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GEOTHERMAL MAPPING IN THE HRÓMUNDARTINDUR AREA, SW-ICELAND

Jacob W. M. Mayalla
Ministry of Energy and Minerals, Energy Department
P.O. Box 2000, Dar es Salaam
TANZANIA
jobmayalla@yahoo.co.uk

ABSTRACT

A geological map is the foundation on which a geothermal exploration programme needs to be based. All other data need to be interpreted in view of the observed or known geological features. During geothermal exploration, geological maps should emphasize young igneous rocks that could act as heat sources at depths, the distribution and nature of fractures and faults, and the distribution and nature of hydrothermal alteration.

A geothermal map of the Hrómundartindur area, SW-Iceland is presented. Hrómundartindur is part of the Hengill active central volcanic complex. The aim of the study was to familiarize the author with geothermal mapping in young volcanic terrain, including tectonic structures, hydrology and hydrothermal manifestations. Field observations were interpreted in view of the geothermal manifestations mapped. The most prominent manifestations occur in the northwest part of the field area, apparently connected to the volcanic fissures of two volcanic formations, the older Hrómundartindur eruptive fissure of late Pleistocene age and the much younger Tjarnarhnúkur volcanic vent/fissure of early Holocene age.

The widespread hydrothermal manifestations range from slightly altered host rocks (soil, scree, Hrómundartindur hyaloclastite) to host rocks completely transformed to hydrothermal clays. These manifestations are active (hot) and extinct (cold), the extinct ones bearing witness to former activity and indicated separately on the geothermal map. Isotherms were mapped within the warm (>15°C) and hot (>50°C) fields, within which many hot springs, mud pits, steam vents and warm springs occur.

1. INTRODUCTION

The exploitation of geothermal energy within an area is based on the availability of natural heat at shallow depths within the earth's crust. A prospective area will be the one which can deliver relatively large amounts of thermal energy from relatively shallow depths. Natural heat is produced either by cooling magmas at depth, and/or by decaying reactions of radioactive elements contained in the earth's interior, such as uranium and thorium. The heat transfer to the surface is either by conduction or convection. The more effective and faster transfer mode is convection. The purpose of this report is to stress the contribution of geology on geothermal mapping in geological exploration. The first step of geothermal resource development is through geological exploration, which includes geological mapping, structural mapping and hydrothermal mapping. A hydrothermal map should include phenomena like hot and warm grounds, hot and warm springs, steam vents, mud pits, and any kind of surface thermal manifestation. For practical purposes a geothermal map should also include faults, major fractures and young volcanic features like volcanic craters, eruptive fissures etc., as a link is often found to exist between tectonic features and the distribution of geothermal manifestations.

The author was selected to attend the UNU training course as Tanzania is still at an early stage of geothermal development. An opportunity to apply this knowledge at home in geothermal exploration is anticipated. The objective of the study was to give the author on-site practical training in geothermal mapping, including analysis of geological structures, surface hydrothermal manifestations of all kinds and soil temperature measurements for mapping and distribution of the geothermal output.

Tanzania depends on hydro, thermal and natural gas for generating electricity. The Ministry of Energy and Minerals, Department of Energy is responsible for all issues regarding energy in the country. Due to regular droughts, the country is faced with a need for looking at alternative sources of energy, and a need for diversified energy sources also exists. Over the next five years the Ministry is considering geothermal development for electricity production. This will mostly concern people in rural areas; the energy situation in Tanzania is such that only 10% of the population has access to electricity, while in rural areas only 1% of the people are connected to the electricity grid. With respect to geothermal development, Tanzania is one of several countries favourably situated within the East African rift system. Within the rift system a reasonably high geothermal gradient thrives and a number of hot geothermal fields exist, suitable for development of power generation. So far, Kenya is the only country in the rift valley that utilises these conditions. According to the report written by McNitt, (1982), an estimated geothermal potential of 650MWe exists in Tanzania. The Ministry of Energy and Minerals, Department of Energy, and the Geological Survey of Tanzania (GST) is collaborating with the Federal Institute for Geosciences and Natural Resources (BGR) of Germany. Together they have formalized a joint venture project called *"Geothermal as an alternative source of energy for Tanzania"*. The objective of that project is to evaluate the country's geothermal potential. This was the reason for nominating me as a candidate to participate in the UNU Geothermal Training Programme in Iceland in 2006. The author's anticipated role in the Ministry of Energy and Minerals, Department of Energy is to coordinate all issues regarding geothermal development in the country.

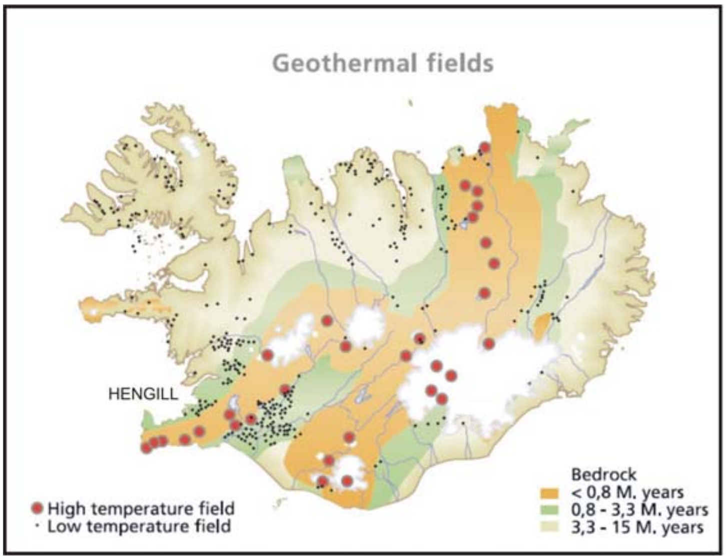

FIGURE 1: Geological and geothermal map of Iceland (compiled by K. Saemundsson and H. Jóhannesson)

The Hengill area is located within the active spreading plate boundary which crosses Iceland (Figure 1). The Hengill central volcano is within the youngest part of the rift zone, with prominent NNE-SSW striking normal faults and fissures. Within the larger Hengill area are predecessors of the presently active centre, namely the older Hrómundartindur system and the oldest Hveragerdi system (Figure 2) and their geothermal systems. Reconnaissance geological mapping in Hengill was carried out in the sixties and later the area was remapped with emphasis on stratigraphic and tectonic history and on geothermal manifestations and hydrothermal alterations (Saemundsson, 1967; 1979, 1995a, 1995b; Saemundsson and Fridleifsson, 1992). Simultaneously and hitherto, several geophysical surveys of the whole area were undertaken including DC-resistivity sounding, TEM and MT resistivity surveys, as well as gravity and aeromagnetic surveys (e.g. Björnsson et al., 1986; Árnason et al., 1967; Árnason et al., 1987; Eysteinsson et al., 1993; Pálmason and Saemundsson, 1974; Sigurgeirsson, 1970).

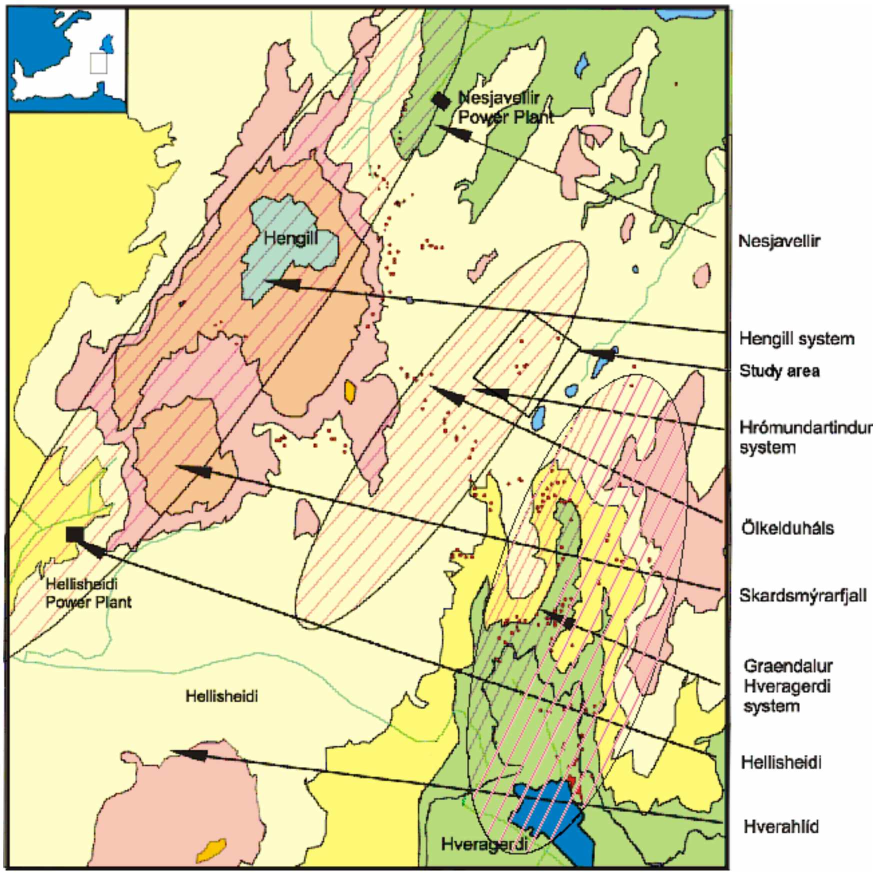

FIGURE 2: Location of the study area in the Hrómundartindur system

1.1 Duration of the study

Field work was initiated by the end of July and continued intermittently through September. Field work in Iceland is strongly weather dependent and the closeness to the UNU office allowed field work to only be undertaken during days with relatively good weather. Reconnaissance of the researched area was done in two days at the beginning with the guidance of a supervisor, and again later as work proceeded. Altogether, the detailed geothermal mapping of the research area took some twenty days.

1.2 Previous work

Over the years, geothermal research in the Hengill area has been conducted by a number of scientists in many different disciplines. Relatively few scientists, however, have studied the Hrómundartindur area. K. Saemundsson in 1967 mapped the Hengill area and produced a geological map of scale 1:25,000. Björnsson and Hersir in 1981 summarized the results of geophysical reconnaissance studies of the Hengill area using DC-resistivity soundings, aeromagnetic measurements, MT-surveys and seismicity. A low-resistivity anomaly at a depth of 400 m covering 120 km^2 was found to delineate the high-temperature geothermal area. The aeromagnetic map produced shows negative anomalies caused by hydrothermal alteration. K. Saemundsson, with a team of geologists (G.I. Haraldsson, G.Ó. Fridleifsson and S. Snorrason), re-mapped the Hengill area during several summers mainly in the nineties resulting in detailed geological and geothermal maps of the Hengill area on a scale of 1:50,000 and 1.25,000, respectively (Saemundsson, 1995a and b). In the present study, the existing geological map was used exclusively, while the geothermal activity of the Hrómundartindur field was remapped in closer detail, as digital mapping and GPS positioning accuracy enables and simplifies the mapping exercise. The Hrómundartindur field is connected to and located just north of the Ölkelduhnúkur field, which was geothermally mapped by two UNU Fellows last year (Gebrehiwiot, 2005; Natukunda, 2005).

2. GEOLOGICAL AND TECTONIC SETTING

2.1 Iceland

Iceland is located in the North Atlantic Ocean between Greenland and Norway at 63°23´N to 66°30´N. It is a large land mass that is part of a much larger entity situated at the junction of the submarine Mid-Atlantic Ridge and the Greenland-Iceland-Faeroes Ridge. Iceland is a part of the oceanic crust forming the floor of the Atlantic Ocean. The Mid-Atlantic Ridge defines the constructive plate boundary between the American and Eurasian plates. From magnetic anomalies to the north and south of Iceland, the spreading rate has been estimated as 2 cm/year (i.e. 1 cm per year in each direction) This region is known as the Icelandic basalt plateau, which rises more than 3000 m above the surrounding ocean floor and covers about 350,000 km^2 (Thórdarson and Höskuldsson 2002).

Geologically speaking, Iceland is very young; all of its rocks including its "continental" shelf were formed within the past 25 million years or so. The stratigraphical succession of Iceland spans through three geological periods, that of late Tertiary (Miocene and Pliocene), the Quaternary or Pleistocene, and the Holocene. The creation of Iceland is thought to have begun about 24 million years ago, but the oldest rocks exposed at the surface are 14-16 million years old. The surface of Iceland has changed radically during its brief existence. The forces of nature that constantly mould and shape the face of the earth operate faster in Iceland than in most other places on earth. Erosion removes about a million cubic meters of land from Iceland each year, but volcanism and sedimentation more than counterbalance this loss.

The Greenland - Iceland - Faeroes Ridge is thought to be the trail of the Icelandic hot spot, which has been active from the time of opening the North Atlantic Ocean 60 million years ago to the present. Presently the hot spot is thought to be located under Central East Iceland, close to the volcanic rift zone which crosses Iceland from southwest to northeast in a complicated manner.

Geothermal areas in Iceland are divided into two main groups, high-temperature and low-temperature. The high-temperature areas are found only within the area of active volcanism within the rift zones, characterized by active volcanoes and fissure swarms. The uppermost 1000 m of this zone are made up of highly porous and permeable basaltic lava successions or hyaloclastites. Due to an abundance of cold groundwater, low temperature gradients are expected within the uppermost kilometre, but below that depth the geothermal gradient rises sharply. The high-temperature areas are localized features within the rift zones, mostly confined to central volcanic complexes as said above, and the base temperature within them is typically > 200°C at 1 km depth. The geothermal activity of the high-temperature areas is ascribed to intrusive activity at high levels within the upper crust (e.g. Flóvenz and Saemundsson, 1993). Low-temperature areas are mainly found outside the volcanic rift zones and involve geothermal systems of temperatures ≤ 150°C. They are located within the Pleistocene and Tertiary rocks. The low-temperature areas derive their heat from hot crust through active and localised convection in near vertical fractures. Away from the fractures the bedrock is less permeable and heat transfer is dominated by conduction.

3. HENGILL

3.1 The geology and structure of the Hengill central volcano

The Hengill high-temperature area is located within the western branch of the volcanic rift zone in SW-Iceland. The area is commonly separated into three volcanic systems, the youngest and most active is the Hengill volcano itself in the west, located within the axial rift zone. The second youngest is the Hrómundartindur system, and the third and oldest is the Hveragerdi system (Figure 2). The oldest rocks, about 0.8 my old from the Matuyama epoch, are located in the lowlands southeast of the town of Hveragerdi, and the youngest volcanic rocks are the Holocene lava flows from the Hengill volcanic fissure swarm. The Hrómundartindur system also includes an early Holocene lava flow which erupted on a short volcanic fissure. The prominent Tjarnarhnúkur scoria cone was formed at the very end of the Tjarnarhnúkur lava eruption.

The Hengill area is almost entirely built up of volcanic rocks. Subglacially formed hyaloclastites together with pillow basalts constitute the main rock types in the area. Second in extent are Pleistocene and Postglacial lava flows (Saemundsson, 1967). Basaltic hyaloclastite forms when magma quenches during an eruption into the base of a glacier, and piles up above their orifices as pillow basalts, breccias and tuffs. The Tjarnarhnúkur fissure erupted in the early Holocene (~11,000 years ago) to form basaltic pahoehoe lava, which reached the shores of a preglacial lake that marks an early stage of the present lake Thingavallavatn. The main heat source of the Hengill geothermal area is considered to be cooling magma intrusions within the upper crust, while deep circulation of groundwater in highly fractured rocks transports the heat upwards.

3.2 Geophysics of the Hengill volcano

Resistivity surveys conducted in the Hengill area over the years have shown that a huge low-resistivity anomaly is associated with the geothermal area. It is assumed to be related to highly conductive hydrothermally altered rocks. Figure 3 shows a resistivity map at 100 m below sea level (Knútur Árnason, pers. comm.). The location of the present study area is also shown in Figure 3. A high-resistivity core (cross-hatched) delineates the extent of the high-temperature hydrothermal systems at this depth level, and extends from the Hengill volcano east to the Hrómundartindur system. Dark lines (blue) delineate the major faults, a gray (green) shaded diagonal pattern delineates active seismic fractures at depths, and dark dots (red) mark the most prominent active hydrothermal surface manifestations.

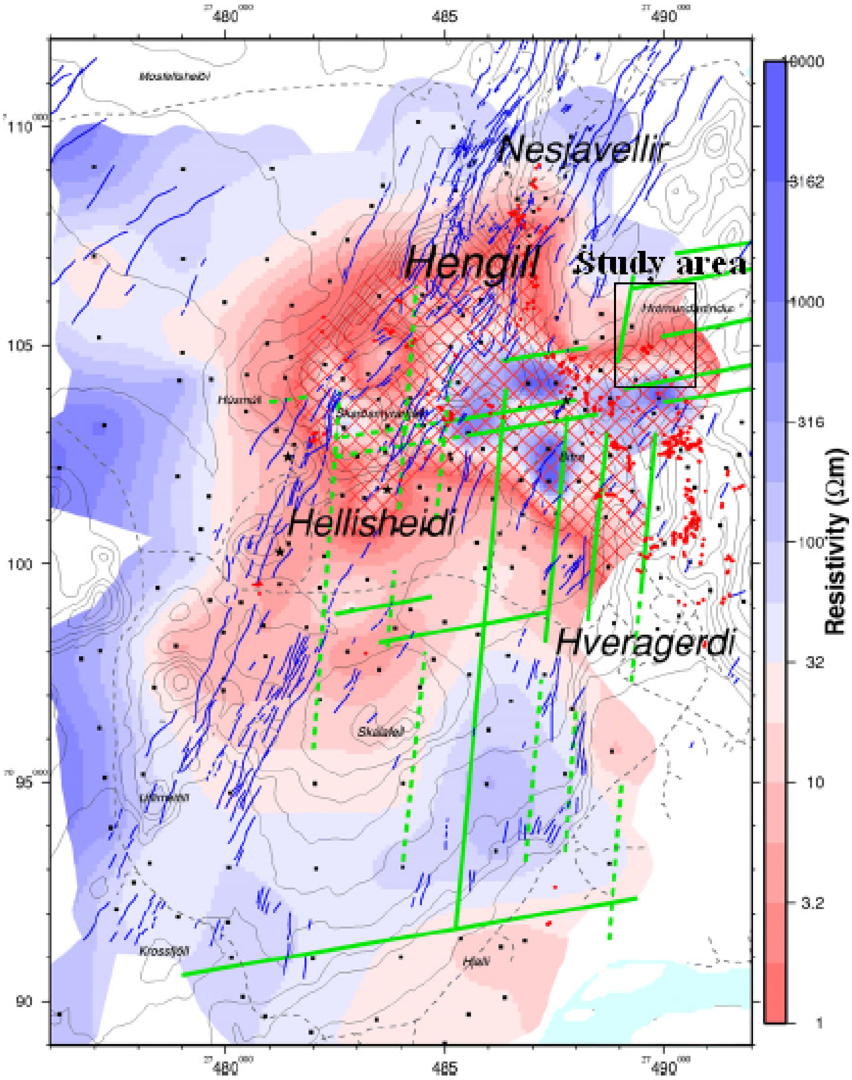

FIGURE 3: Resistivity map 100 m below sea level of the Hengill area (K. Árnason, pers. comm.)

Nearly all surface geothermal manifestations within the Hengill area are located within the boundaries of the low resistivity (Björnsson et al., 1986; Árnason et al., 1987; Árnason, 1993). Aeromagnetic surveys carried out in the Hengill area indicated negative anomalies that seem to be caused by hydrothermal breakdown of magnetic minerals within the active high-temperature systems (Björnsson and Hersir, 1981). Micro earthquake surveys have shown that a correlation exists between high seismic activity and the distribution of fumaroles (Foulger and Einarsson, 1980). From Hengill, there is a line of surface manifestations extending southeast from Nesjavellir into the Hveragerdi central volcano. It coincides with a low-resistivity anomaly connecting the Hengill area and the extinct Hveragerdi central volcano. The main pattern of the anomaly is perpendicular to the active fissure swarm and parallel to the transverse lineaments in the Hengill system (Björnsson et al., 1986).

In South Iceland, the volcanic belt across the island is separated into two branches or zones. The eastern branch is propagating southwards. The two branches are linked by the so-called South Icelandic Seismic Zone, an E-W trending belt of fracture systems, involving destructive earthquakes, that extends across the lowlands in South Iceland. The active zones join in some kind of a triple point near 64°N and 21°W in the Hengill area (Foulger and Einarsson, 1980). Earthquake activity is distributed over the whole of the high-temperature geothermal area and some are peripheral to it. It shows a correlation between continuous microseismic activity and the distribution of surface geothermal activity. A seismic study between 1993 and 1997 registered nearly 24,000 earthquakes exceeding 0.5 on the Richter scale in the Hengill area. About 12,000 of these occurred in 1997 alone (Sigmundsson et al., 1997). The largest earthquake seems to have reactivated the geothermal activity in the area, causing the emergence of new geothermal manifestations in new localities or the rejuvenation of extinct ones (K. Saemundsson, pers. comm.; Natukunda, 2005).

3.3 Geothermal drilling in Hengill area

Geothermal activity in the Hengill area is connected to the three volcanic systems (Figure 2), i.e. the Hengill, Hrómundartindur and Hveragerdi systems. The geothermal area close to the town of Hveragerdi belongs to the oldest system, the Hveragerdi central volcanic system (Saemundsson and Fridleifsson, 1996). Deep exploratory drillholes have been drilled in the Hengill area, as well as a number of deep production wells in the Nesjavellir, Ölkelduháls and Hellisheidi geothermal fields. Reykjavík Energy, the energy company of Reykjavík, the capital of Iceland, has constructed two power plants for the production of electricity and warm water for domestic heating at Nesjavellir in the early nineties, and at Helllisheidi, commissioned in October 2006. Hot water is transported to Reykjavík and used for house heating in the city. The power plants produce electricity for use in Reykjavík as well as for energy intensive industry (aluminium plants).

4. GEOLOGICAL EXPLORATION

Geological exploration and geothermal mapping are tools for defining parameters that control the movement of hot and cold groundwater and steam within different rock types. By conducting geological exploration, i.e. mapping geothermal manifestations and hydrothermal alteration, and mapping tectonic- and volcanic structures, the key elements in understanding the nature of a geothermal system are systematically investigated. Such geothermal exploration is then followed by systematic fluid sampling for geochemistry from within hydrothermal manifestations, and by various geophysical methods, as discussed above. The most recent geological and hydrothermal maps of the Hengill area were published in 1995 (Saemundsson 1995a and b) on the scale of 1:50,000 and 1:25.000. In the present study, extensive use was made of the geological maps, revealing the main volcanic and tectonic elements; a new geothermal map is presented here on a scale of 1:3,000, which obviously allows for more details.

There are two peaks in the Hrómundartindur area, Tjarnarhnúkur crater and the Hrómundartindur ridge. The Hrómundartindur ridge is composed of hyaloclastite tuff in the lower part but pillow basalts at higher levels, and probably formed during the second last glacial period (up to 200,000 years old), but possibly during the last glacial period (<100,000 years old) (K. Saemundsson, pers. comm. and 1995a). Part of the geological map is shown in Figure 4. Most prominent is the widely distributed Tjarnarhnúkur lava which formed about 11,000 years ago. The Tjarnarhnúkur lava erupted on top of the Ölkelduhnúkur hyaloclastite ridge, and partly on the younger Hrómundartindur hyaloclastite ridge which, however, is mostly exposed north of Tjarnarhnúkur. Other bedrock formations shown on the geological map in Figure 4 (and tabulated in Table 1) are mostly composed of hyaloclastite formations of different age. They are the volcanic products of sub-glacial fissure eruptions and, therefore, characteristically form elongated ridges striking parallel to the rift zone.

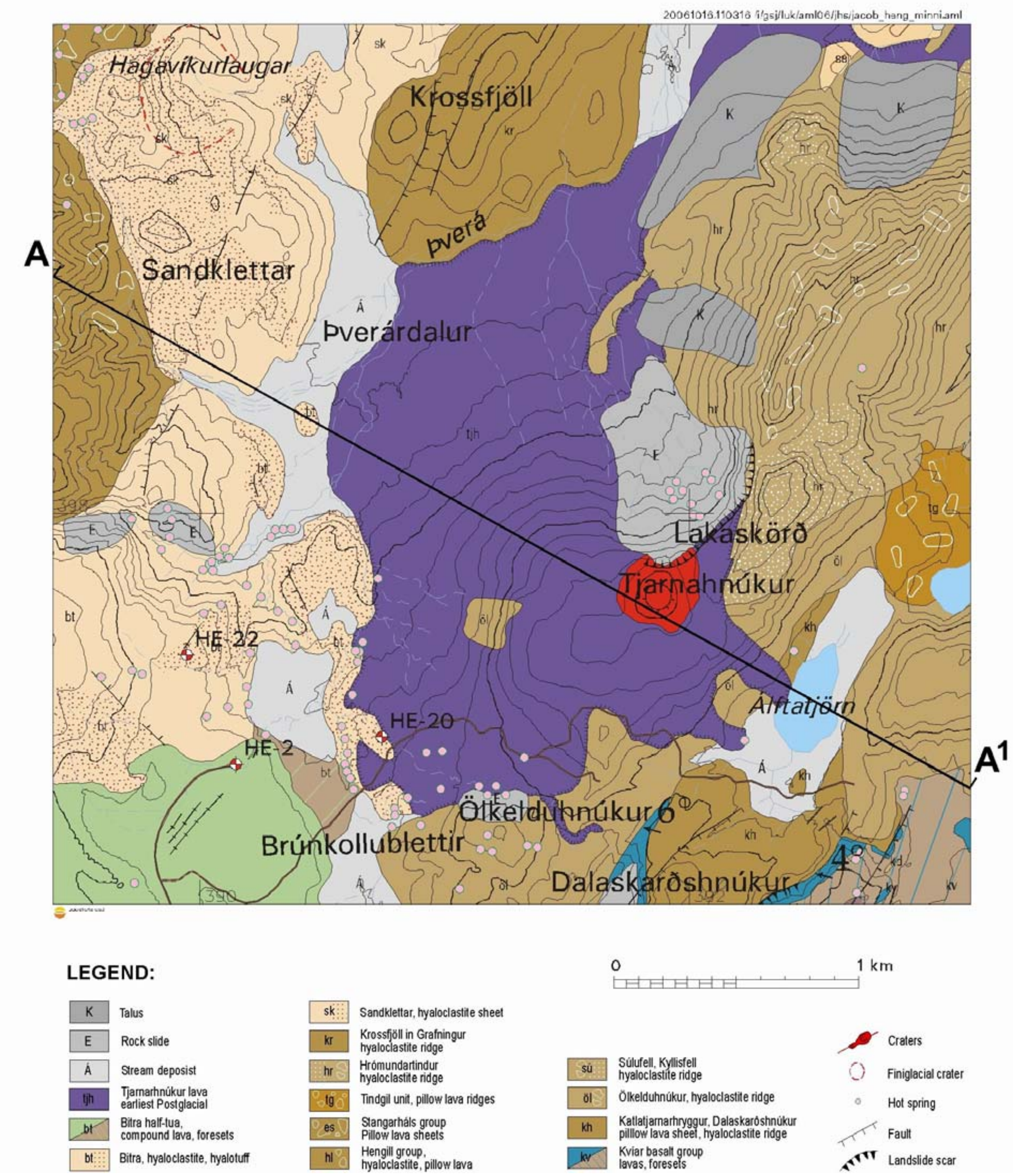

FIGURE 4: Geological map of part of the Hrómundartindur area (from Saemundsson, 1995a)

Superficial deposits of different kinds, like soil, and weathering products, like screes etc., are not shown on the geological map in Figure 4. Exceptions to this are major land slides (marked E), major rock slides (K) and major stream deposits (marked A). More detailed explanations of the lithological units are shown in Tables 1 and 2, starting with the youngest volcanic rocks down to the oldest, i.e. from the Tjarnarhnúkur lava (tjh) down to the Kvíabasalt formation (Kv). The age of these formations in the study area ranges from early Holocene back some 400,000 years into Pleistocene. Most superficial deposits were deposited during Holocene.

TABLE 1: Bedrock lithology of the present study area

No.	Unit (Acronym)	Name	Description of rock types	Age
11	tjh	Tjarnarhnúkslava	Densely porphyritic lava (plagioclase olivine pyroxene)	11,000 years
10	bt	Bitra	Composed of plagioclase-phyric hyaloclastite tuffs and lava	11,000 - 13,000 years
9	se	Selhólsmyndun	Pillow lava sheet	<200,000 years
8	hr	Hrómundartindur hyaloclastite	Hyaloclastite tuff ridge and pillow basalt formation	<200,000 years
7	öl	Ölkelduhnúkur	Hyaloclastite tuff and aphyric pillow basalt	<200,000 years
6	sú	Kyllisfell hyaloclastite	Hyaloclastite, sparsely porphyritic	<200,000 years
5	kh	Katlatjarnahryggur hyaloclastite	Hyaloclastite with variable phenocryst content	<200,000 years
4	kr	Krossfjöll hyaloclastite	Hyaloclastite, sparsely porphyritic	<200,000 years
3	hl	Hengill formation	Tuff and pillow basalt	
2	tg	Tindgilsmyndun hyaloclastite	Composed of pillow lava	
1	kv	Kvíabasalt hyaloclastite and lava foreset	Plagioclasephyric	400,000 years

TABLE: 2: Superficial deposits of Holocene age

No.	Unit (Acronym)	Name	Description of rock types
1	E	Land slides	Composed of brecciated hyaloclastite and lava blocks
2	K	Talus	Major rock slides
3	A	Stream deposits	River gravels and other stream deposits
5	Not on map	Soil and boggy areas	Vegetated parts of the field and weathering talus
6	Not on map	Loose screes	

4.1 Structures

One of the tasks of this study was to re-evaluate structural features within the field area by mapping tectonic features, such as crater rows, faults and fractures. Tectonic features most probably control the flow of the hydrothermal fluids upwards; an attempt to demonstrate that needed be undertaken.

Tectonic features, however, may be difficult to deal with because of soil or scree covers, even though clear lineaments may be seen on aerial photos, for instance. In other cases, when exposures are good, fractures and faults can easily be mapped. In the present field area, only a few clear fractures and faults could be mapped with reasonable accuracy. This contrasts markedly with the younger Hengill volcano where active major faults and rift structures are very prominent features in the landscape. Within the Hrómundartindur field, the NE-SW trends of the many subglacial volcanic hyaloclastite ridges, like the Hrómundartindur ridge itself, and the trend of the Tjarnarhnúkur eruptive fissure, are easily mappable. Other tectonic features, like the prominent landslide scar shown on the maps, are also quite clear. Judging from lineaments within the geothermal manifestations, it seems that there are faults or fractures, hidden underneath, which control the flow of the hydrothermal fluids upwards. According to geophysical data shown in Figure 3, a diagonal pattern delineating active seismic fractures at depth also occurs within the field area, and one of these trends towards the main hydrothermal manifestation.

5. GEOTHERMAL MAPPING

The mapping of the geothermal manifestations includes mapping and observations on springs of different types, steam vents, hot and warm grounds, mud pools, hydrothermal surface alteration, vegetative changes, surface conditions and soil temperature measurements. GPS positioning of some of the hydrothermal phenomena was extensively applied and transferred to a topographical map. So-called soil temperature measurements of temperatures at convenient depths in the soil can give important structural information related to the geothermal prospect (Flóvenz, 1985). Soil temperature measurements around warm and hot geothermal manifestations were taken by delineating the 15°C and 50°C isotherms. The soil temperature was measured carefully by using a digital thermometer connected by a cable through a 1 m long metallic rod, fixed at the tip with a thermistor. Measurements were made by inserting the rod into the soil to a depth of 0.1-0.3m for recording the 15°C and 50°C isotherms with locations tracked by GPS instrument (Global Positioning System). The collected data were downloaded into the computer after each field day and edited by the Map Sources Programme. The final result was a geothermal map on a scale of 1:3,000 produced by a skillful technician using the ArcInfo programme. The isotherms of 15°C and 50°C shown on the map are also used to distinguish between warm and hot grounds. Hot and warm springs, steam vents, mud pits, slight alteration and extinct clay were also mapped with GPS accuracy. Figure 5 shows the geothermal map at a reduced scale.

5.1 Geothermal manifestations

Within the research area the main geothermal manifestations are located northwest of Tjarnarhnúkur and northeast of the Hrómundartindur peak, at an elevation of about 420-440 m above sea level. The former manifestations have all the characteristics of being vividly active geothermally, including boiling mud pools, steaming fumaroles, hot and warm grounds, springs and steaming ground. The geothermal manifestations are surrounded by hydrothermally altered soil, altered to clay of different compositions with iron oxide, sulphur and calcite.

Considerable effort was made to determine the extent of the hot ground and warm ground in the area. Vegetative changes are quite clear where geothermal manifestations occur in areas covered by vegetation. Also a relationship between groundwater, hot springs and mud pits exists. At high altitudes, geothermally active areas are characterized by steam vents and grounds with hardly any mud pits, while at lower altitudes where the geothermal activity intercepts the ground water level, hot springs and mud pits are common. Rainwater and seasonal variation in surface waters also affect the hydrothermal manifestations. It was concluded that when surface water level lowers, some hot springs change to mud pits and further to steam vents as the water table lowers more.

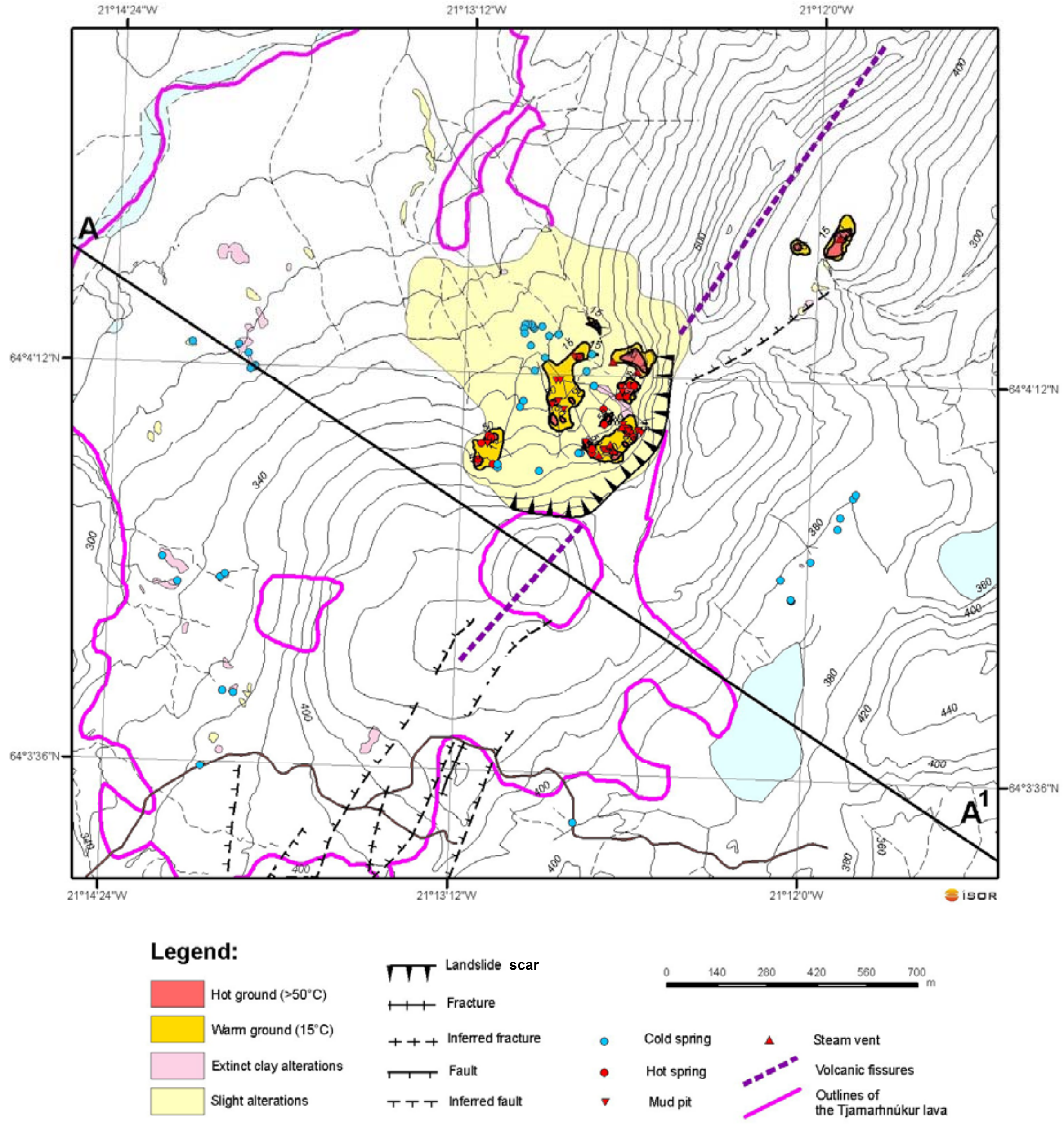

FIGURE 5: Geothermal map of the study area; A-A' location of cross-section in Figure 11

TABLE 3: Mapped geothermal manifestations in Hrómundartindur

Manifestation	Quantity
Steam vents	7
Hot springs	12
Cold springs	32
Mud pits	17
Hot grounds	19
Warm grounds	9
Extinct clays	20

5.2 Mud pits

Mud pits form in high-temperature geothermal fields somewhat deficient in surface water. Numerous mud pits occur within the research area. Table 3 shows that 17 boiling mud pits were mapped. The mud pits are greyish in colour, and the temperature of the boiling mud is most commonly 98-100°C. In some of the mud pits, dark oily looking fluid is observed floating on the surface of the mud; this indicates the presence of pyrites in the system. Some of the boiling mud pits erupt constantly up to a height of 0.5 metre (e.g. Figure 6). Mud pits deficient in water end as hot clayish earth. Figure 7 shows an example where hardly any water is left.

5.3 Steam vents

Steam vents occur mostly in hot grounds especially at high altitudes and on hilly slopes above the surface water table (Figure 8). Most of them characteristically have a hissing sound, indicating boiling water at relatively shallow depth below the surface. Seven main steam vents were observed (Table 3) within the studied field and one of them was particularly forceful. Forceful steam vents and erupting hot springs indicate the occurrence of open fractures below. These steam vents have similar lineaments as the manifestations within the Ölkelduháls field, mapped by Natukunda (2005), due south of the present field area. Temperatures of the steam vents range from 92.4°C up to 101.3°C.

5.4 Springs

Numerous hot, warm and cold springs were observed in the field area. The cold springs characteristically occurred at low grounds below the steepest rock slide slopes (compare Figures 4 and 5), and presumably indicate a false water table from rainwater seeping through the relatively loose landslide material. Above them, warm or hot water springs occur in similar settings, but are heated up by steam escaping upwards through fractures from a boiling high-temperature system at depth (described later).

The average cold groundwater temperature in SW-Iceland is about 4°C (Hjartarson and Sigurdsson, 1993). The springs in the field area, however, are grouped into three categories; i.e. hot springs, with temperatures above 50°C, warm springs with temperature ranging from 15°C to 50°C, and cold springs when temperatures below 15°C. Within the researched area the coldest groundwater springs were about 7°C.

Calcite and iron oxide deposits seem to be common around the hot springs. Some of the hot springs bubble CO_2 gas. Table 3 lists 12 hot springs and 32 cold springs. The total discharge (flowrate) of the run off streams was estimated to be about 5-6 l/s. Cold springs are widely distributed and are useful in delineating the

FIGURE 6: Boiling mud pit

FIGURE 7: Boiling mud pit deficient in water

FIGURE 8: Steam vents within the landslide in the slopes of Hrómundartindur, Tjarnarhnúkur crater in the background

FIGURE 9: Hot ground

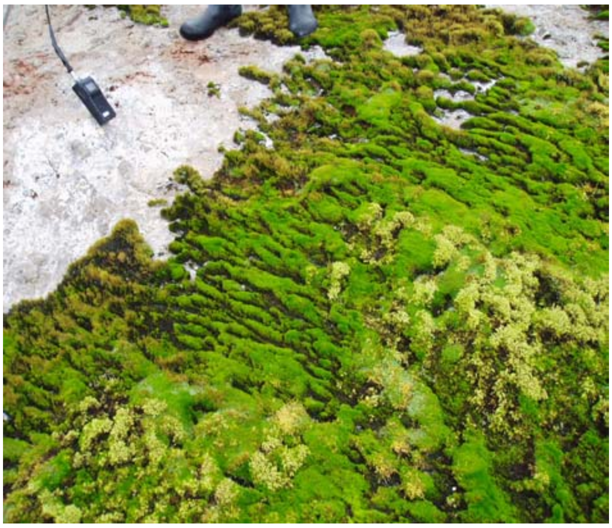

FIGURE 10: Hot ground with colourful moss

water tables within the area, both true ones and false.

5.5 Hot and warm grounds

Warm ground characteristically surrounds the hot ground within the thermal manifestations (Figure 5). The distinction between warm ground (above 15°C), and hot ground (above 50°C) is somewhat arbitrarily fixed at these two isotherms. Soil temperatures on sunny days can easily reach 12°C, but not much higher, so the 15°C isotherm is convenient in the climatic condition of Iceland for delineating geothermal heat. In warmer countries like Tanzania for example, a higher temperature isotherm would need to be chosen for similar mapping. Within the warm ground, vegetation colour typically changes to a more yellowish colour with increasing heat (Figure 9).

5.6 Steaming ground

Steaming ground indicates a boiling water table at relatively shallow depths. The soil temperature in such areas is close to 100°C. The steaming grounds observed are characterized by yellowish green to grey wilting moss (Figure 10) and a bare whitish brown surface. They are easily recognized from a distance. The soil, where present, is often clayish; white calcite may be seen and occasionally yellow native sulphur.

5.7 Hydrothermal alteration

Hydrothermal surface alteration, hot or cold, indicates the presence of a hydrothermal system beneath, either current or in the past. Therefore, mapping surface alteration is useful in delineating a hydrothermal system. The alteration intensity increases with increasing activity. By distinguishing between unaltered rocks (fresh or weathered) and slightly hydrothermally altered rocks, one can make a distinction between some hydrothermal activity and intense hydrothermal activity. Similarly, a distinction between slightly altered rocks and intensively altered rocks, which characteristically has altered completely to clays, is useful. Such mapping has been done for the entire Hengill area (Saemundsson 1995b). One of the aims of the present study was to review the existing map, using a detailed GPS survey, in order to confirm and/or add to it.

5.8 Surface alteration

Apart from the extinct (cold) surface alterations, active (warm or hot) surface alteration processes could be observed within the hot spring field; clay alteration to various degrees; iron oxide stains and precipitates, silica and aluminous rich light-coloured mud are seen, associated with the active manifestations. The distribution of slightly altered cold ground and extensively altered cold clayish ground is shown in Figure 5, while the clayish grounds within the hot areas are camouflaged within the 15°C and 50°C isotherms. The slightly altered ground is characterized by yellow-brown to red-brown soils, gravel and bed rock. At a depth of 0.1-0.3 m within the field of slight alteration, temperatures measured less than 9°C. The largest hydrothermal surface manifestations all occur within the relatively young rock slide shown on the geological map in Figure 4. Hardly any surface alteration is seen within the slightly older Tjarnarhnúkur lava, although it does not mean that the hydrothermal surface alterations (now near the surface) were not more widespread within the Ölkelduháls-Hrómundartindur hyaloclastite ridges. Some alteration is seen on the flanks of the lava in the south, while the presently mapped surface manifestations within the lava at low ground level in the western part of the study field may indicate hydrothermal activity younger than the Tjarnarhnúkur lava. The other alternative for explaining the altered superficial deposits would be to connect it to run-off deposits from the altered grounds above.

Compared to the existing map (Saemundsson 1995b), the distribution of the surface alterations is very similar; a few minor alteration spots have been added on the low ground west of the main field within the rock slide.

The most obvious conclusion that can be drawn from the distribution of the hydrothermal manifestations within the rock slide, and the distribution of the host rocks within the field, is that the presently active field existed within the very same field in late glacial time and early Holocene time, prior to the eruption of the Tjarnarhnúkur lava. The Tjarnarhnúkur lava flowed over the active hydrothermal field, which somewhat later collapsed under the weight to form the very prominent rock slide which, to a large extent, is composed of the lava itself and to some extent by the underlying hyaloclastite. Whether the heat supply to the active hydrothermal field increased or not with the Tjarnarhnúkur eruption remains speculative. The distribution of the active hydrothermal fields and the relatively young volcanic fissures of the Hrómundartindur and Tjarnarhnúkur eruptives are unlikely to be coincidental but rather the opposite.

6. GEOTHERMAL MODEL

In order to envisage the underground conditions of the researched area, a hydrothermal model along the cross-section line A-A' was drawn, based on the geological and geothermal maps (Figures 4 and 5). Also, near-surface data from wells HE-20 and HE-22 were used to model the near-surface lithology along the profile. The cross-section in Figure 11 (location of the cross-sectional line is shown in Figures 4 and 5) is used to show schematically the geothermal conduits to the surface manifestations. While a cooling intrusive complex is believed to be the heat source of the Ölkelduháls and the Hrómundartindur volcanic system at large, the chief effect of the Hrómundartindur- and Tjarnarhnúkur dykes and faults is to guide the geothermal fluids upwards. The model assumes a boiling geothermal reservoir at depth. Ascending steam and gas, boiled off from the hot reservoir at depth, flows upwards along fractures to shallower levels where it mixes with and heats up the local ground water and surface water systems.

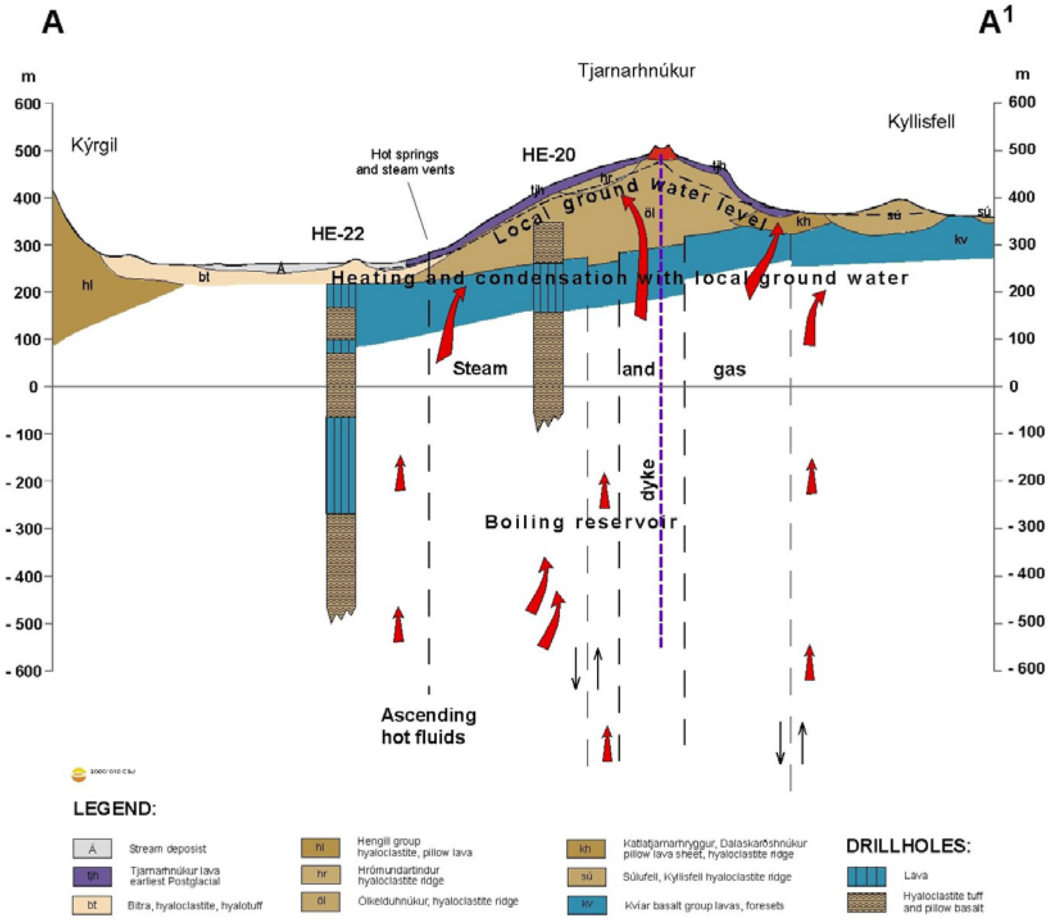

FIGURE 11: Cross-section showing the geothermal model of the Hrómundartindur area

7. CONCLUSIONS

Geothermal mapping was carried out in the Hrómundartindur area where all types of geothermal manifestations and surface alterations were mapped, along with the chief structural elements of the field. The geothermal manifestations on the surface are of relatively restricted distribution along the volcanic axes of the Hrómundartindur formation and the Tjarnarhnúkur lava, chiefly on its west side. A link to the Ölkelduháls geothermal system in the south is pretty clear, while the relatively young and unaltered Tjarnarhnúkur lava is believed to blanket the much more hydrothermally altered formation of the Ölkelduhnúkur hyaloclastite.

On the geothermal map, isotherms of >15°C and of >50°C delineate warm and hot fields pretty neatly. Intense clay alteration is mostly confined to the hot fields, while extinct clay alteration implies cooling within that part of the manifestations. A geothermal map of scale 1:3000 was produced, shown in a diminished scale in Figure 5.

While a cooling intrusive complex is believed to be the heat source of the Ölkelduháls and the Hrómundartindur volcanic systems, the chief effect of the Hrómundartindur- and Tjarnarhnúkur dykes and faults is to guide the geothermal fluids upwards. The model assumes a boiling geothermal reservoir at depth. Ascending steam and gas, boiled off from the hot reservoir at depth, flows upwards along fractures to shallower levels where it mixes with and heats up the local groundwater and surface water systems.

The following findings from the field are worth mentioning:

- Faults and fractures that control the flow of the hydrothermal fluids upwards are hidden underneath a major landslide.
- Calcite precipitation, attached to some hot springs and hot grounds, shows that there is diminishing geothermal activity, whereas the occurrence of native sulphur is taken to indicate the opposite.
- The local groundwater level affects the appearance of hot springs, mud pits and steam vents in such a way, that high groundwater table results in boiling hot springs, which then change to mud pits and eventually to steam vents upon lowering of the water level. This can vary between seasons.
- Colour changes in vegetated manifestations, revealing shades of yellow to green moss and grass, reflect temperature distribution pretty neatly, the yellower the hotter.

8. RECOMMENDATIONS

If Tanzania wants at least one geothermal power plant, the following can be recommended:

- More people should undergo training in various fields relevant to geothermal development, in surface geophysics and geochemistry, borehole geology and geophysics and reservoir engineering, for the purpose of increasing the number of qualified geothermal personnel.
- There is a need to create and increase awareness among decision makers and politicians on the importance of geothermal energy as a clean renewable energy source.
- The mobilization of funds for detailed geothermal resource assessment in my home country is strongly recommended.

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REFERENCES

Árnason, B., Theodórsson, P., Björnsson, S., and Saemundsson, K., 1967: Hengill, a high-temperature thermal area in Iceland. *Bull. Volcanologique, XXXIII-1*, 245-260.

Árnason, K., 1993: Relationship between resistivity and geothermal activity in basaltic rocks. English translation of a chapter in: *Geothermal activity at the Ölkelduháls field, resistivity soundings in 1991 and 1992*. Orkustofnun, Reykjavík, report OS-93037/JHD-10 (in Icelandic), 82 pp.

Árnason, K., Haraldsson, G.I., Johnsen, G.V., Thorbergsson, G., Hersir, G.P., Saemundsson, K., Georgsson, L.S., Rögnvaldsson, S.Th., and Snorrason, S.P., 1987: *Nesjavellir-Ölkelduháls, surface exploration 1986*. Orkustofnun, Reykjavík, report OS-87018/JHD-02 (in Icelandic), 112 pp + maps.

Björnsson, A., and Hersir, G.P., 1981: Geophysical reconnaissance study of the Hengill high-temperature area, SW-Iceland. *Geoth. Res. Council, Transactions, 5*, 55-58.

Björnson, A., Hersir, G.P., and Björnsson, G., 1986: The Hengill – Hellisheidi area in SW – Iceland: Regional geophysical survey. *Geoth. Res. Council, Transactions, 10,* 205-210.

Eysteinsson, H., Árnason, K., and Flóvenz, Ó.G., 1993: Resistivity methods in geothermal prospecting in Iceland. *Survey in Geophysics, 15,* 263-275.

Flóvenz, Ó.G., 1985: Application of subsurface temperature measurements in geothermal prospecting in Iceland. *J. Geodyn., 4*, 331-340.

Flóvenz, Ó.G., and Saemundsson, K., 1993: Heat flow and geothermal processes in Iceland. *Tectonophysics,* 225, 123-138.

Foulger, G., and Einarsson, P., 1980: Recent earthquakes in the Hengill – Hellisheidi area in SW-Iceland. *J. Geophysics, 47,* 171-175.

Gebrehiwot, K., 2005: Geothermal mapping in Western Ölkelduháls field, Hengill area. Report 7 in: *Geothermal Training in Iceland 2005*. UNU-GTP, Iceland, 61-82.

Hjartarson, Á., and Sigurdsson, F., 1993: *Hydrogeological map, Vífilsfell 1613 iii- SA-V 1:25,000.* Iceland Geodetic Survey, Orkustofnun, Reykjavík.

McNitt, J.R., 1982: The geothermal potential of East Africa. *Proceedings of the Regional Seminar on Geothermal Energy in Eastern and Southern Africa, Nairobi, Kenya,* 3-8.

Natukunda, J.F., 2005: Geothermal exploration in Eastern Ölkelduháls field, Hengill area, SW-Iceland. Report 14 in: *Geothermal Training in Iceland 2005*. UNU-GTP, Iceland, 247-264.

Pálmason, G., and Saemundsson K., 1974: Iceland in relation to the Mid-Atlantic Ridge. *Annual Review Earth Planet. Sci., 2,* 25-50.

Saemundson, K., 1967: *Vulkanismus und Tectonik des Hengill-Gebietes in Sudwest-Island.* Acta Nat. Isl., II-7 (in German), 195 pp.

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

Saemundson, K., 1995a: *Geological map of the Hengill area, 1:50,000.* Orkustofnun, Reykjavík.

Saemundson, K., 1995b: *Geological map of the Hengill area, 1:25,000.* Orkustofnun, Reykjavík.

Saemundsson, K., and Fridleifsson, G.Ó., 1992: *The Hveragerdi central volcano, geological description.* Orkustofnun, Reykjavík, report OS-92063/JHD-35 B (in Icelandic), 25 pp.

Saemundsson, K., and Fridleifsson, G.Ó., 1996. The Hveragerdi central volcano. An extended English abstraction from Saemundsson, K., and Fridleifsson, G.Ó., 1992: *The Hveragerdi central volcano, geological description.* Orkustofnun, Reykjavík, report GÓF-KS-96703, 13 pp.

Sigmundsson, F., Einarsson, P., Rögnvaldsson, S.T., Foulger G.R., Hodgkinsson, K.M., and Thorbergsson, G., 1997: The 1994-1995 seismicity and deformation at the Hengill triple junction, Iceland: triggering of earthquakes by minor magma injection in a zone of horizontal shear stress. *J. Geophys. Res. 102 -B7*, 15151-15161.

Sigurgeirsson, Th., 1970. Aeromagnetic survey of SW-Iceland. *Science in Iceland, 2,* 13-20.

Thórdarson, T., and Höskuldsson, A., 2002: *Iceland.* Terra Publishing, Reykjavík, 200 pp.