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GEOTHERMAL EXPLORATION IN EASTERN ÖLKELDUHÁLS FIELD, HENGILL AREA, SW-ICELAND

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ABSTRACT

Ölkelduháls area is a part of the Hengill volcanic massif located in the western branch of the volcanic rift zone in SW-Iceland. It is a high-temperature geothermal field endowed with impressive geothermal manifestations which include warm springs, hot springs, mud pools, steam vents (fumaroles), warm grounds, hot grounds, travertine deposits, extinct clay alterations and slight bedrock alterations. The main rock formations in the area are basaltic compound lavas, hyaloclastites and pillow lavas which are altered to clays and iron oxides in the areas surrounding the active geothermal manifestations. The geothermal exploration carried out in the area involved mapping surface geothermal manifestations and shallow soil temperature measurements around the active manifestations to delineate the 15°C and 50°C isotherms. The results indicate that tectonic features control geothermal activity in the area. Five normal faults and four fractures were mapped based on the topographic features and alignment of the geothermal manifestations. There is a marked NW-SE trend in the geothermal manifestations from Klambragil valley to well HE-20, probably controlled by the suspected regional transform fault zone. However, on closer observation, most of the manifestations locally follow the NE-SW trend coinciding with most of the faults and fractures in the Ölkelduháls area. The feeder dykes of Molddalahnúkar appear to have created several fractures in Ölkelduhnúkur, enhancing the upflow of hydrothermal fluids and the occurrence of numerous manifestations. Most of the springs are carbonated and precipitate calcite and aragonite, an indication of vanishing geothermal activity. Extinct clay alterations and mineral scaling reduce the permeability of the bedrock which has caused subsequent extinction of geothermal activity in some localities.

1. INTRODUCTION

1.1 Background

The demand for electric energy in my home country, Uganda has increased tremendously in recent years at a rate of 2% per month. This prompted the government, through the Ministry of Energy and Mineral Development, to conduct a study in 2002 on the utilization of alternative energy resources available in the country. The study covered mini-hydro, geothermal, solar, peat, wind and biomass options. Additional hydropower developments have recently raised socio-economic and environmental concerns. Geothermal energy development and utilization, being environmentally benevolent, have been put high on the agenda to complement hydropower.

The western part of Uganda lies in the western arm of the East African Rift System, referred to as the Albertine Rift. It is endowed with a high geothermal potential that was previously estimated to be 450 MW (McNitt, 1982). Currently, preliminary investigations are being undertaken in the three prospects of Kibiro, Katwe and Buranga. There is need to complete preliminary work in the three prospects and to carry out preliminary geological investigations in other potential prospects. It is for this reason that the author was nominated to participate in the Geothermal Training Programme at United Nations University, Iceland.

Ölkelduháls high-temperature field belongs to Reykjavík Energy Company (Orkuveita Reykjavíkur). Geochemical and resistivity studies confirm that Ölkelduháls and Nesjavellir geothermal fields are not connected at depth and can, therefore, be independently exploited (Ívarsson, 1998). Ölkelduháls field has been earmarked as a potential field for future development of both electricity production and district heating. One deep exploration well (ÖJ-1) was drilled in Ölkelduháls in 1994 down to 1035 m. At this depth, it recorded a temperature of 200°C, less than expected. A second well (HE-20) is currently being drilled and is expected to reach beyond 2000 m depth. It is anticipated to register higher reservoir temperatures (about 300°C) as predicted from the gas geochemistry measurements.

The word "ölkelda" in Icelandic means bubbling mineral spring; be it cold, tepid or hot. Accordingly, the word Ölkelduháls would to Icelanders indicate a hill with numerous mineral springs. To geologists it would indicate a gas rich field. CO_2 is the dominant gas type in all ölkelda in the area.

1.2 Location and accessibility

Ölkelduháls is located in the Hengill volcanic massif east of Reykjavík and north of Hveragerdi town. The area can be accessed by taking the Reykjavík–Hveragerdi main road up to Orustuhóll (a distance of 30 km). Then branch off to the left a distance of 5 km northeastward following a gravel road that runs along the electric power line which crosses through Ölkelduháls. Alternatively, it can be reached by taking a 7 km hiking track that stretches from Hveragerdi town in a northwesterly direction (Figure 1).

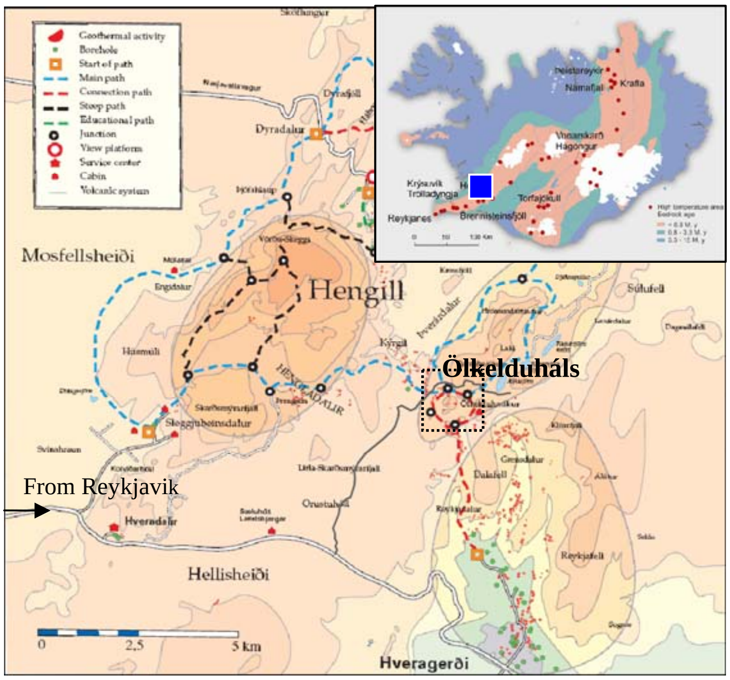

FIGURE 1: Location of East Ölkelduháls area (modified from Gunnlaugsson and Gíslason, 2003)

1.3 Topography and climate

The topography of East Ölkelduháls comprises volcanic hills and ridges elongated in a NE-SW direction with elevations between 280 and 460 m above sea level. They are mainly composed of bare volcanic rocks and in some places overlain by a thin layer of soil. Stream deposits (terraces) occur in two valleys. The main vegetation type is moss covering the volcanic rocks and Icelandic grass common in valleys and around geothermally altered areas. The area is drained by two rivers to the east and west. The river water is derived from the cold and hot springs along the hill slopes and valleys which collects into streams that form tributaries of the main rivers in a dendritic format.

The climate of the area is characterized by cold, windy winters and moderate summers. The area receives a high amount of rainfall annually. The daily weather can change rapidly in any season like elsewhere in Iceland.

1.4 Duration and aim of the study

Reconnaissance of the area was done in the first two days with the guidance of supervisors. This was followed by detailed geothermal exploration that lasted for sixteen days in August and September 2005. The fieldwork was not done continuously as it depended on the prevailing weather conditions each day.

The principle aim of the study was to carry out geological surveying in the area to map the geothermal manifestations, measure shallow sub-surface temperature to delineate the extent of geothermal activity, and trace and map faults and fractures. The relationship between tectonic structures and the geothermal activity was highly emphasized. The information obtained is useful for the strategic siting and location of exploration wells.

1.5 Previous work

A great deal of research work has been done in the Hengill area by different scientists in relation to the geology and geothermal activity. Only a few relevant publications related to Ölkelduháls are mentioned here. Saemundsson (1967) mapped the Hengill mountain and produced a 1:25,000 scale geological map. Björnsson and Hersir (1981) summed up results of a geophysical reconnaissance study of the Hengill area using DC resistivity soundings, aeromagnetic measurements, magnetotelluric measurements and seismics. A low-resistivity anomaly at 400 m depth that covers 120 km^2 was formed to delineate the geothermal area. The aeromagnetic map produced shows negative anomalies caused by hydrothermal alteration. K. Saemundsson carried out, with a team of geologists (S. Snorrason, G.I. Haraldsson and G.Ó. Fridleifsson) a more detailed geological mapping and compiled the bedrock geology map of the Hengill area in a scale of 1:50,000 (Saemundsson, 1995a). They also compiled the geothermal map of the same area in a 1:25,000 scale that shows thermal activity, alteration and hydrology (Saemundsson, 1995b).

2. GENERAL GEOLOGY

2.1 Summary of geological and geotectonic setting of Iceland

Iceland is located at the junction of the Mid-Atlantic Ridge and the Greenland-Iceland-Faeroe Ridge, the former being a part of the global mid-oceanic ridge system (Figure 2). Iceland is regarded as being a hot spot above a mantle plume, and has been piled up through emissions of volcanic material, grown by rifting and crust accretion through volcanism along the NE – SW axial rift zone sometimes referred to as neovolcanic zone (Figure 3). Currently, the plume channel reaches the lithosphere below the northwest part of Vatnajökull glacier. The buoyancy of the Icelandic plume leads to dynamic uplift of the Iceland plateau, and the high volcanic productivity over the plume produces a thick crust. The western part of Iceland that lies west of the volcanic zones belongs to the North American plate and the eastern part to the Eurasian plate. The rate of spreading is estimated to be 1 cm in each direction per year. Iceland is one of the few places on Earth where an active spreading ridge can be observed above sea level. As new crust is created along the rift zone, old bedrock moves further from the plate boundary. Therefore, the oldest rocks exposed on the surface in Iceland, formed about 16 million years ago, occur in the easternmost and westernmost parts of the country (Figure 3).

The active periods of the volcanic systems have been found to vary from 300,000 years to over 1 m.y. They are preserved as entities in the volcanic pile, indicating that they grew, drifted off towards the margin of the volcanic zone and then became extinct. New ones replaced them over the more or less stationary deep-seated zone of magma generation (Saemundsson, 1967).

The volcanic rift zone is connected to the Atlantic ridge across transform faults in both North and South Iceland. In SW-Iceland, the volcanic rift zone is divided into two separate parallel zones characterized by several fissures and fault swarms. The two branches are connected by the E–W trending South Iceland Seismic Zone (Saemundsson, 1978). Thus, the Hengill area is located just north of a triple junction where an oblique spreading ridge, tensional spreading axes and a major seismic zone meet. The tensional spreading in the axial rift zone is the most dominating tectonic feature of the Hengill area. The orientation of the faults and recent eruptive fissures in the zone is N–S, reflecting a change from an extensional fault to a shear fault mode of deformation (Walker, 1992). Local seismicity studies suggest that deformation occurs on N–S oriented fault planes.

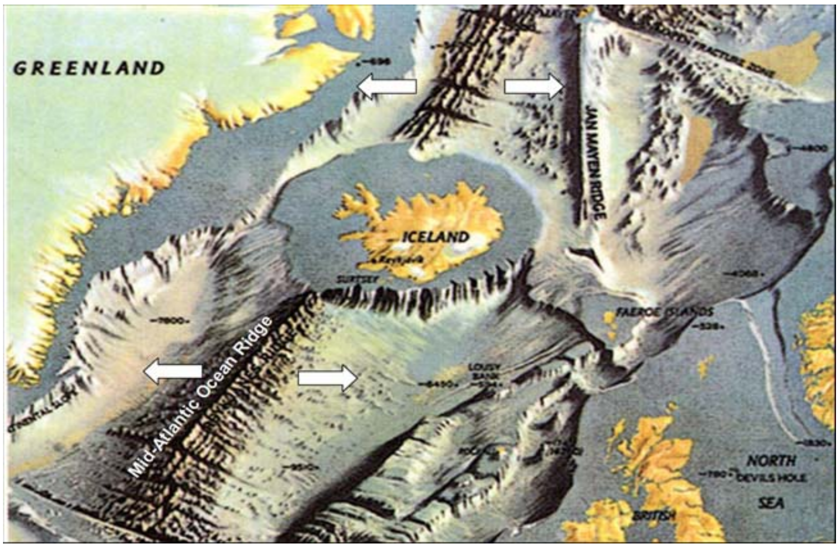

FIGURE 2: Iceland in relation to the Mid- Atlantic ridge

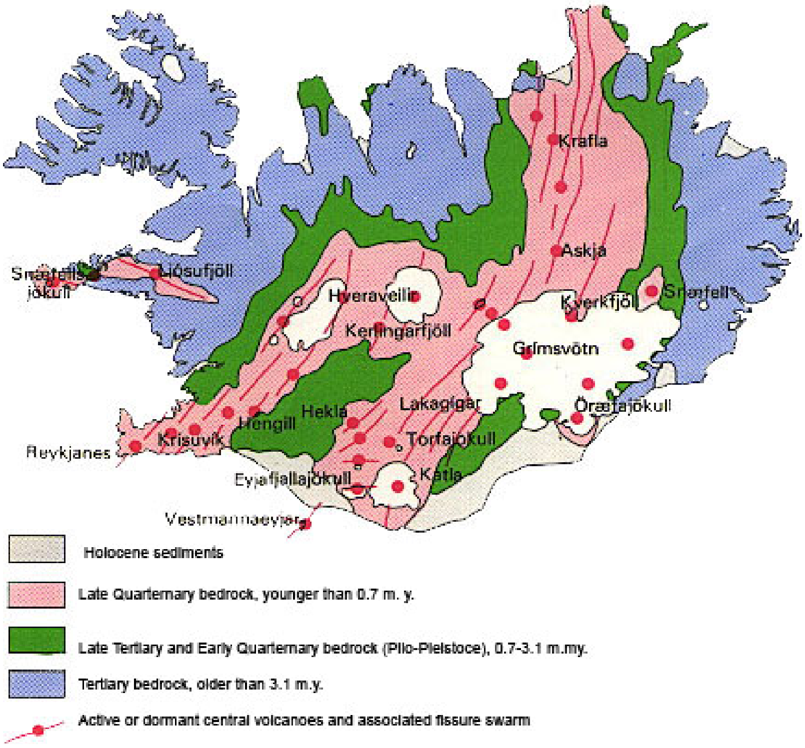

FIGURE 3: Map of Iceland showing distribution of central volcanic systems within the volcanic zones and age of bedrock (H. Jóhannesson, personal communication)

The axial rift zone is characterized by numerous volcanic systems. Each system consists of an active volcano, where lava production is abnormally high, and an associated fissure swarm transecting the central volcano (Saemundsson, 1978). The major volcano-tectonic activity is episodic and occurs almost every 100 years in SW-Iceland. Almost all the high-temperature areas in Iceland are situated within a central volcano or a fissure swarm indicating that the main heat source must be magmatic intrusions in the upper crust.

The exposed part of Iceland is composed of 80–85% basalt, and 10–15% intermediate and acid rocks (Saemundsson, 1979).

2.2 Geology and tectonics of the Hengill area

The Hengill high-temperature area is located in the western branch of the volcanic rift zone in SW-Iceland and is characterized by tensional stress parallel to the spreading direction. Other high-temperature areas, which are a part of this zone are shown in Figure 3. The geology of the Hengill area is dominated by the central volcano, Hengill, which rises about 500 m above the surroundings. It is intersected by a fissure swarm over 50 km long, trending N30°W and has a structure of nested grabens. In addition to the major NE-SW fissure swarm, faults, and hyaloclastite ridges there are some faults and eruptive fissures transecting the centre of Hengill in a NW-SE direction through Ölkelduháls geothermal field towards the Hveragerdi system, i.e. perpendicular to the main tectonic trend (Saemundsson, 1967).

The volcanic forms common in Hengill area are lava shields, eruptive fissures and explosion craters. The lava shields resulted in the formation of table mountains (tuyas) while eruptive fissures formed hyaloclastite ridges.

In Holocene time the Hengill system has erupted several times. Two thousand years ago, the Nesjahraun lava field flowed from the Kýrdalur fracture near Nesjavellir, and Sandey island emerged from the waters of Lake Thingvallavatn.

2.3 Geothermal activity in the Hengill area

The geothermal activity in Hengill area is connected with three volcanic systems (Figure 4). The geothermal area close to Hveragerdi village belongs to the oldest system, the Hveragerdi central volcanic system (Saemundsson and Fridleifsson, 1996). Northwest of this is a volcanic fissure system named after the Hrómundartindur ridge. The youngest eruption there produced the Tjarnarhnúkur lava about 10,000 years ago, a prominent feature in the author's field area. The geothermal heat source in the Öldukelduháls area is connected with the Hrómundartindur system. West of these volcanic systems lies the Hengill system, the youngest and the most active system of the three, located within the axial rift zone, and characterized by volcanic fractures and faults stretching from southwest through

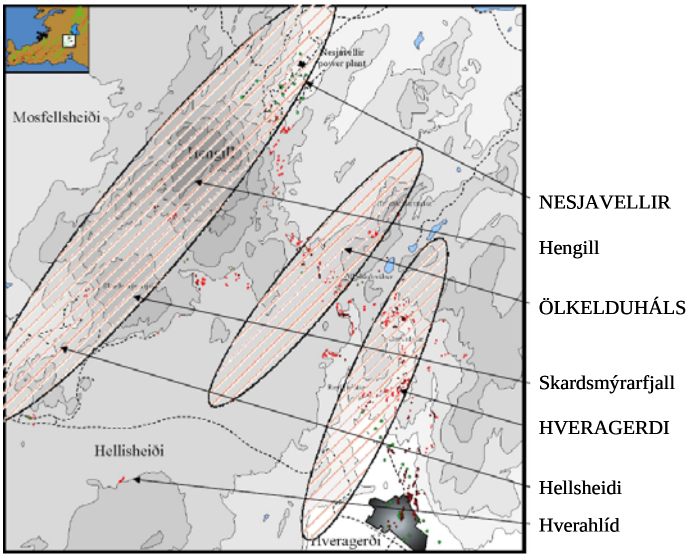

FIGURE 4: Volcanic systems of the Hengill high-temperature area, shown by shaded regions

Hellisheidi, Skardsmýrarfjall, Innstidalur, across the Hengill mountain, to Nesjavellir and across Lake Thingvallavatn in the northeast.

Research shows that precipitation falling on the highlands north of Lake Thingvallavatn seeps deep into the bedrock and flows underground to lower areas. As it comes in contact with the heat source within the Hengill system (cooling intrusions) the groundwater heats up and flows upwards as its density decreases upon heating, and a convection system is established. Deep reaching faults and fractures are structural traps guiding the hot fluids upwards.

A seismic study between 1993 and 1997 registered nearly 24,000 earthquakes exceeding 0.5 on the Richter scale in the Hengill area, 12,000 of these occurred in 1997 alone (Sigmundsson et al., 1997). The largest earthquake in recent times registered 5.3 on the Richter scale in June 1998. The earthquakes seem 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, personal communication).

The aeromagnetic measurements carried out in the area indicated negative anomalies, probably caused by hydrothermal breakdown of magnetic minerals within the active high-temperature system (Björnsson and Hersir, 1981). The micro earthquake study showed high seismic activity and some correlation of epicentres with the distribution of fumaroles (Foulger and Einarsson, 1980). The DC resistivity soundings showed a low-resistivity geothermal anomaly at 400 m depth of about 120 km^2. It also delineated a 50 km^2 resistivity high that represents the hottest central part of the Hengill geothermal area (Björnsson and Hersir, 1981). From Hengill, there is a lineation of surface manifestations extending from Nesjavellir towards the southeast into the Hveragerdi volcano. It coincides with a low-resistivity anomaly connecting the Hengill area and the extinct Hveragerdi central volcano. It shows an anomaly perpendicular to the main fissure swarm and parallel to the transverse lineament in the Hengill system (Björnsson et al., 1986).

3. GEOLOGY OF EASTERN ÖLKELDUHÁLS

The published geology map of the Hengill area (Saemundsson, 1995a) and aerial photographs were used to study the geology and tectonic structures of Eastern Ölkelduháls. The following was done:

- Reconnaissance survey;
- Traverses to observe the lithological units, and
- Mapping of tectonic structures in the area.

The Eastern Ölkelduháls study area is located within the Hrómundartindur system, in the middle of the the greater Hengill volcanic complex (extending from Hengill to Hveragerdi). The bedrock in the study area is mainly comprised of six volcanic units named after the hills in which they occur. They are in a downward chronological order, Holocene Tjarnahnúkur lava (*tjh*), the fini-glacial Bitra lava-hyaloclastite formation (*bt*), Molddalahnúkar (*mo*) pillow formation, Ölkelduhnúkur (*öl*) hyaloclastites, Katlatjarnahryggur – Dalaskardshnúkur (*kh*) hyaloclastites and Kvíabasalt (*kv*) lavas. Stream sediments and a glacial moraine occur in two localities in lower areas while rock slides, screes and soil constitute the overburden (Figure 5).

A vertical basaltic dyke with the same strike as the Molddalahnúkar volcanic axis was mapped in the river canyon northwest of Klambragil valley. It marks a feeder zone through which the Molddalahnúkar pillow lava erupted. It intrudes the older Ölkelduhnúkur formation, creating multiple fractures and faults that constitute pathways for hydrothermal fluids.

3.1 Lithological units

kv: The Kvíabasalt (*kv*) lava occurs in the western part and is the oldest formation in the studied area. It was formed during an interglacial period (probably Holstenian) about 120,000 – 130,000 years ago. It consists of plagioclase phyric lava. The lava flow dips northeastward at an average of 6°.

kh: The Katlatjarnahryggur – Dalaskardshnúkur (*kh*) formation is a glacial (probably Saalian) hyaloclastite with variable phenocryst content and forms Dalaskardshnúkur ridge in the western side of the studied area. The ridge is a part of the Katlatjarnahryggur – Dalaskardshnúkur volcanic ridge that extends 5 km in NE-SW direction. At Dalaskard, it occurs as a subglacial pillow lava sheet. The *kv* formation originated in the Hveragerdi volcano southeast of the Hengill volcanic system.

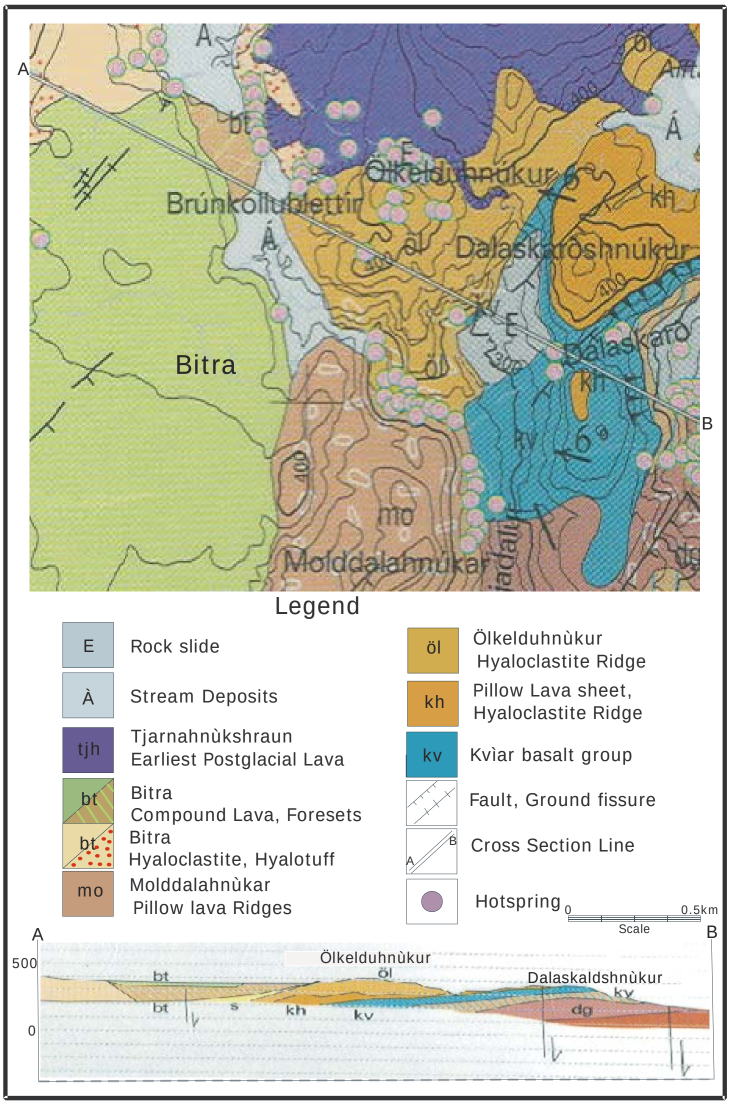

FIGURE 5: Geological map of Eastern Ölkelduháls (modified after Saemundsson, 1995a)

mo and öl: These are Weichselian (glacial) hyaloclastite and pillow lavas ridges of olivine basalt composition (Saemundsson, 1967). The formations constitute the Molddalahnúkur and Ölkelduhnúkur ridges which are parts of the Núpafjall – Stapafell volcanic row that stretches about 14 km in a NE-SW direction. Both *mo* and *öl* are basically aphyric in appearance. Much of *öl* is highly altered due to the prevailing geothermal activity within the Ölkelduhnúkur hill. In places of high geothermal activity, the hyaloclastite and pillow lava have been completely altered locally into pink grey clayish earth. The *mo* formation is insignificantly altered except for its northern part bordering the Klambragil valley. At that point, it is dissected by a river in a hanging valley with fractured pillow lava structures.

bt: The western part of the studied area is covered by a finiglacial lava shield and hyaloclastite of the Bitra formation. It is about 12,000 years old and erupted subglacially at the beginning but surfaced and erupted subaerially at the Bitra crater located at Kýrgilshnúkur, producing the Bitra lava shield. The plagioclase porphyritic Bitra formation is divided into three lithofacies. The largest part of it is composed of compound subaerial lava that extends southwards to Ástadafjall and down to Hamarinn near Hveragerdi. The second facie, forming the northern part of the Bitra, consists of hyaloclastite tuffs which are underlain by the third lithofacie, pillow lavas and lava foresets. Several lava margins appear as terraces within the uppermost lavas, suggesting different episodes of lava flows.

The drill-hole cuttings from well ÖJ-1 show that the Bitra formation extends down to 124 m depth and is mainly composed of pillow basalt (Steingrímsson et al., 1997). The on-going drilling at well HE-20 has indicated basaltic tuff with plagioclase phenocrysts and porphyritic basalt of the *bt* formation down to 60 m depth and porphyritic hyaloclastites believed to be part of the Hrómundartindur (*hr*) unit. Plagioclase-phyric basalt is intercepted below 60 m depth, underlying *hr* hyaloclastites may possibly belong to the *kv* lava, the oldest lava flows in the area. The *öl* formation apparently does not seem to extend to this site as it has not been intercepted.

tjh: The Tjarnahnúkshraun (*tjh*) lava erupted 11,000 years ago from the Tjarnahnúkur crater near the southern end of the Hrómundartindur ridge. It flowed mainly to the north along the Ölfusvatnsá river. Part of it flowed southwards and overlies the northern part of the Ölkelduhnúkur ridge. It is coarse-grained with plagioclase-olivine-pyroxene porphyritic basalt (Saemundsson, 1967). The lava forms the northern part of the studied area. As the lava flowed from the crater, it blanketed the geothermal manifestations prevailing north of the Ölkelduhnúkur hill.

Only the *tjh* lava rocks around the hot springs and hot grounds have undergone intense geothermal alteration; the rest of the lava appears more or less unaltered. Excavations at HE-20 showed that *tjh* overlies extinct clay alterations of *bt* hyaloclastites (Figure 6). At the surface, there is virtually no indication of alterations. This suggests that the geothermal manifestations covered a larger area before the *tjh* lava flows.

FIGURE 6: Extinct clay alteration (grey material) underying *tjh* lava at HE-20

Stream sediments: These occur at two localities in the northwest and northeast parts of the studied area and they were deposited during the finiglacial period. They are made up of several layers of clays, sandy soils and sedge peat material (Figure 7). The occurrence of peat indicates that a swamp with sedge vegetation prevailed in the area after the last glaciation.

Moraine: Moraine deposits occur underlying the stream deposits at the northwest end of the Klambragil valley. They were deposited during the last glaciation when the valley was formed. They are composed of lava boulders and hyaloclastites cemented by glacial silty clay.

FIGURE 7 : Clay, sandy soil and sedge peat layers (dark) in stream sediments in the western side of the study area

Rock slides, screes and soils: A big rockslide occurs between the Ölkelduhnúkur and the Dalaskardshnúkur ridges. It is believed to have formed in early Holocene time. It is characterized by brecciated hyaloclastite boulders and, typically, cold springs emanate from beneath it. Various small-scale rock slides also occur in several places in steep slope areas, especially in the Klambragil valley.

Prominent screes are derived mainly from the pillow lavas and hyaloclastite breccia covering the steep slopes on the eastern side of the Molddalahnúkar hills and Ölkelduhnúkur overlooking the Klambragil valley.

Fine brown soils, mostly from weathering of hyaloclastite and pillow lavas, form the topmost layers in most parts of the area except in steep slopes.

3.2 Tectonic features of Ölkelduháls

Ölkelduháls is tectonically active. Previous seismic studies carried out in the area indicated that an unusually intense seismic activity was centred around the Ölkelduháls and Grensdalur area since the summer of 1994 – 1995. It consisted mostly of minor earthquakes and several larger ones, which registered 4 and 5 on the Richter scale, causing some minor changes in the geothermal activity. A vertical movement of 2 cm was interpreted as minor magma injections occurring underneath the Ölkelduháls area at a depth of 6 km (Sigmundsson et al., 1997). Similar seismic swarm activity later took place in the Hellisheidi area in 1999, southwest of the present study area.

East Ölkelduháls is characterized by several faults and fractures most of which follow the NE–SE regional structural trend of the Hengill system. Two NE–SW striking faults occur parallel to each other in the eastern part of the study area and are already marked on the 1:50,000 scale geology map of the Hengill area (Saemundsson, 1995a). The geothermal manifestations in the valley between Ölkelduhnúkur and Dalaskardshnúkur ridges are related to these faults (see later). The author noted that the fault along the valley appears to extend southwestwards towards Klambragil valley. No fractures of the study area were shown on the published geology map, apart from one within the Bitra formation.

The volcanic axis south of Ölkelduháls exhibits a predominant NNE–SSW trend from Molddalahnúkar to Ölkelduhnúkur. It then swings in a NE–SW direction from Ölkelduhnúkur towards the Tjarnahnúkur crater. This explains why the strikes of faults and fractures in the area change in the same manner (see geothermal model).

The preliminary study of faults occurring in East Ölkelduháls was done using aerial photographs covering the area. Three fault / fracture patterns, trending NE–SW and N–S were identified. Field ground – verification and interpretation confirmed the NE – SW, while the N – S was interpreted as a fracture (see below).

Inferred faults: Based on the preferred alignment of the geothermal manifestations, limited topographic features and the orientation of the 15°C isotherms, the author inferred four NE–SW striking faults (see later). They all appear to be normal faults cutting through the Ölkelduhnúkur hill, extending towards Klambragil valley and disappearing in the Molddalahnúkar undulating hills. The disappearance suggests that the faults are older than Molddalahnúkar formation and are probably dormant. They can be traced on aerial photographs covering the area. Topographically, the faults exhibit slight surface depressions and aligned ravines. At the northern part of Klambragil valley the faults can be traced in the hanging pillow lava structures that characterise the deep river-cut canyon.

Inferred fractures: The author inferred two NNE–SSW striking fractures that appear to cross – cut the NE–SW inferred faults in Ölkelduhnúkur hill. One fracture manifests itself in a 15 m line of fumaroles on the northern slopes of Ölkelduhnúkur hill. Two other perpendicular N–S and E-W fractures were mapped in the Klambragil hot spring valley (Figure 8). The river that originates from the western side of the studied area flows alongside the fractures. Hot water from the hot springs heats up the cold river water and also increases its volume. The junction of the two fractures is characterized by a series of warm springs whose temperatures range from 9 to 21°C. The springs flow from the fractures in the *mo* pillow lava bedrock into the river.

The impressive geothermal manifestations at the northwestern end of the valley, which include powerful steam vents, strong erupting hot springs, hot grounds and mud pools, suggest a NE–SW fault cutting through the area.

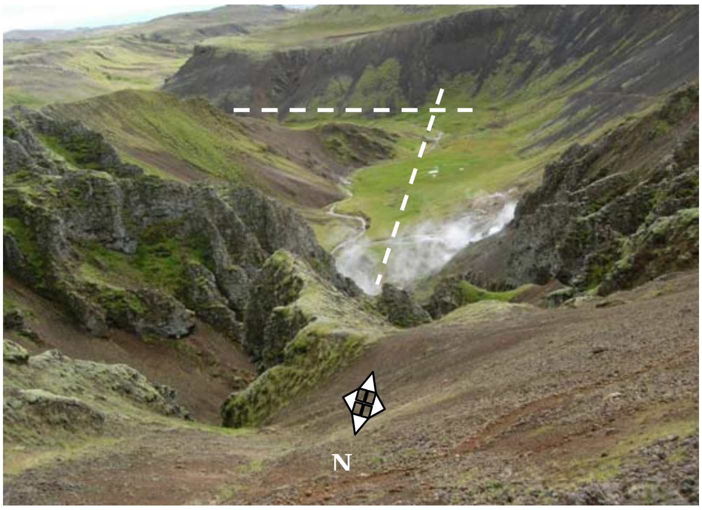

FIGURE 8: Inferred fractures at Klambragil valley

4. GEOTHERMAL EXPLORATION

Geological surveying is the prerequisite to understanding the underlying geological structures and hence the nature of a geothermal resource. It creates awareness of the likely pathways of the geothermal fluid flow and the fault/fracture mechanism. A good perception of geological characteristics of the reservoir and its surrounding area is of paramount importance for the construction of a credible geothermal model of the reservoir.

Previous fumarole gas geochemistry studies in Ölkelduháls area show that sub-surface temperatures may reach 300°C, which is attractive for exploitation (Ívarsson, 1998).

4.1 Methodology

Soil temperature measurements are important for identifying aquifers in places where structures intersect (Flóvenz, 1985). In carrying out the geothermal exploration in the study area, the following was done:

- Mapping surface geothermal manifestations; and
- Measuring shallow soil temperatures.

During the mapping of the geothermal manifestations, areas covered by vegetation were regarded as being unaltered.

Temperature measurements in the soils around the warm and hot geothermal manifestations were done to delineate the 15 and 50°C isotherms. The 50°C isotherms indicate areas of high geothermal activity while the 15°C isotherms show the extent of geothermal activity in the vicinity of the manifestations. The soil temperature was measured by a digital thermometer connected by a cable to a 1 m long metallic rod fixed with a thermistor tip. The measurements were done by carefully inserting the rod into the soil to 0.3-0.5 m depth except in places where the soil layer was thin. The 15 and 50°C isotherms were tracked and recorded using the Global Positioning System (GPS). The local points of geothermal manifestations and tectonic structures were also taken and recorded by GPS. The data obtained was downloaded into the computer after each field day and then edited using the *Map Source* programme. The final processing and production of the 1:2000 geothermal map (Figure 9) of the area was done using an *Arc Info* program. The map also shows inferred faults and fractures. The temperature measurements were done over a one-month period and it was assumed that the annual variations in temperature of the area did not affect the results. The limitations of the survey included the following:

- Thin soil layers made it virtually impossible for the temperature probe to penetrate up to the preferred 0.5 m at some investigated sites.

- Very steep slopes with loose rock scree at some geothermal manifestations hampered consistent tracking of the isotherms. In one locality in the Klambragil valley the 15°C track had to be inferred.
- In some places the isotherms would extend into steep rocky surfaces and cliffs.

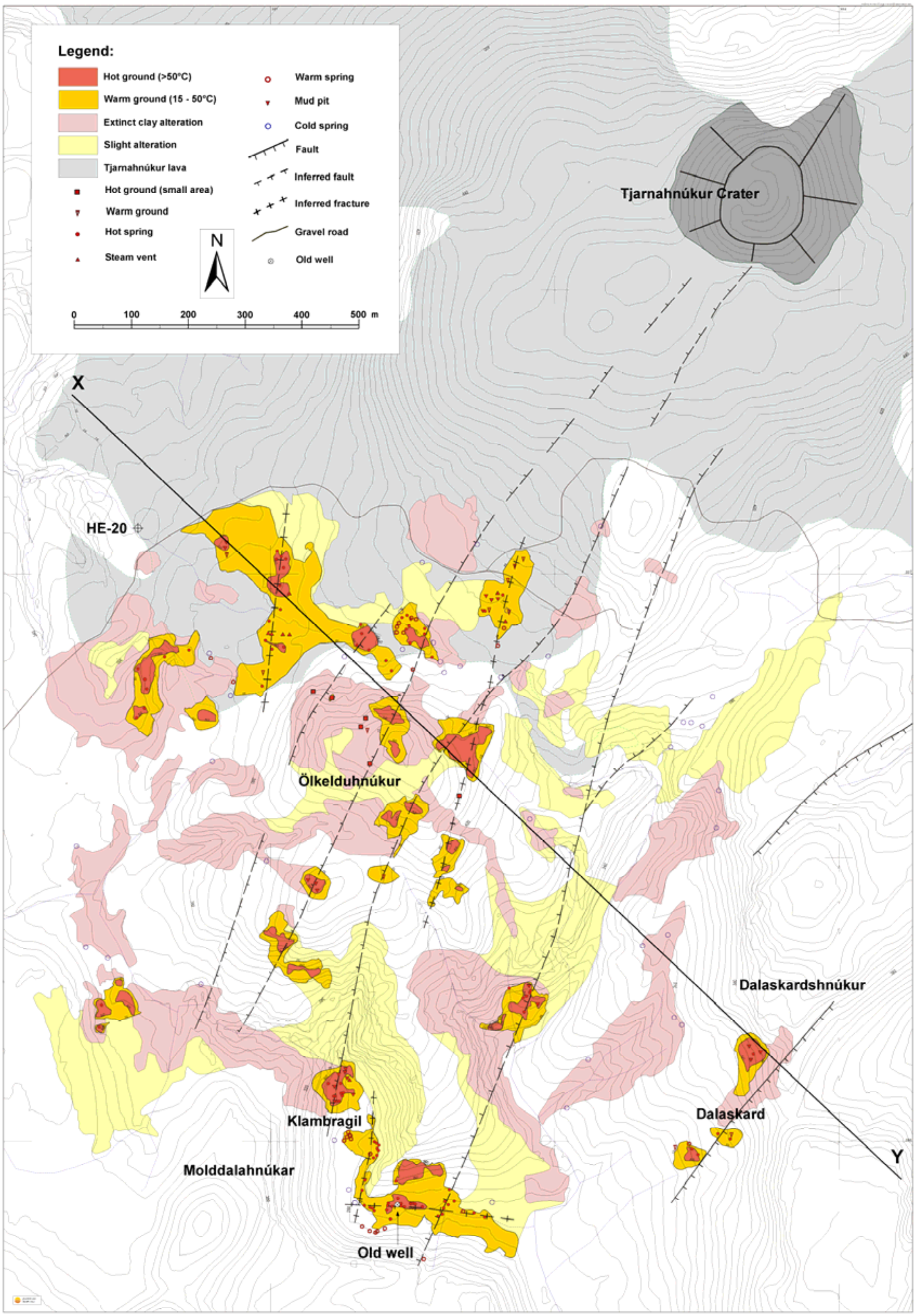

FIGURE 9: Geothermal map of Eastern Ölkelduháls high-temperature area

4.2 Geothermal manifestations

The geothermal manifestations that occur in the study area include warm springs, hot springs, mud pools, steam vents (fumaroles), warm grounds, hot grounds, travertine deposits, extinct clay alterations and slight alterations (Table 1).

There is a notable relationship between groundwater level (water table), hot springs, mud pools and hot springs in the area. At low altitudes where the geothermal activity intercepts the groundwater level, hot springs and mud pools are common while at high altitudes, active geothermal areas are characterized by steam vents and non-steam hot grounds with hardly any hot springs or mud pools. It was, thus, concluded that when the water table lowers (in periods of less rain) some hot springs revert to mud pools and eventually to steam vents as the water table reduces further. In fact, most of the steam vents investigated showed this character.

TABLE 1: Manifestations mapped in Eastern Ölkelduháls

Manifestation	Total number
Boiling springs	15
Hot springs	73
Warm springs	12
Cold springs	32
Mud pools	10
Steam vents	22
Hot grounds	87
Warm grounds	12

4.2.1 Hot springs and water pools

In the studied area, the springs with temperatures exceeding 50°C were classified as hot springs. They define areas of greater geothermal activity. The clustered hot springs were mapped as one entity. They produce clear colourless to grey–brown muddy waters due to suspended clay particles. The water in these hot springs is meteoric water having percolated through the formations and is heated by the steam boiled off from the circulation zones of the geothermal system. Some hot springs show eruptive behaviour as noted at one site where a hot spring erupts to a height of 1 m. Some springs produce vapour saturated with H_2S which, upon condensing, deposits pale yellow sulphur coatings on vegetation and rocks. Others are boiling and the rest are simply hot with temperatures between 50 and 99.7°C. In most cases, many hot springs at different temperatures occur in one locality and have formed water pools in depressions caused by intense geothermal alterations and erosion. As a result, hot and warm streams flow out of them and collect into a river like the hot springs north of Ölkelduhnúkur hill and the Klambragil valley.

Most of the hot springs encountered in the area are carbonated. In some springs calcite has precipitated around them, typical of hot springs in high-temperature geothermal fields. Calcite precipitation also indicates that the geothermal activity is on the wane which is in conformity with the general trend of geothermal fields towards Hveragerdi. The source of the carbonated spring water is groundwater while the source of the CO_2 is emitted geothermal gas. The rocks surrounding the hot springs are intensely altered to grey, white or yellow-brown clays.

The hot spring at a 60 year old abandoned shallow drillhole in Klambragil has the highest flow rate estimated at 40 l/s at a temperature of 84°C. Two hot springs near by occur at the riverbed. They are identified by a coating of the gravel by red–brown iron oxides, which can be seen through the colourless river water. The hot river water (at 45°C) then mixes with the cold water (at 10.4°C) of the eastern river to give a mixture at 35-40°C, in which hikers bathe near the river confluence.

4.2.2 Warm springs

Springs with temperatures between 15 and 50°C were categorised as warm springs. They occur in the vicinity of hot springs especially in the Klambragil valley and in the valley north of Ölkelduhnúkur hill. Their origins could probably be:

- Run–off groundwater heated by the hot geothermal water and ascending steam which then flows to the surface through the fractures and faults.

- Cooling hot springs due to clay alterations and scaling, or diminishing geothermal activity. This can be observed at sites (near Dalaskard), e.g. where the warm springs are covered with brownish-green moss and grass floating over the seemingly extinct hot springs area.

4.2.3 Cold springs

The average regional groundwater temperature outside the Ölkeduháls area is about 4°C (Hjartarson and Sigurdsson, 1993). The groundwater in Ölkelduháls field is, however, heated geothermally and the average groundwater temperature is higher than the surrounding areas. Hence, all springs with temperatures below 15°C were classified as cold springs. Most of them occur along the intersect between Ölkelduhnúkur and Dalaskardshnúkur ridges, north of Ölkelduhnúkur hill and the presumed fracture junction in the Klambragil valley. Some flow from the fractures (joints) in the bedrocks as a result of raised groundwater level during heavy rains, while others occur in water-saturated land slides (rock slides). It was observed that as rainfall reduces, the flow rate of the springs reduces and some springs disappear. The cold springs in the area are recognised by characteristic brown-green boggy moss, reddish-brown scree and reddish-brown water due to the presence of iron oxides. Some springs have colourless water and some bubble out CO_2 and are, hence, classified as mineral springs.

4.2.4 Mud pools

Mud pools are very common in places of high geothermal activity. They occur in the vicinity of hot springs and some appear to be extinct hot springs. They are characterized by grey to brown boiling mud, sometimes bubbling and spreading around the pit. In some boiling mud pools, black scum of iron sulphides occurs. The majority of the mud pools had temperatures above 90°C.

4.2.5 Fumaroles (or steam vents)

Steam vents occur mostly in hot grounds especially in high altitudes or hill slopes where the water table is low. Most of them exhibit a characteristic hissing sound. Two steam vents at Dalaskard and Klambragil valley produce high-pressure steam and sound like silencers at the power plants. Their strong hissing sound can be heard in a radius of a kilometre when on raised ground. Strong steam vents and erupting hot springs indicate the occurrence of open fractures in their respective localities. At one site on the northern slopes of Ölkelduhnúkur hill, the fumaroles are aligned in a straight line in an inferred fault zone. The bedrock in the immediate vicinities of fumaroles is highly altered into grey, yellow-brown or pink clays with characteristic cracked and dry surfaces blown above the ground's surface by the steam. In some places sulphur crystallizes between and below the cracked surfaces in the clay alterations and the whole assemblage is, hence, referred to as a solfatara or sulphur heap (Figure 10). Native sulphur deposits out of the hot mixture of geothermal gases and steam that emanates from the boiling (or circulation) zone of the geothermal reservoir at greater depth. The deposits are common in fumarole areas with very hot grounds and high pressure steam vents (Table 2). Occurrence of sulphur implies greater geothermal activity and a high-

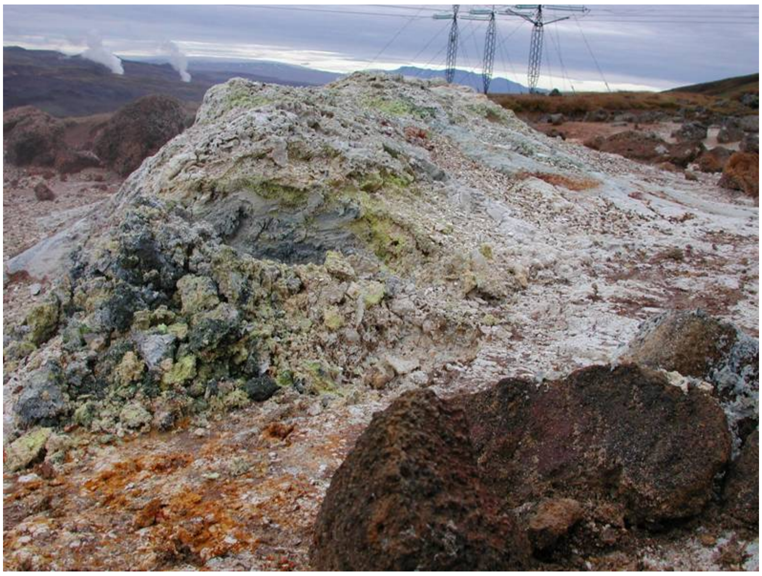

FIGURE 10: Solfatara and steam vents in a hot altered ground

temperature reservoir. Other minerals that crystallize on the surface are halloysite, pickeringite and sometimes langite.

TABLE 2: Solfatara sites in the eastern Ölkelduháls area

Way point	Location coordinates	Elevation (m)	Description	Tempereture (°C)
3	N64 03.513 W21 13.465	416	Steam vent	98.8
70	N64 03.551 W21 14.067	373	Hot ground	68.2
71	N64 03.555 W21 14.070	370	Hot ground	98.4
101	N64 03.391 W21 14.085	364	Hot ground	98.7
125	N64 03.453 W21 14.161	365	Hot ground	98.4
162	N64 03.057 W21 13.773	296	Steam vent	98.7
163	N64 03.062 W21 13.759	289	Steam vent	98.2
176	N64 03.046 W21 13.781	277	Steam vent	99.8
270	N64 02.966 W21 13.615	298	Hot ground	99
441	N64 03.377 W21 13.520	408	Hot ground	97.9
442	N64 03.375 W21 13.523	412	Hot ground	98.4
443	N64 03.372 W21 13.528	409	Hot ground	98.1
444	N64 03.370 W21 13.533	415	Hot ground	98.2
445	N64 03.366 W21 13.540	417	Hot ground	98
446	N64 03.362 W21 13.545	420	Hot ground	98
542	N64 03.085 W21 12.884	361	Steam vent	99.6
543	N64 03.092 W21 12.864	367	Steam vent	99.7
545	N64 03.098 W21 12.889	365	Steam vent	99.1

4.2.6 Travertine deposits

Travertine deposits occur around the old well in the Klambragil valley where several hot springs are aligned along an inferred fracture (Figure 11). The nearly calcite-saturated hot springs precipitate calcite that has piled up into travertine deposits in all springs around the old well. Some travertine deposits also occur north of the Ölkelduhnúkur hill.

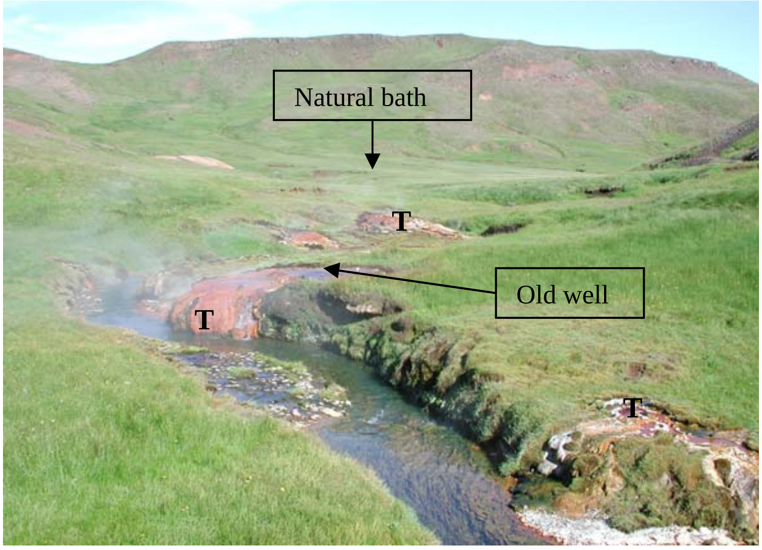

FIGURE 11: Travertine deposits around old well (marked by **T**s) in Klambragil valley; temperature of the hot spring is 84°C

4.2.7 Warm grounds

The grounds with temperatures between 15 and 50°C were mapped as warm grounds. They include isolated spots and areas between the 15 and the 50°C isotherms. They are widely distributed in the study area. In places with vegetation, warm grounds are characterized by bright yellowish - green moss and thick green grass (where temperatures are below 30°C). In bare grounds, warm grounds are easily identified by wet smooth clayey surfaces and in most cases with whitish or cream-white colouration of the surface due to calcite precipitation.

4.2.8 Hot grounds

Non-steaming grounds with temperatures greater than 50°C were mapped as hot grounds. They are a common manifestation in places of high geothermal activity i.e. in areas enclosed by the 50°C isotherm (Figure 9). Isolated hot ground units with temperatures above 50°C were also mapped. They are characterized by yellowish-green to grey wilting moss and bare whitish brown surfaces coated with amorphous silica, halloysite, pickeringite, and in some places calcite and aragonite which make them easy to recognise from a distance. At a site near Dalaskard black manganese compounds occur in combination with calcite and aragonite (Table 3). The bedrock which is either basaltic lava, hyaloclastite or pillow basalt is completely altered to white, grey or yellow-brown clayish material. All the hot grounds surveyed registered temperatures above 98°C at 0.5 m depth with the highest temperature of 99.7°C at Dalaskard and Klambragil, implying high geothermal activity in the area.

TABLE 3: XRD analyses of mineral samples collected from some geothermal manifestations

Sample	Location	Description
J1	N64 03.098 W21 12.889	Amorphous silica
J2	N64 03.098 W21 12.889	Mg – Silicate clays
J3	N64 02.993 W21 12.990	Calcite
J4	N64 02.993 W21 12.990	Mn – compounds
J5	N64 02.935 W21 13.636	Calcite, aragonite
J6	N64 02.935 W21 13.636	Very poorly crystalline Fe – oxides / hydroxides
J7	N64 03.371 W21 13.350	Amorphous silica (opal) with sulphur
J8	N64 03.190 W21 13.943	Amorphous silica (opal) with calcite and aragonite

4.2.9 Extinct clay alterations

The extinct clay alterations represent areas which previously experienced high hydrothermal activity for a long time. The bedrock had been completely altered to fine clay-rich geothermal mud, residual alteration minerals or mineraloid like iron oxides and silica mud. The XRD analyses of some clay samples from the areas indicate smectite, kaolinite and montmorillonite compositions (Table 4). The clay colours are mainly white, grey, yellow-brown and red-pink. The alteration clays and precipitated minerals (scaling) reduce the porosity and, hence, the permeability of the near surface bedrock. This shifts the geothermal activity from place to place within the manifestation. Due to the hydrothermal activity being extinct, the temperatures at 0.5 m depth are, in most cases, less than 10°C. In some places the extinct clay alterations are covered by eroded soils and grass as noted at well HE-20 drill site (Figure 6).

TABLE 4: Results of XRD analyses of clay samples from some extinct geothermal manifestations

Sample	d values for untreated samples (Å)	d values for glycolated samples (Å)	d values for heated sample (Å)	Description
N1	No peak	No peak	No peak	No clay
N2	14.33567	16.79548	10.14844	Traces of smectite
N3	No peak	No peak	No peak	No clay
N4	7.30865	7.30865	No peak	Kaolinite
N5	7.17778	7.17778	No peak	Kaolinite
N6	7.23502	7.23502	No peak	Kaolinite
N7	13.55174	13.55174		Mixed clays,traces of kaolinite
N8	No peak	No peak	No peak	No clay
N9	13.58995	13.58995	No peak	Smectite, montmorillonite

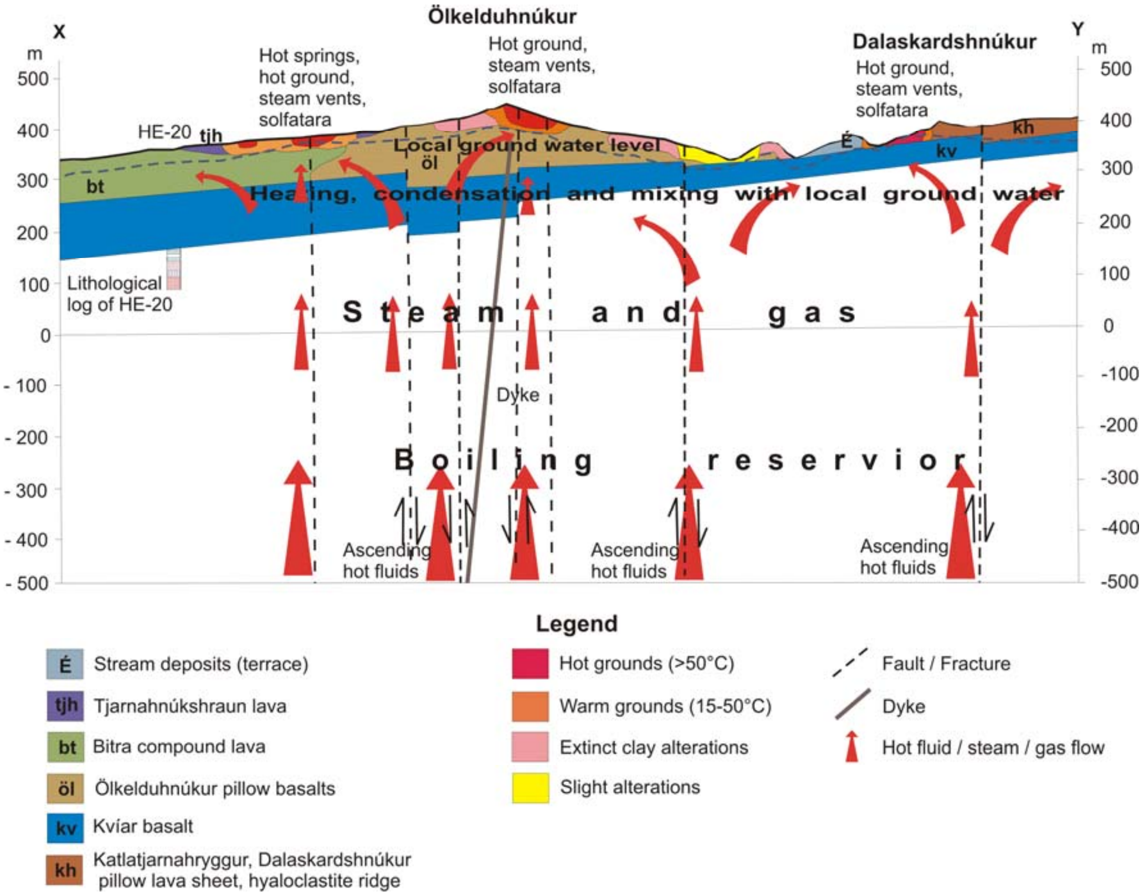

FIGURE 12: Geothermal model of the Eastern Ölkelduháls field

4.2.10 Slight alterations

Slight clay alterations are widespread in the Ölkelduháls geothermal field (Figure 9). They are characterized by yellow-brown to red-brown soils, gravels and bedrock. At 0.5 m depth the slight alterations measured temperatures less than 10°C. They represent extensive regional geothermal activity that prevailed in the area, probably subglacially during Pleistocene.

4.3 Geothermal model of the Ölkelduháls field

The geothermal model developed for the study area (Figure 12) is taken through the cross-section line XY shown in Figure 9. A cooling intrusive complex, believed to be the heat source underneath the Hrómundartindur volcanic system, heats up the groundwater descending through intrusive boundaries, faults and fractures. The lower density hot water then ascends upwards due to buoyancy which offsets further infiltration of cold water from the regional deep-seated groundwater source outside Ölkelduháls (highlands neighbouring Lake Thingvallavatn in the north). If the rising plume of hot water is hot enough boiling may occur at different depths, controlled by the boiling point with depth (BPD) curve. The NE–SW, NNE–SSW faults and fractures in the area act as upflow zones from which the hot geothermal manifestations emerge at the surface. Some of the run – off local ground water is heated by the steam from ascending hot water and flows out through fractures as warm springs. The hot springs and mud pools occur at the foothills of the Ölkelduhnúkur hill where the groundwater intersects the surface. Hot grounds and steam vents only occur at relatively low groundwater levels.

5. CONCLUSIONS

- There is a close relationship between the geothermal manifestations and the tectonic structures in the area. The faults and fractures act as outflow zones through which hydrothermal fluids find their way to the surface.
- The abundant fault–fracture system accounts for the occurrence of widespread geothermal manifestations in the Eastern Ölkelduháls geothermal field. This is why most of the Ölkelduhnúkur hill has undergone intense hydrothermal alteration.
- Extinct clay alterations and scaling decrease the permeability of country rocks and thereby block the pathways of the hydrothermal fluids. This shifts the geothermal activity within the area of relatively higher permeability while aligned above the same fracture or fault system. The perpetual shifting of the geothermal activity leaves an alignment of extinct clay alterations which partly form a basis for inference of either a fault or a fracture.
- Extensive geothermal manifestations occur in the area and that predate the Tjarnahnúkur eruptions that produced the *tjh* lava. Hence, the geothermal activity in the area is older than 11,000 years.
- Calcite precipitation in hot springs and hot grounds imply a diminishing geothermal activity. However, the occurrence of sulphur implies a high-temperature geothermal field.
- Earthquakes, which are common in the South Iceland Seismic Zone, reactivate the geothermal activity of the study area regularly. This has led to the emergence of new hot grounds in the area, especially on top of the Ölkelduhnúkur hill.
- The local groundwater level determines the occurrence of hot springs and steam vents in the area. If groundwater level lowers, hot springs regress to mud pools and eventually change to steam vents.

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