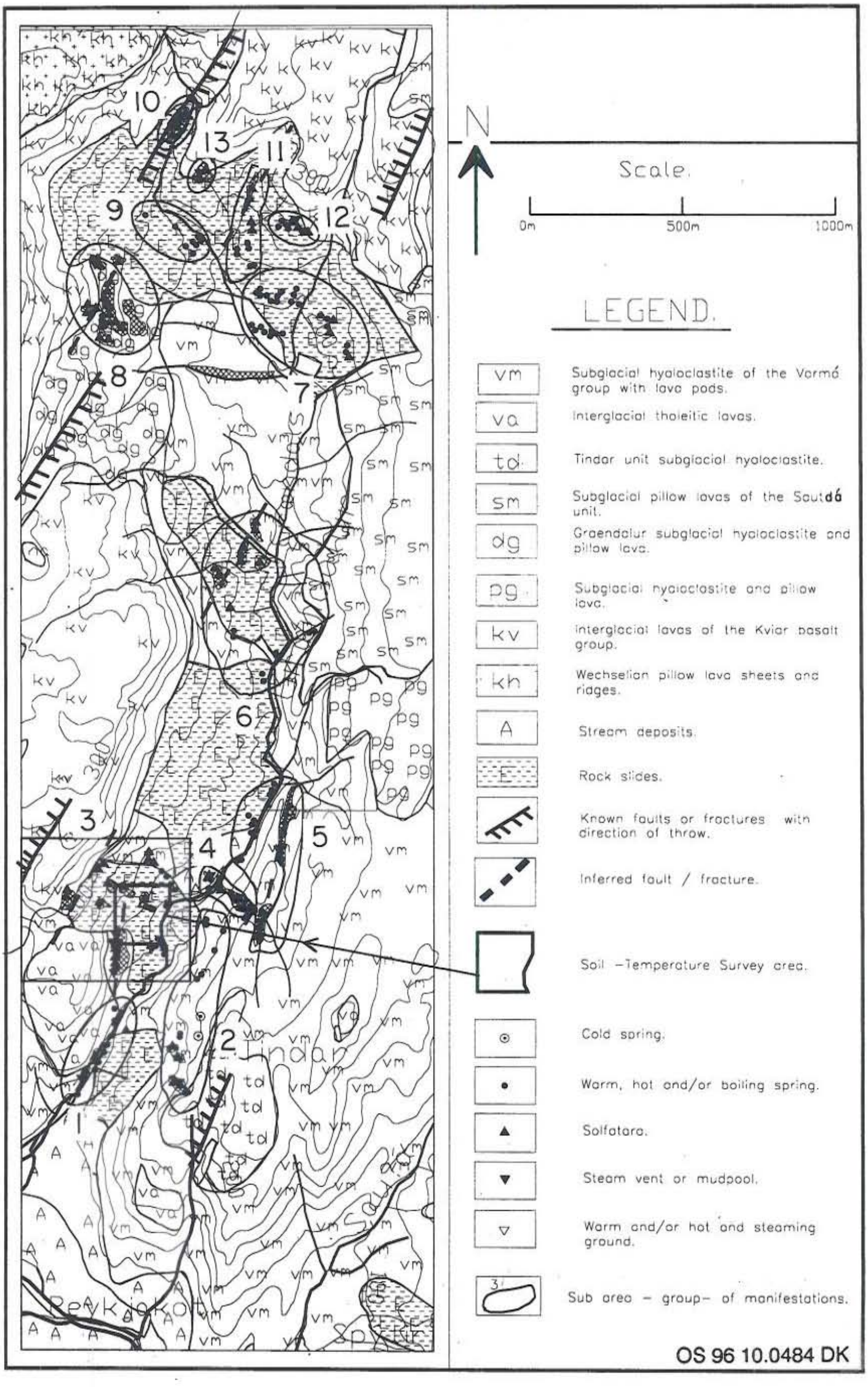

FIGURE 3: Compiled geothermal map of the Graendalur area

Geothermal phenomena in this area are manifested in the form of warm, hot and boiling springs, steam vents, solfataras, warm and hot ground, mudpools and boiling springs, silica and other encrustations and hydrothermal clay alteration.

The area was mapped by Saemundsson (1995b), but on a smaller scale.

3.1.1 Springs

The springs were located and plotted on the base map. The temperature of individual springs was measured using a digital thermometer and their flow rates estimated. Notice was taken of the surroundings of the spring to see whether there were any precipitates being deposited by the spring on the surrounding rock fragments or if there was any alteration of the country rocks relating to the spring discharge. In addition, if a spring was located very near a much bigger stream or river, the stream or river temperature was noted, the air temperature at the time of taking the measurement, the approximate cloud cover, and the weather conditions i.e. whether it was windy, raining or sunny.

3.1.2 Fumaroles, solfataras, mudpools and 'frying pans'

These forms of geothermal manifestations are grouped together since in many cases they were found to be not only interlinked but usually also in the same location. 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. 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 water discharge areas of these manifestations.

3.1.3 Hydrothermal alteration, silica and mineral salts precipitations and/or sinters, warm and hot ground

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 an 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 or some form of mineral salt. A thick layer of siliceous sinter, sub-circular in shape and extending for about 24 metres in its shorter dimension was mapped in part in the detailed soil temperature survey area.

3.2 Characteristics of the manifestations

3.2.1 Springs

These are the most common hydrothermal manifestations in the study area and they have a wide temperature range. The springs are divided into four categories, (i) cold springs, springs whose temperatures measure below 10°C; (ii) tepid springs with temperatures between 10 and 30°C; (iii) warm springs with temperatures between 30 and 70°C; and (iv) hot springs with temperatures above 70°C. In Figure 3, these groups are not distinguished.

Only two **cold springs** were found in the area and their temperatures were 8.6°C and 4.6°C having flow rates of less than 0.1 l/s. Their points of discharge were just through the vegetation layer in group 2 of manifestations and were found to lie along the same contour (Figure 3).

Those which are referred to as **sulphurous springs** have relatively great quantities of sulfur deposited along their flow paths just outside their points of discharge and the smallest of these could be most easily identified by the sulfur alone. The sulfur is usually manifested in the form of yellow powderlike depositions lying not far from the point of discharge and along the spring flow path. Their flow rates are generally below 0.05 l/s.

Tepid and warm springs together constitute the largest percentage of the springs. The temperatures of these are very varied and range from 10°C to boiling. Most of these could be easily located by the presence of precipitates on the rock fragments at their points of discharge and along their flow paths. The flow rates of both the warm and hot springs ranged from very little to about 0.5 l/s and the water frequently smelled of hydrogen sulphide. They were often found to be concentrated in small areas.

3.2.2 Fumaroles, solfataras, mudpools and boiling hot springs

These were frequently found clustered together within the same locale. Lots of sulphur deposition are evident in these areas accompanied by equally intensive precipitation of mineral salts. These areas are frequently being intensively altered. Mud pools are filled with fine grey clay and some upon cooling have become blocked with clay and some enlarged to boiling mud 'caverns' which throw out grey clay in a way similar to the boiling of a thick porridge. They infrequently have a halo of ferruginous earth around their margins. Collapse of the intensively altered ground around them has led to the formation of boiling mud ponds which, when filled with surface waters, having temperatures of up to 80°C. Around these, kaolinisation is observed to be well advanced. The temperatures of these areas were as a rule near to or at boiling.

3.2.3 Hydrothermal alteration

Alteration is widespread in the area and composes two distinct types. In areas where there is active and usually relatively quite intensive heat transfer to the surface, there is what has been termed as active alteration. Extinct alteration is much more widespread and is basically of the grey clayey, kaolinitic, smectitic and chloritic types. Ferruginisation is also widespread though to a much lesser extent.

Silica and mineral salts precipitations are being actively formed in areas of geothermal activity. This includes spots or localities which are not far from boiling temperatures forming the hot grounds which are as a rule devoid of vegetation. In some of these areas, most alteration and precipitation is occurring along fractures within the rock mass. The process of sintering is sometimes manifested in the form of a thin crust of mineral salts and silica accompanied by sulphur deposition.

Warm grounds are usually identifiable by the yellowish green moss. Apparently the only vegetation which can thrive above 35°C in this climate and soil type is yellowish green moss, and below 27°C it is grass (soil temperature survey). Warm grounds usually but not always surround the hot ones and in places where progressively more heat is being transferred and or lost through them, thick grass is observed to die or dry away. Shifting of the thermal phenomena is usually manifested in dying or drying-away of the thick green grass (Figure 4).

The geothermal map that has been compiled by the author as a result of geothermal mapping in the Graendalur area shows some differences with the already published maps (Saemundsson, 1995b).

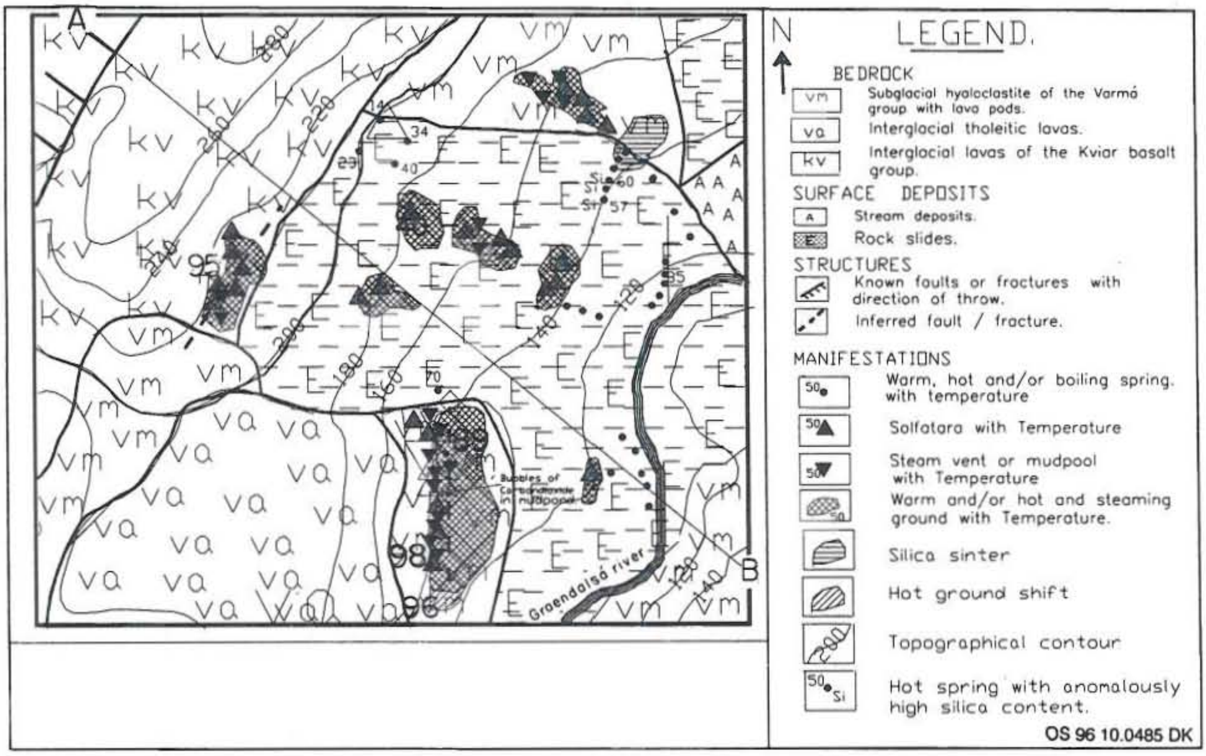

FIGURE 4: Detailed geothermal map of sub area 3, temperature in °C (for location see Figure 3)

3.2.4 Description of a sub area

In sub area 3 several types of surface manifestations are found (see Figure 4). Three geological units make up the bedrock in the sub area. These are the Varmá formation, which forms the bedrock in the area, lava flows (Va) and two composed of Kvíar basalts. The rest of the area is covered by rock slides and stream deposits.

The characteristics of the individual geothermal manifestations in this area are the same as those described above. The description of the geothermal situation in this sub area is best given by Figure 4, where the geothermal manifestations are shown with the geology and topography of the area.

Figure 5 shows a geothermal map of sub area 4, with a special focus on a part of it. There temperatures and descriptions are given.

4. FLOW RATE MEASUREMENTS

4.1 Methodology

Flow rate measurements were carried out in one location within the area of work to determine the amount of convective heat transfer there. This location (sub area 3) has one of the most spectacular hydrothermal phenomena in the area, several hot springs and/or boiling mud-pond and mud-pool overflows.

Six spring outflows and boiling mud-ponds / mud-pools labelled A, B, C, D, E and F, which later combine to form a streamlet, were studied (see Figure 6). The rate of flow of this streamlet was measured initially, approximately fifty metres (H) from the individual hot water sources (and is referred to here as the 'combined flow rate' but does not include E). Later the individual hot water outflows were measured to determine the extent of heat loss in the form of evaporation and percolation over this distance. At D there was a cold inflow of approximately 0.1 l/s of 19.5°C hot water (see Figure 6).

The time (in seconds) that was necessary to fill 1.0, 5.5 or 10.6 litre plastic containers was measured using a stopwatch. The capacity of the container to be used was selected in consideration of the visible volume of flow to ensure that the measuring process was not too fast as to lead to errors of measurement and not so slow as to lead to time wastage. Six individual flow rate measurements were taken at each site and the average was used in the final calculation of the flow rate (Table 1).

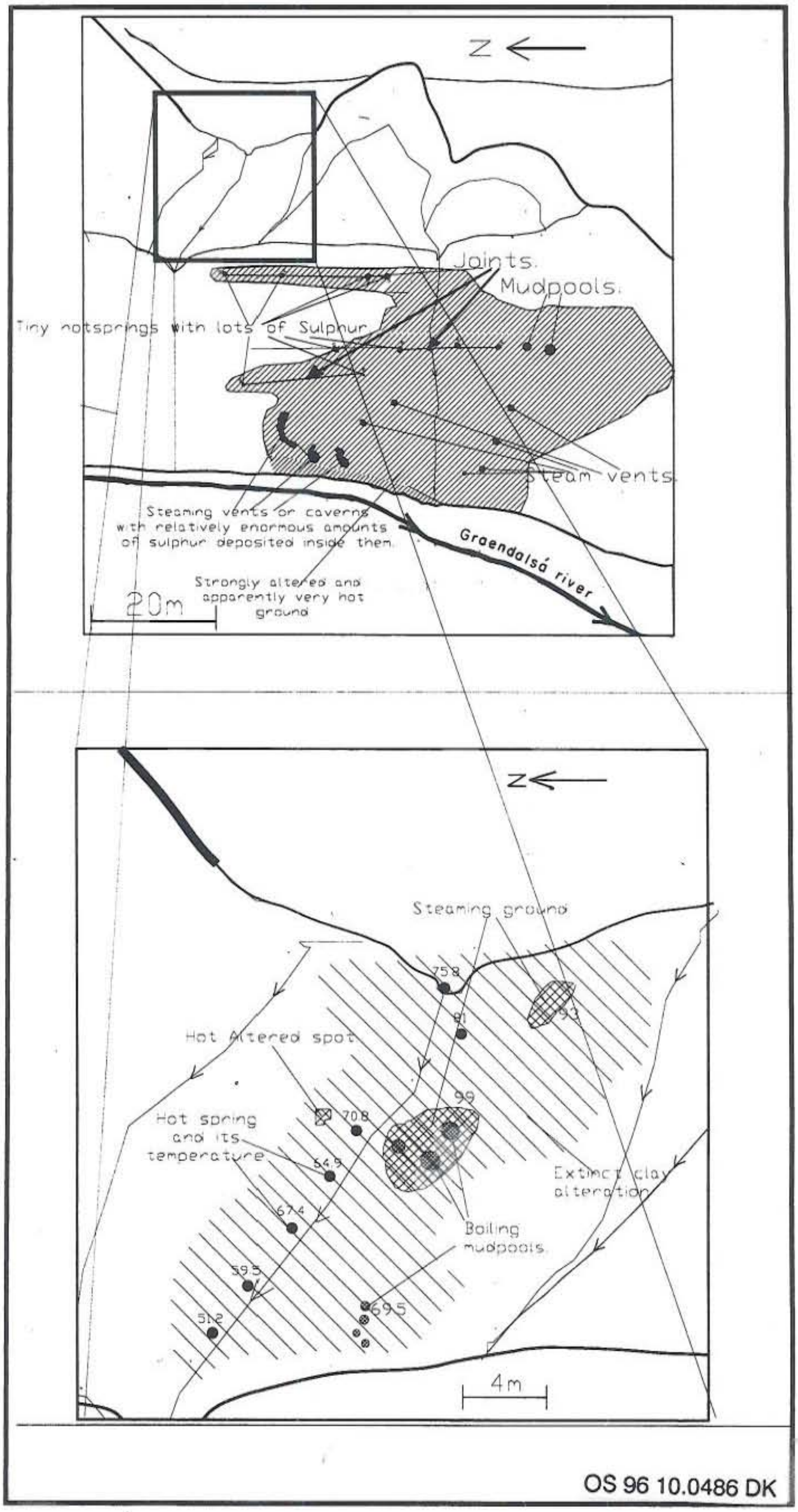

FIGURE 5: Detailed geothermal map and description of sub area 4

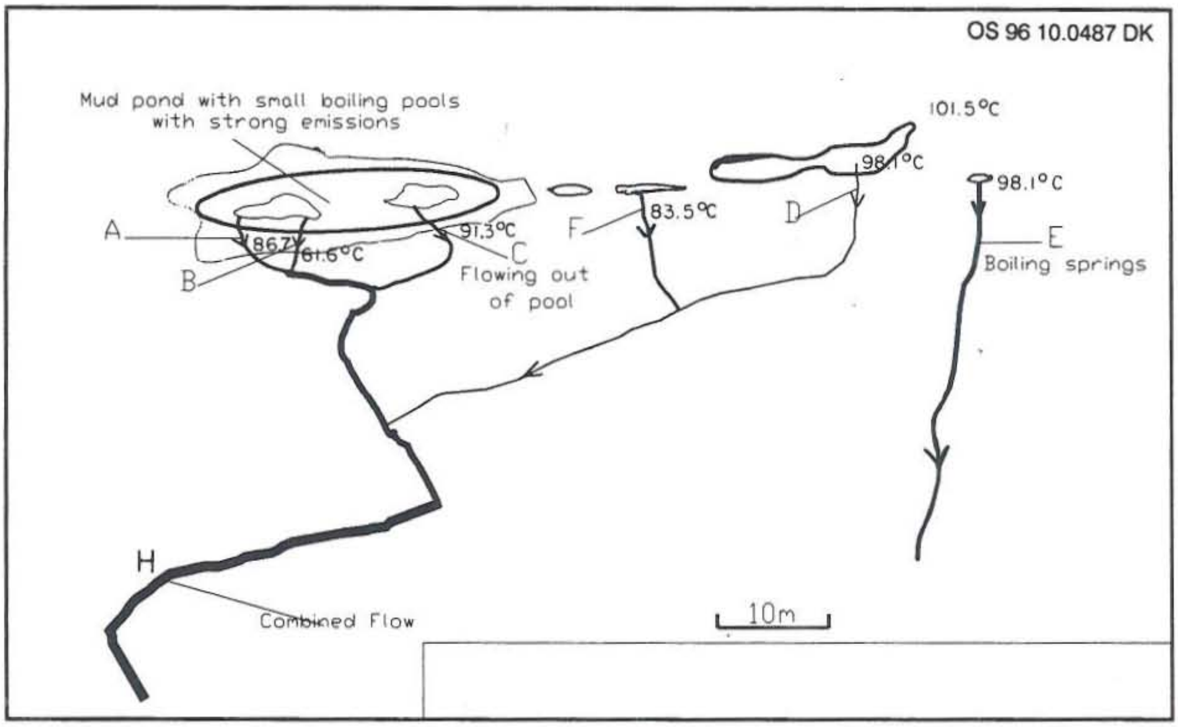

FIGURE 6: Relative location of hot springs in sub area 3, where flow was measured

TABLE 1: Temperature and flow rate in measured springs

Spring	Temperature (°C)	Flow rate (l/s)
A	86.7	0.68
B	61.6	0.02
C	91.3	0.19
D	98.1	0.30
E	98.1	0.24
F	83.5	0.15
Total		1.58
Combined flow at H	30.3	1.41

The sum total of the individual flow rates is 1.58 l/s with an average temperature of 86.6°C. The energy loss of 16.5 kJ as calculated from the combined flow is mainly caused by the loss of heat energy to the surface environment, i.e. cooling in the course of flow. The power, or heat energy, in kW, of these springs is equal to the product of the flow rate in l/s, the heat capacity of water in kJ/kg/°C and the difference between the measured and the annual average temperatures. This was found to be equal to 507 kW. This is enough to heat approximately 100 households if we assume that the supply temperature is equal to the average temperature of the outflows and the return temperature is 40°C.

5. SOIL TEMPERATURE SURVEY

A large scale map of the heat distribution was made of one part of the work area where an approximately 190 by 190 m survey grid was laid out. This was done specially with regard to an inferred fracture running immediately to the south of the base point of the survey grid area (Figure 7).

A baseline was measured trending north and profile lines at 10 m intervals were lain east of it. Station readings were then taken along these lines at 5 m intervals. The profile lines were terminated at the river Graendalsá and the longest ones were about 190 metres long. A total of twenty profile lines constituted the survey grid.

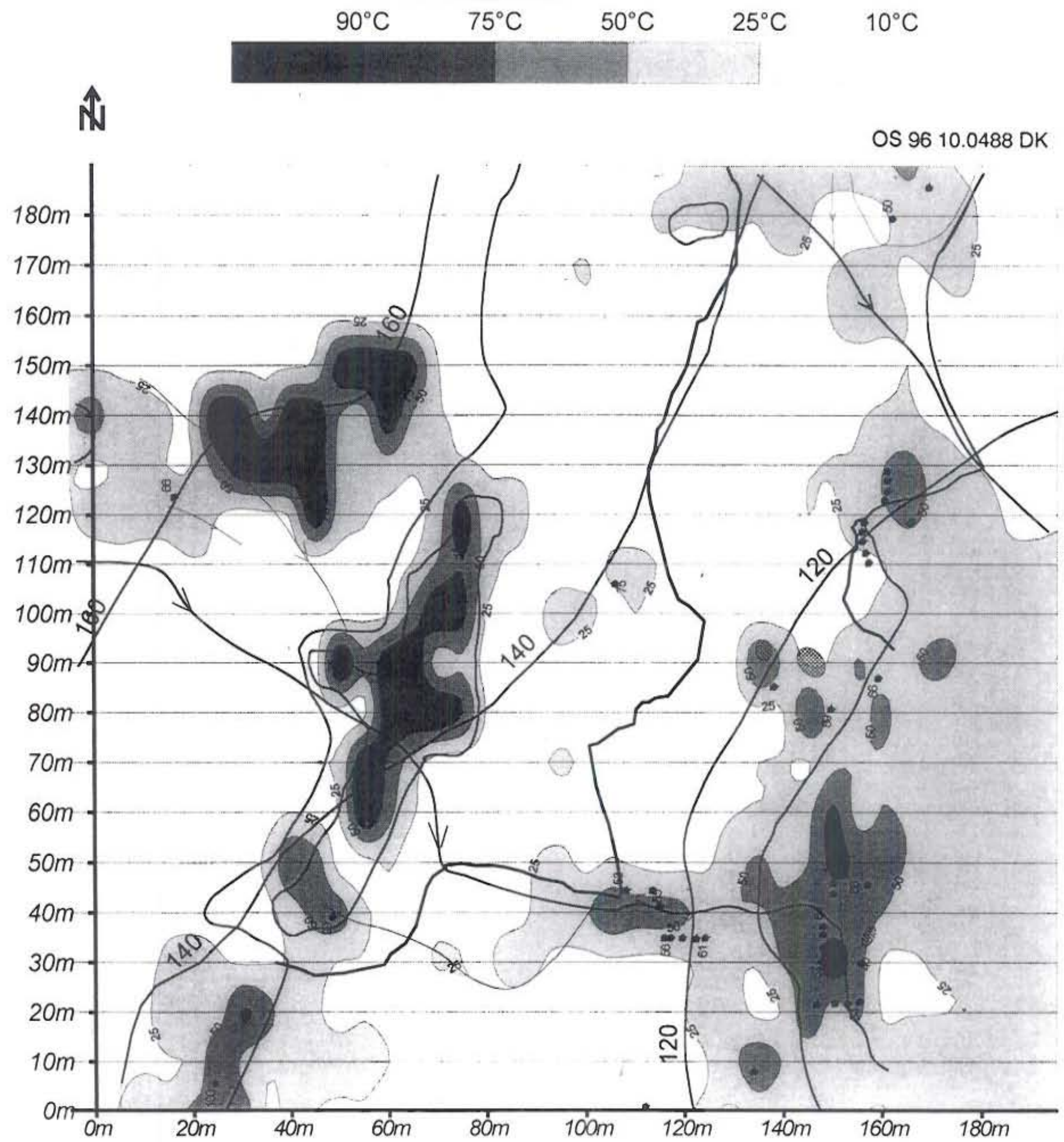

FIGURE 7: Detailed geothermal and iso-temperature map based on a soil temperature survey

A narrow 60 cm deep hole was made using a steel rod and the temperature was measured by pushing a digital thermometer (rod with a thermistor) to the same depth and recording the temperature to a ±0.1°C accuracy. During the course of the survey an attempt was made to map the presence or absence of the main vegetation types in order to see if a relationship could be formulated between these and particular soil temperature regimes or ranges. In addition, streamlets, springs and other surface phenomena were mapped.

The data acquired during this survey was gridded and contoured; a contour map of the survey area is shown in Figure 7.

6. CONCLUSIONS

The field area in Graendalur is located in the southeastern part of the large Hengill high-temperature area. Very high steam proportions in manifestations such as steaming grounds and others are indicative of fractures (Sigurdsson, 1987) as is the quasilinear distribution of these in many locations (Figures 3 and 4). In neovolcanic areas such as this, fractures play a dominant role in the occurrence and transportation of deep waters from the reservoir to the surface or near surface ground water systems. On the basis of geothermal mapping it is indicated that geothermal manifestations are controlled by the tectonics, topography and sedimentary cover.

An attestation to this is the inferred fracture to the south of the temperature survey grid which continues about 150 m into the surveyed area, trending NE-SW and facilitating the transfer of heat to the surface and in the process forming a zone of warm and hot ground about 25 m broad. Following the heat distribution pattern in the surveyed area, a similar fracture can be inferred approximately 100 m to the east of it, trending N-S and continuing beyond the boundaries of the surveyed area (Figure 7).

Large parts of the area of work are covered by rock slides or avalanche deposits and, therefore, the presence at the surface of the geothermal phenomena may be heavily dependent on the individual sizes of the rock slide blocks and their thickness. The process of geothermal alteration is far more intensive in these areas than in the areas of primary rock masses. The high permeability of these areas enables quick percolation of water through these loose materials. The same high permeability is envisaged for the Kviar basalt, lava flows and the Saudá units which form the topographically highest areas.

In the area of study, the depth to the ground water is partly determined by the aquifugal properties of the underlying heavily altered Varmá formation. Because of this, numerous springs are found in groups at relatively low topographical heights. The rapid weathering of the rock slides has led to the formation of relatively thick layers of soil with thick vegetation cover. In some cases the above mentioned factors combine and are leading to the formation of perched acquifers even in relatively high topographic heights making very difficult the plotting of a piezometric surface level applicable to the area as a whole.

Shallow ground water is mixing with steam and forming boiling hot springs, hot springs, warm and tepid springs in increasing order of the proportion of shallow ground waters. Mud pools form when intensively altering ground is infiltrated by surface waters which are then heated by the rising steam. Where the water to steam ratio is very low and the ground water level is low (i.e. where there is little mixing) solfataras and steaming grounds form. Certain springs, like those indicated in the temperature survey area, appear to have a larger proportion of geothermal waters due to the relatively large amounts of silica being deposited. In support of this is the fact that about 40 m further to the north, a thick layer of cold silica sinter is found. The silica-rich water is thought to represent the main deep reservoirs from which steam and gas is boiled off to produce all the other manifestations.

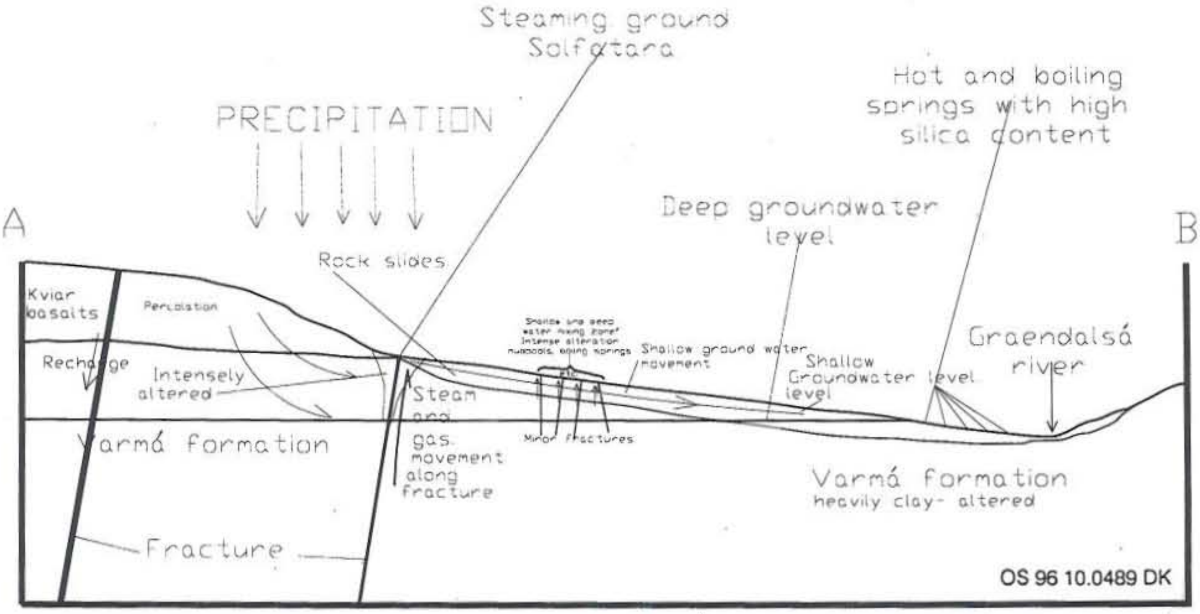

FIGURE 8: Proposed geothermal model for the Hveragerdi-Graendalur area (based on sub area 3)

Figure 8 is a proposed model of the geothermal situation in the study area and is mainly based on the geothermal setting of sub area 3 (see Figure. 4).

ACKNOWLEDGEMENTS

Acknowledgements go to the staff of the UNU, the Director, Dr Ingvar B. Fridleifsson, for his ever present help and advice, Mr. Lúdvík S. Georgsson, the Deputy Director for the great trouble that he had in ensuring that I could attend this training programme even when I had despaired of doing so, this in addition to always being ready to help me in any difficulties that I encountered. Mrs. Gudrún Bjarnadóttir for her non-complaining willingness and kindness to ferry us to the field during the field work period. Drs. Gudmundur Ómar Fridleifsson and Helgi Torfason I thank for their professional guidance in and out of the field and special acknowledgements go to Dr. Kristján Saemundsson for his supervisory role in the project work and constant willingness to share his vast experience with us during the course of this training programme. Last but not least, acknowledgements go to all the staff of ORKUSTOFNUN for their professional experience which they were always glad to share with us.

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