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# GEOTHERMAL MANIFESTATIONS AND STRUCTURES IN INNSTIDALUR AND MIDDALUR, SW- ICELAND

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## ABSTRACT

Geothermal activity is considerable in the Innstidalur and Middalur valleys of the Hengill central volcano. Detailed geological, structural and geothermal mapping was carried out, presented by maps in the scale of 1:15,000. This included mapping of 165 springs, by measuring their temperature, pH and conductivity, and estimating flow rate. A description is given of hydrothermal manifestations in the area. The main geothermal activity on the surface is in the southeast part, in Middalur valley, and in the northwestern part of the area. The geothermal activity relates to a volcanic fissure and faults trending close to NE-SW.

By activity, the geothermal manifestations can be divided into three main areas. In the northwestern part, geothermal activity is characterized by boiling water, mud pools and steaming ground, with some sulphur fumaroles, altered grey to brownish rock. In the central part of the field, extinct alteration is evidenced by brownish grey altered hyaloclastites with smectitic clays and calcium carbonates as main alteration minerals. In the third area, in Middalur valley, it is characterized by hot ground, mud pools, steam vents and some travertine deposits. Cold water springs in the area are located at an altitude of 350-500 m a.s.l., above the geothermal alteration zone. In some cases, the cold water has passed through heated or steaming ground and has been heated up. The proposed geothermal model of the area shows the geothermal activity associated with active fissures and faults.

## 1. INTRODUCTION

Availability of cheap energy has a profound effect on the development and the living standard in modern society. For countries that rely on imported fossil fuel, its increase in price has adversely affected economical development, especially of the least developed countries. In addition, the carbon dioxide pollution of fossil fuel is of global concern. Therefore, renewable energy can be expected to be of increasing importance for the world, being environmentally friendly.

Eritrea has a shortage of electricity and is currently entirely dependent on imported oil for the production of its electricity. With no known oil resources and only minor hydropower possibilities, the high-temperature geothermal resources associated with the Afar rift zone may be Eritrea's best possibility for production of electricity from local sources. Geothermal exploration and development is governed by the Ministry of Energy and Mines under the Department of Mines. The Department of Mines plans to carry out geothermal exploration in the eastern part of Eritrea, with emphasis on the Alid volcano area, to a pre-feasibility stage, which will hopefully lead to investment in the geothermal energy sector. The government of Eritrea needs trained scientists to participate in the geothermal exploration. Training of the first two UNU Fellows from Eritrea at the UNU Geothermal Training Programme is an important part of that.

This report is the final part of a six-month training course the author undertook in Geological Exploration at the UNU Geothermal Training Programme. The objective of the field study presented here was to give the author practical training in geothermal exploration and geological mapping, by analysing geological structures, mapping geothermal surface manifestations, measuring temperature and pH, estimating the flow rate of hot and cold springs, and studying the field relationship between structures and the distribution of the geothermal manifestations. The report describes the results of a geothermal exploration in the Innstidalur and Middalur valleys in the Hengill high-temperature geothermal area in SW-Iceland.

## 2. GEOLOGICAL INTRODUCTION

### 2.1 General aspects

Iceland is the largest sub-aerial exposure at constructive plate boundaries in the world, with more than a 700 km long zone exposed of a spreading plate boundary and two transform zones. The constructive plate boundary comprises many volcanic systems, which are made up of dense fissure swarms, mostly of normal faults and eruptive fissures, and commonly including a central volcanic complex within the middle part of the fissure swarms, and dyke swarms at depth. Also associated are high-temperature geothermal areas (with temperatures >200°C in the upper-most 1 km). The volcanic systems are usually arranged en-echelon within the volcanic zones, which cross Iceland from southwest to northeast (Figure 1) (e.g. Saemundsson, 1979).

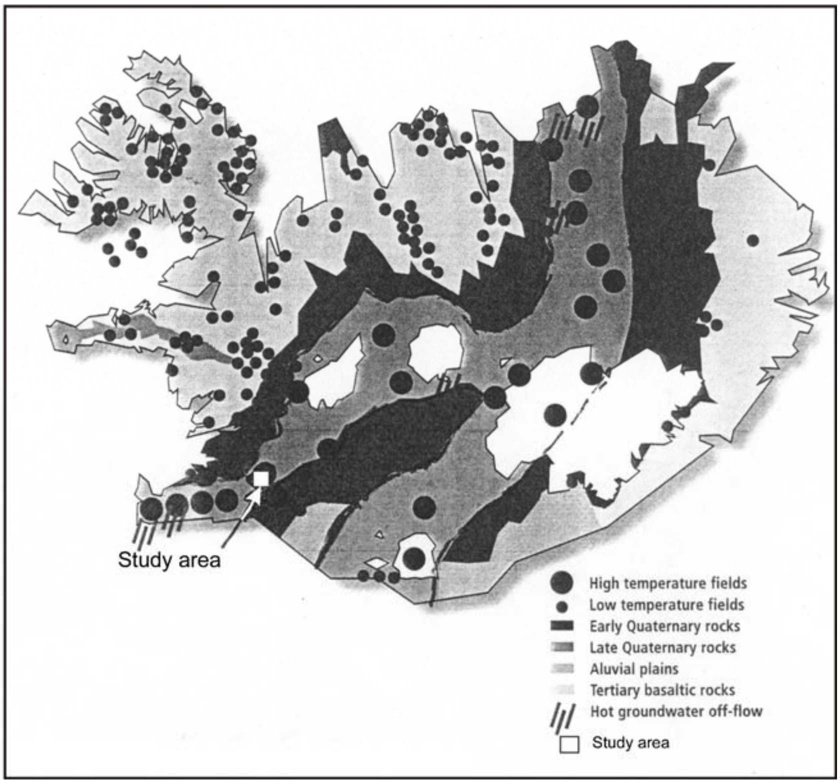

FIGURE 1: Map showing the geological units and geothermal areas in Iceland and the location of the study area

The structure of the plate boundary is strongly influenced by the Iceland hot spot. The relative motion of the Mid-Atlantic Ridge with respect to the hot spot leads to ridge jumps, propagating rifts and other complexities. Most large earthquakes in Iceland occur within two transform fault zones that connect the presently active northern and eastern volcanic zones with the main Mid-Atlantic

Ridge. The largest earthquakes occurring within the transform zones have been of a magnitude just over 7 on the Richter scale. In many ways the geological conditions of Iceland are unique.

### 2.2 The rift zone and volcanic systems

The Reykjanes Peninsula in SW-Iceland is the onshore continuation of the Mid-Atlantic Ridge. Several NE-SW trending volcanic systems cross the peninsula along the plate boundary, arranged in an en-echelon pattern along the ridge axis. These are the Reykjanes, Grindavík, Krýsuvík, Bláfjöll and Hengill systems (Figure 2), which define the peninsula. The Hengill volcanic system is located at a "triple junction", defined by the W-E-trending Reykjanes Peninsula, the NE-SW-trending Hengill-Langjökull volcanic zone, and the Southern Lowlands transform tectonic zone. The study area is located within the Hengill volcanic system (Figures 1 and 2).

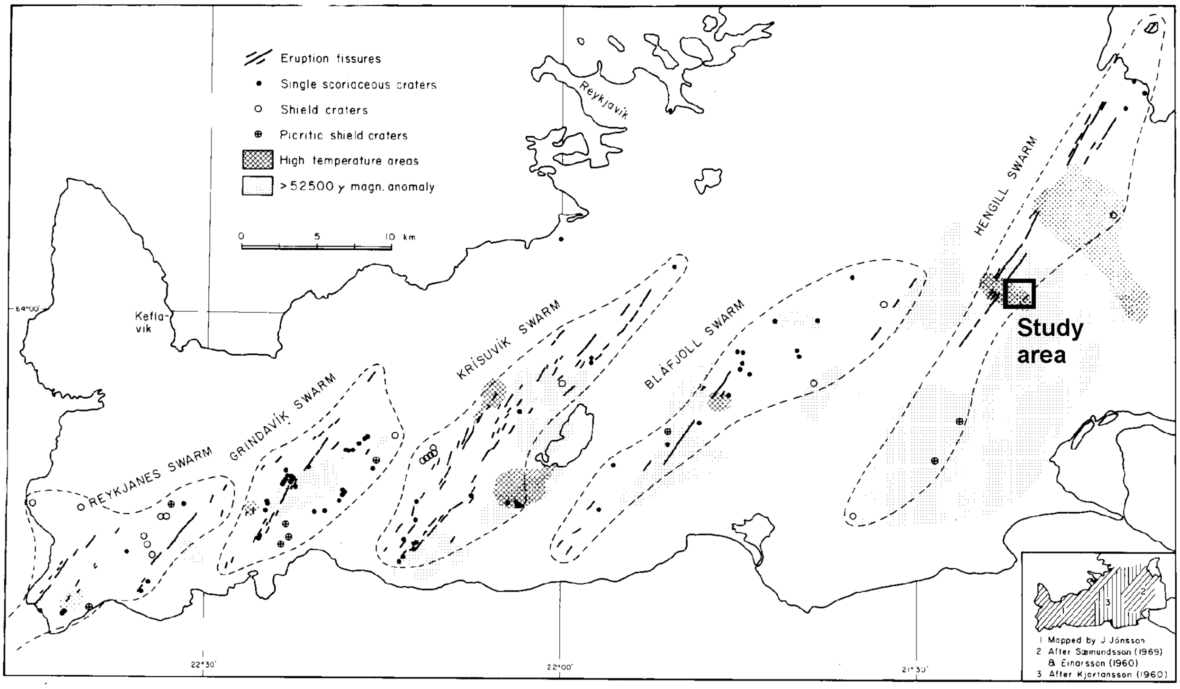


FIGURE 2: The volcanic systems and fissure swarms in SW-Iceland and the location of the study area (modified from Jakobsson et al., 1978)

### 2.3 Geothermal systems

Geothermal areas in Iceland are divided into two main groups, high-temperature geothermal systems and low-temperature geothermal systems. For the low-temperature geothermal systems, the reservoir temperature is below 150°C. They are characterised by hot or boiling springs, and exist outside the volcanic zones in Quaternary and Tertiary formations.

High-temperature geothermal systems are characterized by reservoir temperatures above 200°C in the uppermost kilometre of the crust. They are characterized by fumaroles, steam vents, mud pools and highly altered ground (surface manifestations). They are usually within or close to central volcanic complexes. Permeable fractures, fault zones and calderas mostly control the flow of water inside volcanic systems.

## 3. THE HENGILL AREA

### 3.1 Location of the study area, topography and climate

The Hengill area is one of the bigger active geothermal areas in Iceland, and is divided into several sub-areas or fields, one of which is in the Innstidalur and Middalur valleys between the Hengill mountain and the Skardsmýrarfjall mountain, northeast of the Hellisheidi geothermal project.

The topography of the area comprises mountains of volcanic rocks and valleys covered by a lava flow. The altitude of the valleys is 240-500 m a.s.l. and the surrounding mountains reach 500-700 m a.s.l elevation. The area is drained by Hengladalir river, emanating on springs on the mountain slopes, but most of the water drains from lavas on the valley floor of Innstidalur valley.

The climate of the area is characterized by reasonably cold winters and moderate summers, the temperature range being from -20°C in winter up to +20°C in the summer. During the summer of 2004, the temperature ranged between 10 and 25°C in one of the hottest summers in Iceland recently. The weather is highly unpredictable, rainfall may occur at any time, and snowfall can prevail in the winter.

### 3.2 The Hengill volcanic system

The Hengill central volcano is located 45 km east of Reykjavik. It has one of the larger high-temperature geothermal fields in Iceland. The Hengill volcano is elongated NE-SW, lying across the rift graben. The geothermal activity is derived from the volcanic activity, and covers an area of about 100 $km^2$. The volcano is still active and hot springs and steaming ground are very prominent in many areas. A 60-100 km long fissure swarm associated with the Hengill volcano, cuts through the volcanic centre trending NE-SW. The most intensive geothermal prospects are associated with this fault zone. The Hengill complex includes two older volcanic systems, the Hrómundartindur system to the east which last erupted about 10,000 years ago, and the older and more eroded Hveragerdi system, further eastwards. Several potential geothermal fields are within the Hengill complex. Only two of these have been developed, the Nesjavellir field in the north, and to a much smaller extent, the Hveragerdi field in the southeast. The third field, Hellisheidi, southwest of mountain Hengill is being developed at present. The Hengill area is an important energy source for the southwestern part of Iceland.

The Hengill mountain itself, is in the central part of the 60-100 km long volcanic fissure/fault swarm. It is composed of several hylaoclastite formations erupted underneath ice-sheets during the last two glacial periods. Interglacial and postglacial lavas flowed down and accumulated in the surrounding lowlands. The volcano is still quite active, with four postglacial eruptions, the last one about 2,000 years old.

### 3.3 Previous work

Geological mapping of the Hengill area has mainly been carried out by Kristján Saemundsson, (1967, 1995a) and co-workers, completed with a geological map in the scale 1:50,000, but also maps on the geothermal activity, alteration and hydrology on scale 1:25,000 (Saemundsson, 1995b). A geological map of the southern Hengill area between Hengladalir and Krossfjöll was a part of this mapping (Saemundsson et al., 1990). Geological and geothermal mapping is usually among the first exploration steps in geothermal prospecting (Flóvenz, 1985).

### 3.4 The Hengill high-temperature geothermal area

Geothermal activity in the Hengill system includes the Innstidalur, Hellisheidi and Hveradalir geothermal fields south of Mt. Hengill, and Nesjavellir, north of the Hengill mountain (Figure 3). At Nesjavellir, there is a geothermal power plant producing 90 MWe of electricity and 500 MWt of hot water for district heating in the Reykjavik capital area. At Hellisheidi, construction of a new power plant of 80 MW is taking place at present. Already 14 deep production wells have been drilled, and more wells will be drilled in the next coming years. The drilling started in 2001 and the power plant is scheduled to be on line in 2006 (Gíslason and Gunnlaugs-son, 2003)

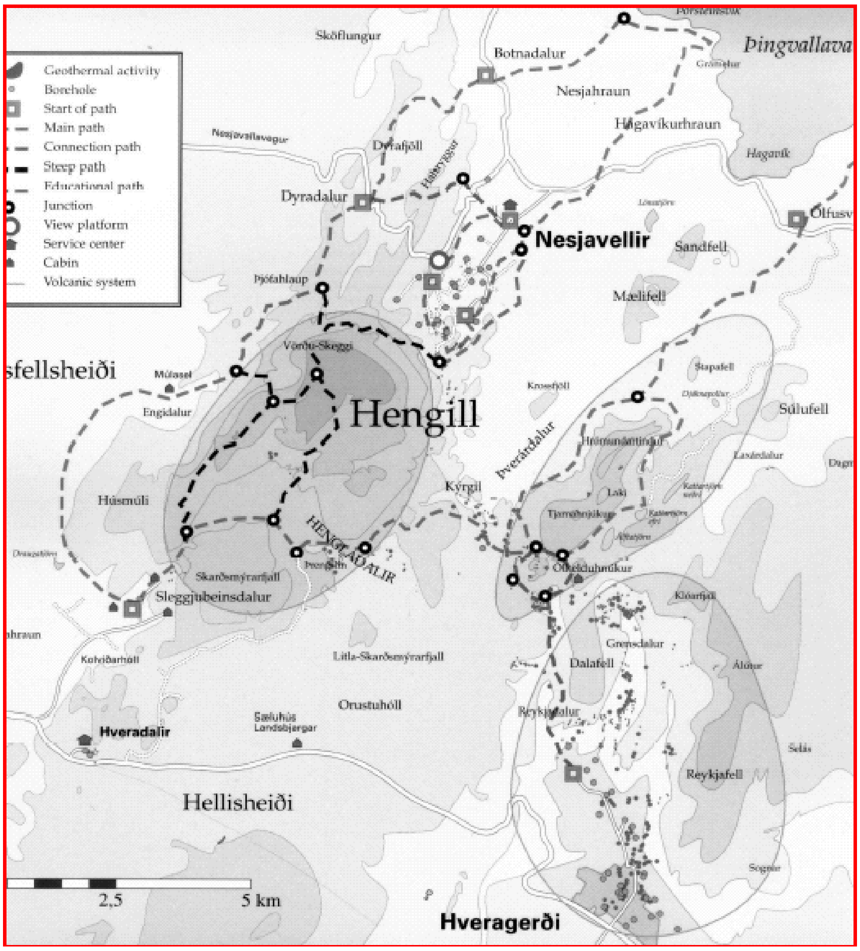


FIGURE 3: Geothermal systems related to the Hengill complex (modified from Gíslason and Gunnlaugsson, 2003)

## 4. GEOLOGY

### 4.1 General geology of the area

The study area is located south of the Hengill mountain. It is about 3 km long and 1.5 km wide, and includes the valley floor of the Innstidalur and Middalur valleys and the slopes of the Hengill and Skardsmýrarfjall mountains to the north and south. The Hengill mountain itself was mostly accumulated in two large sub-glacial eruptions during the last two glacial periods. The lower and eastern part of the mountain may have formed during the 2nd last glacial period (Saemundsson and Fridleifsson, 2003).

### 4.2 Lithologic description (surface deposits)

The surface geological formations are important for the geothermal manifestations. Innstidalur geothermal field is characterized by the presence of several kinds of rocks or surface deposits: the bed rock consists of hyaloclastite and a lava flow. Surficial deposits include landslides, travertine, screes, stream deposits and soil. The main divisions are shown on the geological map in Figure 4 and in cross-section A-B in Figure 5.

*Bed rocks (hyaloclastites)*. Three main types of rock may result from sub-glacial eruptions. Pillow lavas, hyaloclastite, breccias and well bedded fine-grained hyaloclastite tuffs. The bedrock around Innstidalur was formed in sub-glacial eruptions. An elongated ridge of intermediate-acid chemical compositions marks the western boarder of the valley (outside the map in Figure 4) and is not discussed further. The Hengill mountain forms the northern border of the valley. It is mainly composed of basaltic breccias and tuffs. The southern border of the valley is formed by the pillow lava formation of the Skardsmýrarfjall mountain, which mainly consists of pillow basalts with only subordinate tuffs.

*Lava flows,* in the Innstidalur area emanate from two main volcanic fissures, trending NE-SW and are

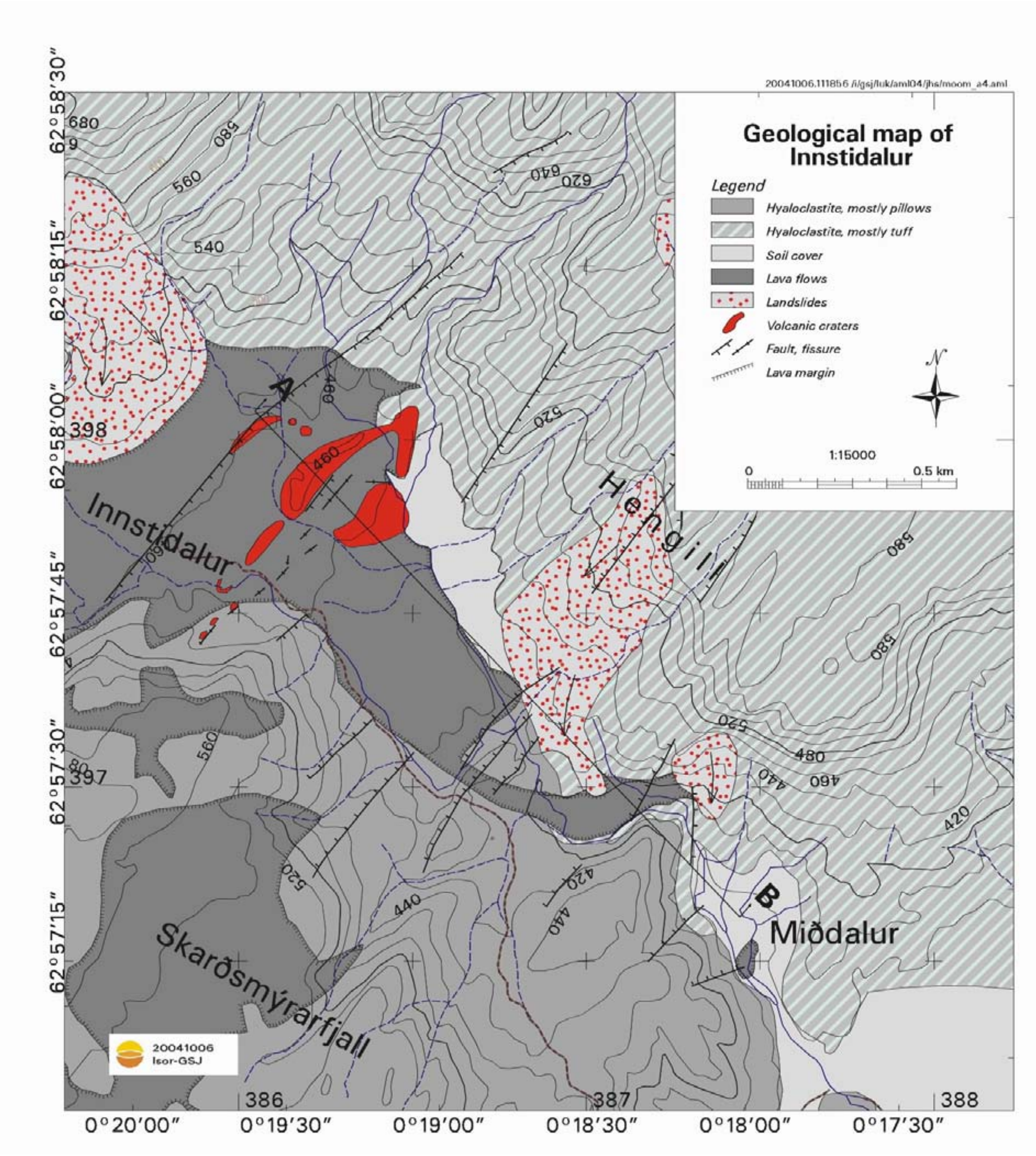


FIGURE 4: Geological map of Innstidalur

approximately 5,500 years old. The lava flow is widespread on the valley floor in the western part of the field area.

Some of the *landslides* are younger than the lava flow and were probably accompanied or triggered by seismic activity, possibly related to the South Iceland seismic zone.

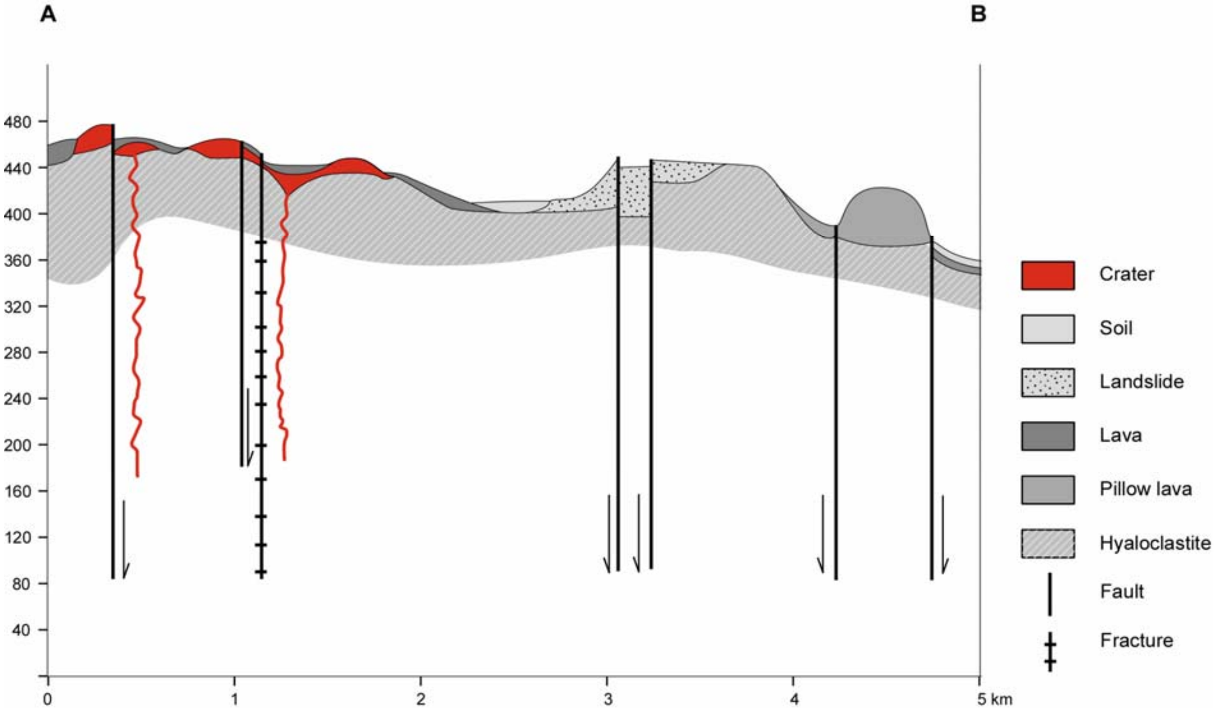


FIGURE 5: Cross-section A-B, see location in Figure 4

*Travertines* were deposited around some of the $CO_2$–rich hot springs, found mostly in the slope of the Hengill mountain in the eastern part of the Innstidalur field, and also to a lesser extent in the hot spring area of Middalur, further east. The geothermal water appears richer in $CO_2$ in this part of the field, precipitating $CaCO_3$ (travertine) at the surface, possibly in relation to the mixing of hot and cold springs close to the surface, but forming a crust along faults with distinct layering around the hot springs.

Superficial *screes, gravel and soil.* Erosional deposits, on the slopes in the north part of valley, are composed of angular to subangular debris of hyaloclastites and lava fragments, mixed with loose silt, clay and gravel transported by streams in the Innstidalur area. The area is shown on the geological map in Figure 4.

The Middalur valley, in the southeast, is covered by soil, silt, and clay and also, in places, by a thin crust of calcium carbonates precipitated from the hot springs. This is especially prominent at localities I 162, I 163, I 166 and I 168 (see Section 5.5). Mud pools are filled with fine grey clay. Upon cooling these look like grey clayish soil.

*Bedded clayey, silt and soil formations* (1-2 m thick) were deposited through the Holocene, over the last 10,000 years. Some of the layers show episodic hydrothermal activity close to the study site. Tephra (ash) layers are also interbedded in the soil sections. Many of the tephra layers are recognisable and can be traced to individual volcanic eruptions in Iceland of different age. The black tephra layer (marked by the knife) close to the top of the soil section in Figure 6 is, for instance, from the Katla volcanic eruption in 1485. The hydrothermally altered soil layers in the area imply that the surface geothermal

FIGURE 6: Layered soil, overlying hydrothermally altered soil indicating episodic hydrothermal activity in Holocene times, photo from Middalur valley

activity varies from time to time. Dating of the soils, either by using tephrochronology, or $C^{14}$ dating, enables mapping of and interrelation of geothermal activity to tectonic or volcanic events in the Holocene. Vivid hydrothermal activity, for instance, took place about 5,000 years ago in the Innstidalur field area, during and after the volcanic eruption mentioned above.

### 4.3 Surface manifestations of the geothermal activity

The purpose of the mapping of surface manifestations in the study area south of the Hengill mountain, was to investigate the relationship between the geothermal manifestations, the tectonic and volcanic structures and the rock types. The manifestations include warm, hot and boiling springs, hydrothermal clay alteration at different temperatures, and travertine deposits. Their location is shown on the map in Figure 4. Geothermal activity observed in the area is of two types:

1) Older regional alteration, which is evidenced by greenish and black to brownish altered hyaloclastite bedrock. In this type of alteration, the primary volcanic glass has been partly replaced by smectitic clays, to somewhat varying degree, and is partly also infiltrated by travertine deposits around the carbonate springs. This type of alteration is related both to hydrothermal alteration and weathering.

2) Presently active geothermal activity, includes $CO_2$ rich hot springs, steaming vents, hot ground and boiling mud pools.

The main geothermal activity occurs in the Middalur valley in the southeast, and in the northwestern part of the field area north of the volcanic craters.

### 4.4 Tectonics of the area

Tectonic features of the study area are characterized by the occurrence of *faults and open fissures* that have a general NE-SW trend. These fissures are divided into two categories, those that were observed in the field, and those that were deduced from examination of aerial photographs. Geothermal activity is commonly found associated and controlled by some of the major faults.

The main fissure swarm, trending NE-SW, is a part of the regional feature. In the study area, these faults are believed to represent the western margin and central part of the Hengill fissure zone (Árnason et al., 1986; Saemundsson, 1995a).

During this field study, 10 major faults and fractures in the field were studied in some detail. They have the general trend NE-SW, and include a few normal faults with variable downthrows. Three of the studied faults are still active faults. One of them, for instance, runs just west of a volcanic crater of the 5,000 year old eruption. The fault is younger than the volcanic eruption, and controls the geothermal activity just north of the crater row. Another studied fault is 50 m to the east in the central crater, also dipping eastwards. The third one is in the Middalur valley, with a westward throw and dipping westwards. This fault, in particular, controlled the geothermal phenomena causing the main travertine deposits in the field, and was apparently associated with high permeability, or large flow of hydrothermal waters. A fourth fault studied from the central area, runs parallel to the volcanic craters. No Holocene activity was found associated with it, the faults dipping to the west.

*Open fissures.* Open fissures are quite common in all rock types in the study area, but some of them are covered by erosional material. Therefore they are often difficult to ascertain but identified and inferred by the author from the consistent alignment of geothermal manifestation along preferred directions. Measurements of two open fissures were also done. One of them, from within the eruptive crater area, trends NE-SW and stretches for 200 m towards the south. And another fissure in the centre of the area trends NE-SW at locality I 172.

## 5. GEOTHERMAL EXPLORATION

### 5.1 Studies undertaken

The following studies were carried out:

a. Mapping of geothermal manifestations was undertaken;
b. Flow rates of running springs were estimated, their pH and conductivity measured;
c. Geothermal model of the Innstidalur area was suggested.

The geothermal mapping showed a clear relationship to the structural geology.

### 5.2 Geothermal manifestations

The geothermal manifestations distinguished were springs, warm, hot and boiling springs and mud pools, hydrothermal clay alteration and calcium carbonate deposits. Data on 166 springs was collected and is listed in Table 1 and also shown in Figure 7. Springs were located and plotted on the geological map, the temperature of individual springs was measured, their flow rate estimated and also pH and conductivity. The springs are divided into three categories:

1) Cold springs, whose temperature measured below 10°C;
2) Warm springs with temperature between 10 and 50°C; and
3) Hot springs with temperature above 50°C up to 100°C.

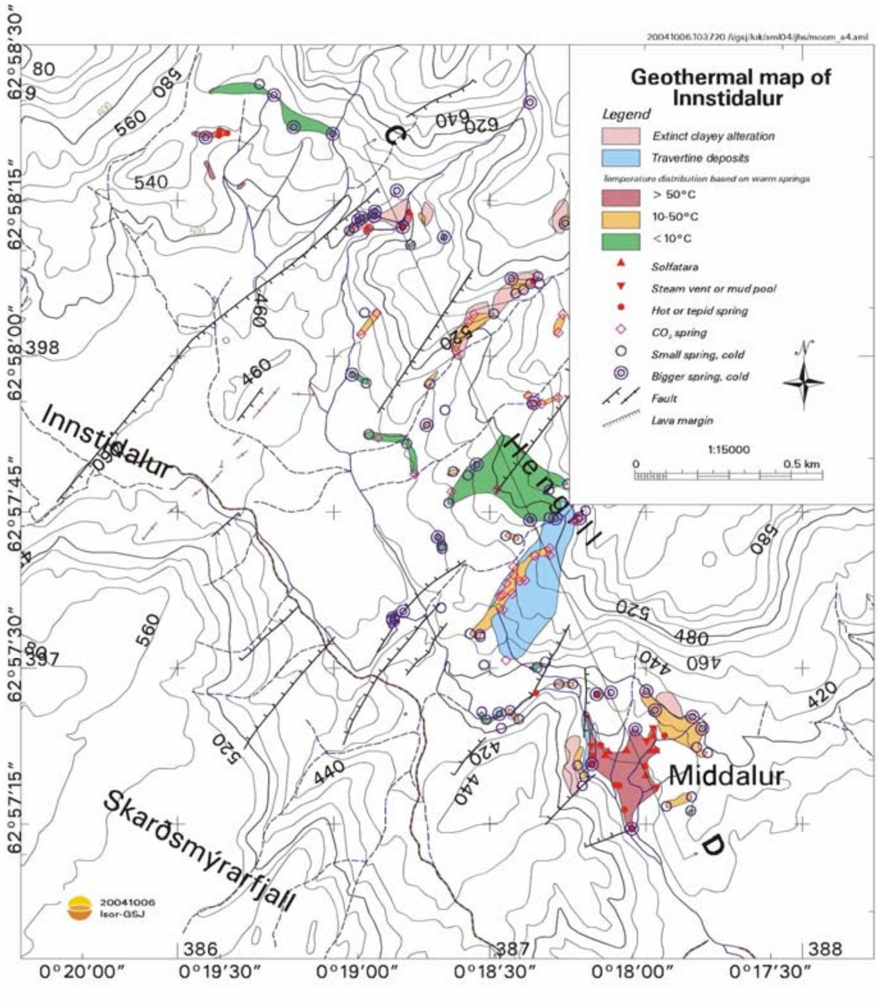


FIGURE 7: Geothermal map of Innstidalur and Middalur area

### 5.2.1 Cold water springs

Cold springs in the study area, altogether 69 springs, are distributed at an altitude between 350 –500 m a.s.l., all having temperatures below 10°C. Most of these springs exist within or below a landslide, which has higher permeability than the bedrock below. The water origin is in all cases rainwater, while some of the springs are very cold (3.2-4.8°C) groundwater, emanating out of the bedrock, while the sources of the warmer springs are from greater depths.

### 5.2.2 Warm and carbonate ($CO_2$) springs (travertine deposits - $CaCO_3$)

Carbonate springs in the area, 73 by number, are distributed in bed rock, thinly covered by surficial deposits. They have quite different temperatures and flow rates, on average though about 0.35 l/s. Travertine deposits are formed around some of these warm springs, in some cases due to water boiling and evaporation, in other cases due to scaling in runoff water. Also, in some areas, reddish-brown coloured carbonate springs exit, but these are normally of much lower temperatures, and range between 4.8 and 10°C .

### 5.2.3 Hot springs and mud pools

Hot boiling springs and mud pools mapped include about 20 springs. These mainly occur in two areas in the Middalur field, and in the geothermal field north of the eruptive fissure. Temperatures in all cases are above 50°C. Most often boiling springs and steam vents cluster together along structures. Hot boiling springs and mud pools contain fine grey clay or boiling mud. Some of them throw out grey clay, especially at localities I 137, I 151, I 152, and I 167 in Middalur, and at localities I 106, and I 107, in the northwestern area. Hot springs, mud pools and steam vents in the latter locality have a higher quantity of yellow coloured sulphur around their discharge, than elsewhere, especially at locality I 110. Associated with these springs are also the highest temperatures measured, close to 100°C.

### 5.2.4 Hydrothermal alteration

Three areas with extinct surface alteration were studied, two in the northwestern part at localities I 80 - I 90, where the surface deposits are slightly altered to reddish brown and grey colours, especially at locality I 83, where greenish grey and black colours are prominent, and also further north at localities I 99, I 100, and towards I 104. Three main factors seem to control the degree of alteration:

1) Temperature; 2) Rock type; and 3) Extent of water circulation.

The rock type is controlling, and has varying susceptibility to alteration depending on the degree of crystallization and mineral composition. Glassy tuffs are the most easily altered rocks where the tuffs are first hydrated and oxidized upon weathering, turning the colour of the rocks from dark glass to yellowish brown weathering colours. Upon further alteration, the glass gradually runs colours until it becomes completely replaced by smectitic clay minerals.

Where vegetation covers the hot ground, warm ground is usually identifiable by the yellowish green moss colour of the grass. In most cases, the vegetated areas represent diminishing hydrothermal activity.

### 5.2.5 Travertine deposits

The distribution of the travertine deposit is shown on the geothermal map. Below the travertine deposits is a major fault, which is more or less covered by the travertine. The fault appears to have discharged large quantities of hot and warm water towards the surface. A remnant of this is seen along the hot spring line in the western part of the travertine area.

TABLE 1: Surface geothermal manifestations measured in the Innstidalur area

| Group | No. | Serial no. | N | E | Conductivity (S/m) | Temperature (°C) | pH | Flow rate (l/s) |
|---|---|---|---|---|---|---|---|---|
| alt | 1 | I - 78 | 64.07039 | 21.31062 | 119 | 18.7 | 6.7 | 1 |
| alt | 2 | I - 79 | 64.06863 | 21.31218 | 160 | 8.8 | 7.1 | 0.1 |
| alt | 3 | I - 80 | 64.06883 | 21.31229 | 85.6 | 9.8 | 7.2 | 0.1 |
| alt | 4 | I - 82 | 64.06868 | 21.31258 | 318 | 22.9 | 6.9 | 0.2 |
| alt | 5 | I - 83 | 64.06861 | 21.31277 | 299 | 14.1 | 7.1 | 0.1 |
| alt | 6 | I - 84 | 64.06843 | 21.3132 | 173 | 16.3 | 7.4 | 0.01 |
| alt | 7 | I - 85 | 64.06832 | 21.31371 | 105 | 16.9 | 7.4 | 0.5 |
| alt | 8 | I - 86 | 64.06874 | 21.31402 | 176 | 14.2 | 7.2 | 2 |
| alt | 9 | I - 87 | 64.06771 | 21.31509 | 109.8 | 11.6 | 7.4 | 0.1 |
| alt | 10 | I - 88 | 64.06767 | 21.31639 | 156 | 17.4 | 7.4 | 0.5 |
| alt | 11 | I - 91 | 64.06562 | 21.31912 | 120 | 16.7 | 7.2 | 0.1 |
| alt | 12 | I - 98 | 64.06994 | 21.32476 | 110 | 17.5 | 7.8 | 0.1 |
| alt | 13 | I - 99 | 64.07002 | 21.32474 | 140 | 10.9 | 8.2 | 0.2 |
| alt | 14 | I - 100 | 64.07004 | 21.32447 | 130 | 9.5 | 8.1 | 0.02 |
| alt | 15 | I - 101 | 64.07026 | 21.32402 | 125 | 10.2 | 8 | 1 |
| alt | 16 | I - 102 | 64.07033 | 21.324 | 155 | 13.7 | 8.2 | 2 |
| alt | 17 | I - 103 | 64.0704 | 21.32315 | 191 | 7.2 | 8.2 | 2 |
| s | 19 | I-01 | 64.05881 | 21.31252 | 112 | 5 | 7.4 | 1 |
| s | 20 | I-03 | 64.05765 | 21.31083 | 67 | 7.5 | 7.6 | 0.5 |
| s | 21 | I-04 | 64.05735 | 21.3084 | 226 | 19.3 | 7.6 | 0.2 |
| s | 22 | I-09 | 64.05621 | 21.31377 | 130 | 7.8 | 6.8 | 1 |
| s | 23 | I-13 | 64.0558 | 21.31361 | 88 | 4.9 | 8.2 | 0.2 |
| s | 24 | I-14 | 64.05632 | 21.31307 | - | - | - | Low/s |
| s | 25 | I-15 | 64.05685 | 21.31142 | 248 | 28.5 | 7.3 | 1.5 |
| s | 26 | I-16 | 64.05713 | 21.30994 | 204 | 11.9 | 7.6 | 0.5 |
| s | 27 | I-17 | 64.05715 | 21.30903 | 158 | 8.6 | 7.9 | 0.2 |
| s | 28 | I-18 | 64.05758 | 21.31141 | 93 | 4.4 | 7.8 | 0.1 |
| s | 29 | I-26 | 64.0608 | 21.31181 | 108 | 6.2 | 7.2 | 0.1 |
| s | 30 | I-27 | 64.06083 | 21.31085 | 84 | 4 | 7.8 | 0.5 |
| s | 31 | I-32 | 64.06214 | 21.30861 | 74 | 4.4 | 7.6 | 0.1 |
| s | 32 | I-33 | 64.06191 | 21.309 | 65 | 3.2 | 7.4 | 2 |
| s | 33 | I-34 | 64.06352 | 21.30676 | 57 | 4.2 | 7.5 | 5 |
| s | 34 | I-35 | 64.06289 | 21.30985 | 144.7 | 7.4 | 6.9 | 0.5 |
| s | 35 | I-38 | 64.0576 | 21.31489 | 61.9 | 5.4 | 8.2 | 0.1 |
| s | 36 | I-39 | 64.05848 | 21.31523 | 82.6 | 10.3 | 7.4 | 0.2 |
| s | 37 | I-40 | 64.05841 | 21.3152 | 1008 | 8.6 | 7.6 | 0.2 |
| s | 38 | I-41 | 64.05849 | 21.31588 | 109 | 4.4 | 7.8 | 0.1 |
| s | 39 | I-42 | 64.0592 | 21.31784 | 96.1 | 4.4 | 7.7 | 0.2 |
| s | 40 | I-45 | 64.06134 | 21.31378 | 49 | 13.7 | 7.6 | 0.2 |
| s | 41 | I-46 | 64.0609 | 21.3179 | 164.3 | 6.1 | 7.6 | 0.5 |
| s | 42 | I - 47 | 64.06098 | 21.31794 | 91.6 | 4.7 | 7.4 | 0.2 |
| s | 43 | I - 48 | 64.06123 | 21.31822 | 201 | 4.4 | 7.4 | 3 |
| s | 44 | I - 49 | 64.06221 | 21.31758 | 57 | 4.1 | 7.7 | 0.2 |
| s | 45 | I - 52 | 64.06255 | 21.31743 | 130 | 5.6 | 7 | 0.5 |
| s | 46 | I - 53 | 64.06304 | 21.31641 | 211 | 10.5 | 7.2 | 0.2 |
| s | 47 | I - 54 | 64.06324 | 21.31648 | 107.1 | 4.7 | 6.9 | 0.5 |
| s | 48 | I - 55 | 64.06336 | 21.31586 | 107.7 | 5.5 | 7 | 1 |
| s | 49 | I - 56 | 64.06313 | 21.31738 | 178.2 | 9.7 | 7.1 | 0.2 |
| s | 50 | I - 58 | 64.06388 | 21.32048 | 82.1 | 8.2 | 7.5 | 0.1 |
| s | 51 | I - 59 | 64.06489 | 21.31806 | 65.5 | 11.9 | 7.6 | 0.1 |

| Group | No. | Serial no. | N | E | Conductivity (S/m) | Temperature (°C) | pH | Flow rate (l/s) |
|---|---|---|---|---|---|---|---|---|
| s | 52 | I - 60 | 64.06444 | 21.31922 | 80 | 8 | 7.4 | 1 |
| s | 53 | I - 62 | 64.06411 | 21.32299 | 60.5 | 9.4 | 7.5 | 0.1 |
| s | 54 | I - 63 | 64.06558 | 21.32329 | 83 | 5.3 | 7.6 | 0.5 |
| s | 55 | I - 64 | 64.06425 | 21.31412 | 102 | 4.4 | 7.1 | 0.2 |
| s | 56 | I - 77 | 64.0711 | 21.30996 | 120 | 19 | 6.6 | 3 |
| s | 57 | I - 92 | 64.06581 | 21.32423 | 50.2 | 6.7 | 7.6 | 1 |
| s | 58 | I - 95 | 64.0676 | 21.32356 | 169 | 8.4 | 7.5 | 0.1 |
| s | 59 | I - 96 | 64.0696 | 21.32071 | 98.9 | 6.7 | 7.6 | 0.2 |
| s | 60 | I - 97 | 64.06986 | 21.31854 | 94.4 | 7.5 | 7.4 | 5 |
| s | 61 | I - 104 | 64.07053 | 21.32313 | 189 | 8.4 | 8.1 | 3 |
| s | 62 | I - 105 | 64.07115 | 2132174 | 166 | 9.8 | 8 | 1 |
| s | 63 | I - 111 | 64.07383 | 21.31323 | 40 | 13.1 | 9.1 | 4 |
| s | 64 | I - 114 | 64.07272 | 21.32608 | 160 | 8.8 | 8.2 | 4 |
| s | 65 | I - 116 | 64.07287 | 21.32866 | 193 | 5 | 8.2 | 3 |
| s | 66 | I - 117 | 64.07377 | 21.33002 | 167 | 6 | 8 | 3 |
| s | 67 | I -118 | 64.07407 | 21.331 | 12.6 | 20 | 7.6 | |
| s | 68 | I - 158 | 64.05702 | 21.30419 | 244 | 21.3 | 8.4 | 3 |
| s | 69 | I - 169 | 64.05694 | 21.30651 | 101.7 | 6.5 | 8.7 | 2 |
| s | 70 | I - 170 | 64.05688 | 21.30743 | 144 | 24.2 | 8 | 5 |
| s | 71 | I - 173 | 64.05879 | 21.32005 | 140 | 5.4 | 6.9 | 5 |
| s | 72 | I - 174 | 64.05885 | 21.32098 | 130 | 5.7 | 7 | 3 |
| s | 73 | I - 175 | 64.05901 | 21.32093 | 140 | 6.2 | 7 | |
| s | 74 | I - 176 | 64.05906 | 21.32032 | 154 | 6.7 | 7 | 5 |
| t | 75 | I-02 | 64.0576 | 21.31109 | 95 | 5 | 7.4 | 3 |
| t | 76 | I-05 | 64.05697 | 21.30826 | 590 | 40.7 | 5.6 | 0.2 |
| t | 77 | I-06 | 64.05687 | 21.30894 | 204 | 9.3 | 5.6 | 0.1 |
| t | 78 | I-10 | 64.05629 | 21.31363 | 231 | 16.8 | 6.8 | 0.5 |
| t | 79 | I-12 | 64.05608 | 21.31249 | 132 | 11.7 | 7.7 | 0.5 |
| t | 80 | I-19 | 64.05998 | 21.31362 | 310 | 6.1 | 7.8 | 0.1 |
| t | 81 | I-20 | 64.05921 | 21.31456 | 430 | 9 | 7.2 | 0.5 |
| t | 82 | I -21 | 64.05921 | 21.31379 | 484 | 11.8 | 6.9 | 0.1 |
| t | 83 | I-22 | 64.05964 | 21.31386 | 1265 | 32.5 | 5.6 | 0.2 |
| t | 84 | I-23 | 64.05964 | 21.31386 | 1265 | 33 | 6 | 2 |
| t | 85 | I-24 | 64.05968 | 21.3132 | 1050 | 25.2 | 6.1 | 0.1 |
| t | 86 | I-25 | 64.0602 | 21.31269 | 1807 | 30.8 | 6 | 0.2 |
| t | 87 | I-28 | 64.06103 | 21.31087 | 148 | 6.2 | 7 | 0.2 |
| t | 88 | I-29 | 64.06191 | 21.31099 | 700 | 5.8 | 5.7 | 0.5 |
| t | 89 | I-30 | 64.06189 | 21.31056 | 1033 | 9 | 5.8 | 2 |
| t | 90 | I-31 | 64.06184 | 21.30931 | 161 | 4.8 | 7.6 | 1.5 |
| t | 91 | I-36 | 64.0627 | 21.31105 | - | - | - | dry- |
| t | 92 | I-37 | 64.05776 | 21.31347 | 91 | 6 | 7.8 | 0.2 |
| t | 93 | I-43 | 64.06181 | 21.31222 | 54 | 6.6 | 6.2 | 1 |
| t | 94 | I-44 | 64.06125 | 21.31296 | 187.5 | 15.5 | 7.1 | 0.1 |
| t | 95 | I - 50 | 64.06267 | 21.31446 | 195 | 5.2 | 7.4 | 0.5 |
| t | 96 | I - 51 | 64.066257 | 21.31738 | 654 | 5.9 | 6 | 0.2 |
| t | 97 | I - 57 | 64.06302 | 21.3199 | 91 | 7.5 | 7.6 | 0.1 |
| t | 98 | I - 61 | 64.06402 | 21.32237 | 50.1 | 5.2 | 7.4 | 0.1 |
| t | 99 | I -65 | 64.06539 | 21.31264 | 242 | 12.1 | 5.7 | 0.1 |
| t | 100 | I - 66 | 64.06518 | 21.31226 | 519 | 8.6 | 6.2 | 2 |
| t | 101 | I - 67 | 64.06515 | 21.31233 | 313 | 11.8 | 6.5 | 0.1 |
| t | 102 | I - 68 | 64.06518 | 21.31174 | - | - | - | Low/s |
| t | 103 | I - 69 | 64.06537 | 21.31068 | 160 | 7.8 | 4.5 | 0.2 |

| Group | No. | Serial no. | N | E | Conductivity (S/m) | Temperature (°C) | pH | Flow rate (l/s) |
|---|---|---|---|---|---|---|---|---|
| t | 104 | I - 70 | 64.06929 | 21.30158 | 280 | 21 | 6 | 1.5 |
| t | 105 | I - 71 | 64.06922 | 21.30183 | 275 | 19 | 6.1 | 0.01 |
| t | 106 | I - 72 | 64.06913 | 21.30197 | 101.7 | 16.1 | 6.5 | 0.5 |
| t | 107 | I - 73 | 64.06905 | 21.3054 | 102 | 19.5 | 6.8 | 1.5 |
| t | 108 | I - 74 | 64.06893 | 21.30824 | 65.9 | 11.9 | 6.7 | 0.1 |
| t | 109 | I - 75 | 64.06776 | 21.31058 | 57.7 | 12.4 | 6.8 | 0.01 |
| t | 110 | I - 76 | 64.06723 | 21.31082 | 45.4 | 14.7 | 6.6 | 0.2 |
| t | 111 | I - 89 | 64.06745 | 21.31675 | 214 | 5.4 | 7.4 | 0.2 |
| t | 112 | i - 90 | 64.06661 | 21.31749 | 76.6 | 11.4 | 7.3 | 0.5 |
| t | 113 | I - 93 | 64.06698 | 21.32374 | 106 | 19.1 | 7.1 | 0.01 |
| t | 114 | I - 94 | 64.06761 | 21.32277 | 160 | 12.3 | 7.1 | 0.5 |
| t | 115 | I - 106 | 64.07011 | 21.32127 | 1070 | 100 | 6 | 2 |
| t | 116 | I - 107 | 64.07053 | 21.32086 | 1064 | 90 | 8 | 0.5 |
| t | 117 | I - 108 | 64.0743 | 21.32019 | 261 | 18.1 | 7.5 | 0.5 |
| t | 118 | I - 109 | 64.07039 | 21.31991 | 110 | 12 | 8.1 | 0.01 |
| t | 119 | I - 110 | 64.07003 | 21.32359 | - | 98 | - | gas |
| t | 120 | I - 121 | 64.07259 | 21.33529 | 468 | 21.1 | 7.6 | 0.1 |
| t | 121 | I - 122 | 64.07248 | 21.3344 | 330 | 16.1 | 6.6 | 1 |
| t | 122 | I - 123 | 64.07255 | 21.33353 | 1080 | 26 | 6.8 | 0.2 |
| t | 123 | I -124 | 64.0727 | 21.3335 | 1440 | 39.8 | 6.4 | 0.5 |
| t | 124 | I - 125 | 64.07259 | 21.33347 | 748 | 26.8 | 6.6 | 0.01 |
| t | 125 | I - 126 | 64.07263 | 2133290 | 406 | 26 | 8 | 0.01 |
| t | 126 | I - 127 | 64.070206 | 21.33443 | 410 | 9.1 | 8.4 | 0.1 |
| t | 127 | I - 128 | 64.07173 | 21.33423 | 307 | 16.1 | 8.2 | 0.2 |
| t | 128 | I - 129 | 64.07132 | 21.33372 | 130 | 10.9 | 8.4 | 0.5 |
| t | 129 | I - 130 | 64.07107 | 21.33204 | 612 | 13.5 | 6.5 | 0.1 |
| t | 130 | I - 132 | 64.05364 | 21.30538 | 510 | 41 | 6.2 | 0.5 |
| t | 131 | I - 133 | 6405428 | 213075 | 494 | 62.7 | 6 | 0.1 |
| t | 132 | I - 134 | 64.05429 | 21.30601 | 383 | 52.3 | 6.1 | 0.5 |
| t | 133 | I - 135 | 64.05512 | 21.30675 | - | 71 | - | gas |
| t | 134 | I - 136 | 64.05523 | 21.30653 | - | 97.7 | - | gas |
| t | 135 | I - 137 | 64.05529 | 21.30536 | 540 | 78.3 | 2.5 | muddy |
| t | 136 | I - 138 | 64.05525 | 21.30501 | | 97.5 | | gas |
| t | 137 | I - 139 | 64.05487 | 21.30411 | 520 | 58.1 | 3.2 | 0.1 |
| t | 138 | I - 140 | 64.05458 | 21.30403 | - | 86.5 | | muddy |
| t | 139 | I - 141 | 64.05426 | 21.30331 | 5550 | 80.4 | 6.2 | 0.2 |
| t | 140 | I - 142 | 64.05373 | 21.30261 | 58.3 | 13.5 | 8.8 | 0.01 |
| t | 141 | I - 143 | 64.05363 | 21.301 | 83.7 | 9.2 | 8.4 | 0.2 |
| t | 142 | I - 144 | 64.05403 | 21.30098 | 81.1 | 11 | 8.2 | 0.1 |
| t | 143 | I - 145 | 64.05073 | 21.29777 | 153 | 14.6 | 7.8 | 0.02 |
| t | 144 | I - 146 | 64.05531 | 21.30003 | 129 | 10.9 | 8.2 | 0.1 |
| t | 145 | I - 147 | 64.05546 | 21.30076 | 119.6 | 9.8 | 8.2 | 0.2 |
| t | 146 | I - 148 | 64.056 | 21.30045 | 165 | 13.2 | 8.1 | 1 |
| t | 147 | I - 149 | 64.05633 | 21.30111 | 110.4 | 13.6 | 8 | 2 |
| t | 148 | I - 150 | 64.05076 | 21.3029 | 436 | 46.1 | 6.6 | 0.1 |
| t | 149 | I - 151 | 64.05531 | 21.30341 | | 85 | | muddy |
| t | 150 | I - 152 | 64.05531 | 2130373 | | 87 | 3.2 | muddy |
| t | 151 | I - 153 | 64.05648 | 21.30358 | 231 | 20.1 | 8.1 | 4 |
| t | 152 | I - 154 | 64.05597 | 21.30365 | 750 | 96.5 | 6.5 | 0.1 |
| t | 153 | I - 155 | 64.05573 | 21.30364 | | 90 | 3.5 | muddy |
| t | 154 | I - 156 | 64.0556 | 21.30405 | | 81.9 | | gas+t |
| t | 155 | I - 157 | 64.05591 | 21.30483 | 228 | 20.4 | 8.1 | 1 |

| Group | No. | Serial no. | N | E | Conductivity (S/m) | Temperature (°C) | pH | Flow rate (l/s) |
|---|---|---|---|---|---|---|---|---|
| t | 156 | I - 159 | 64.05423 | 21.30817 | 160 | 9 | 8.6 | 0.5 |
| t | 157 | I - 160 | 64.0545 | 21.30807 | 165 | 11 | 8.2 | 0.1 |
| t | 158 | I - 161 | 64.05481 | 21.30852 | 172 | 14.2 | 8.2 | 0.1 |
| t | 159 | I- 162 | 64.05486 | 21.30759 | 640 | 73.1 | 6.2 | 1 |
| t | 160 | I - 163 | 64.05511 | 21.30761 | 342 | 43.1 | 6.4 | 0.1 |
| t | 161 | I - 164 | 64.05526 | 21.30744 | 319 | 23.5 | 7 | 0.5 |
| t | 162 | I - 165 | 64.0553 | 21.30837 | 275 | 12.1 | 7.5 | 0.1 |
| t | 163 | I - 166 | 64.05539 | 21.30767 | 560 | 65.1 | 7.1 | 0.01 |
| t | 164 | I - 167 | 64.05542 | 21.30705 | 388 | 89.7 | 6.9 | muddy |
| ts | 165 | I - 131 | 64.05305 | 21.30482 | 610 | 69.9 | 6.5 | 1 |

### 5.3 Detailed geothermal mapping and comparison with other types of geothermal maps

In geothermal prospecting, the mapping of hot and cold springs and hydrothermal alteration provides important information on underlying geothermal systems. Such maps need to be linked to detailed geological and tectonic maps. Based on both, the next step in geothermal prospecting can be taken, e.g. by siting exploration drillholes for geothermal energy. However, prior to that, a common practice in geothermal prospecting is to add data from hot water and gas samples from the hot springs and fumaroles, as well as to add geophysical data from various geophysical surface exploration. For illustration purposes, an example of such geochemical data is discussed below.

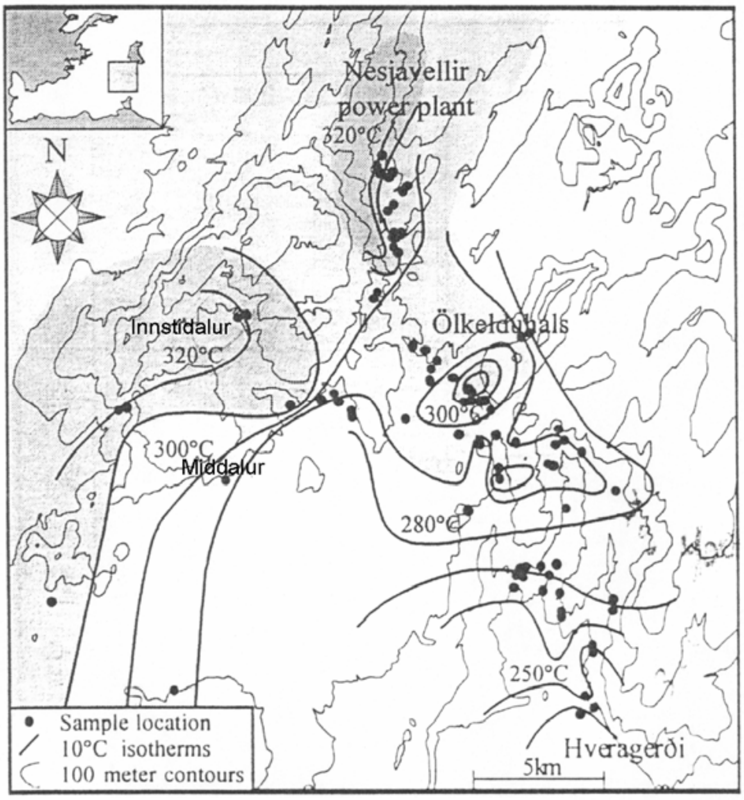


FIGURE 8: $CO_2$ temperature map of the Hengill area (from Ívarsson 1996)

Figure 8 (from Ívarsson, 1996) shows an isothermal map of $CO_2$ deduced from geothermometry, based on gas samples from steaming fumaroles and geothermometry. This map provides an estimate of the subsurface reservoir temperatures of the prospect area, and other prospect fields in the Hengill system, all of which are compared in Table 2. The highest $CO_2$ temperatures are found in the Innstidalur study area. There, the 320°C isotherm is observed, open to the west and southwestwards, while $CO_2$ temperatures in the Middalur field are much lower or about 290°C.

The geothermal map presented here should be compared to the isotherm map in Figure 8. Immediately noteworthy is the fact that the highest temperatures measured in the fumarolic areas occur in the northwestern part of the present study area, just north of the eruptive fissure. There, also, the prominent presence of native sulphur around some of the discharging steam vents was observed as discussed above.

TABLE 2: $CO_2$ temperatures (°C) calculated for different geothermal fields in the Hengill high-temperature area (from Ívarsson, 1996)

| Innstidalur | Middalur | Nesjavellir | Ölkelduháls | Hveragerdi |
|---|---|---|---|---|
| 320 | 290 | 305 | 296 | 262 |

The detailed geothermal manifestation map in the Innstidalur-Middalur study area can be divided into three fields: the northwest field; the central field; and the southeast field. Fumaroles and boiling water and mud pools in the northwest field are controlled by active fissures and faults, that erupted in part some 5,000 years ago, and have episodically been active since, as can be seen by the open fissures and faults that cross the young lava and the craters. Also, in the fumarolic area, the ground is extremely altered as compared to other sites. Those referred to are at locality I 110, showing also sulphuric gas fumaroles and mud pools, which have relatively high quantities of sulphur deposited around their discharges with measured temperature about 98°C.

In the central field, only low-temperature geothermal activity is observed at present. Most of the surface alteration witnesses fossil hydrothermal activity. Alteration minerals include calcite, smectite and iron oxides, and probably pyrite. This area is partly covered by landslide.

In the Middalur field in the southeast, geothermal activity is fairly vivid in the vegetated field, characterised by hot ground fumaroles, boiling water and mud pools. Middalur valley is at a lower elevation than the northwest area, and accordingly the effect of the ground water level is more prominent in the hot spring field, many of which are clayish with kaolinite muddy pools seen at localities I 151, I 154, I 155, and I 156.

### 5.4 Flow rate estimates, measured pH (acidity) and conductivity

The collected data from the hot and cold springs of the area is listed in Table 2, and shown on the geothermal map in Figure 7. The pH and conductivity measured the relative acidity or alkalinity of the springs. Waters with pH of near 7.0 are neutral; lower pH indicating increasing acidity and higher conductivity; while pH higher than 7.0 indicating basic waters and lower conductivity. Most of the springs had pH in the range 6.5–8.5.

Flow rates were estimated for the 166 springs in the study area. The average flow rate is about 0.76 l/s, but for the 20 largest springs the average flow rate was above 1.5 l/s. Very noteworthy is the fact that the thermal springs in the Innstidalur area seemed to be restricted to the fault system.

### 5.5 Hydrothermal model of the Innstidalur area

The hydrothermal model presented in Figure 9, is along cross-section C-D in Figure 7. The model in Figure 9 shows the following:

- The main upflow zone is located in the northwestern part of the area along the major NE-SW trending fault zone and volcanic fissure. Steam and gas flows up along the faults and surfaces as fumaroles with high content of $H_2S$ and $CO_2$, and of high temperatures as well, indicating their source may be partly volcanic.
- Thermal phenomena present in the central area, show steam rising up along faults, meeting ground water close to the surface, forming travertine along some surface faults but elsewhere complete clay replacement of formerly active geothermal fields.
- Travertine deposits formed above the warm and hot springs.
- In the Middalur valley in the southeast, the thermal manifestation present on the surface, are characterized by steam-heated groundwater fields.

- Most of the cold water springs occur in the landslide rocks, which have high permeability, especially at the interface of the underlying bedrock.

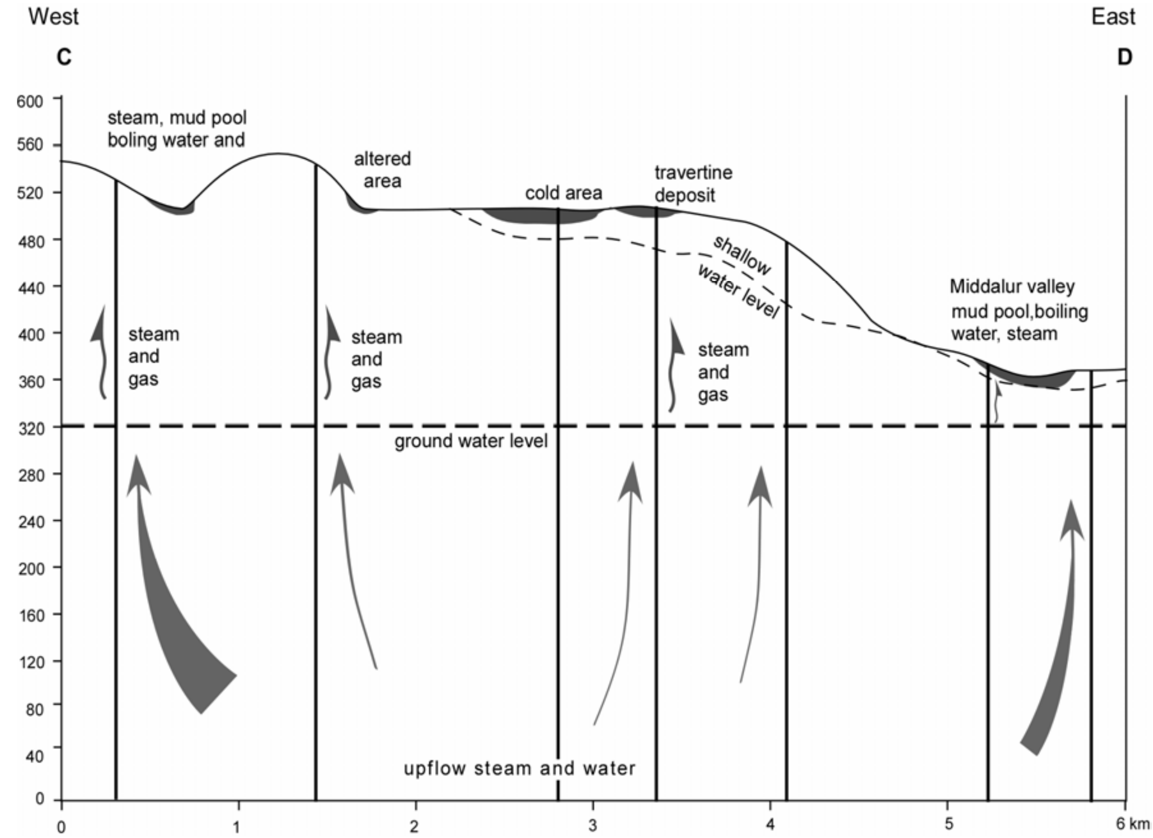


FIGURE 9: Hydrothermal model of Innstidalur area along cross-section C-D (see Figure 7)

## 6. CONCLUSIONS

The following summarizes the field work of the geothermal mapping in the Innstidalur-Middalur area:

- Surface hydrothermal alteration zones trend NE-SW parallel to the fissures and faults in the area.
- Travertine (calcium carbonate) minerals form above $CaCO_3$ supersaturated hot and warm springs along faults.
- Geothermal surface manifestations include high-temperature fumaroles, hot springs and mud pools which are probably fault controlled. The faults provide a high-permeability flow path for deep circulation of meteoric water.
- Measured pH and conductivity show pH range between 6.5 and 8.5.
- Presence of native sulphur in the geothermal manifestation in the northwestern part of the study area shows a field relationship with the location of eruptive fissures, and high $CO_2$ temperatures.

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