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GEOTHERMAL MAPPING IN MIDDALUR FIELD, HENGILL AREA, SW-ICELAND

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ABSTRACT

Middalur 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 and hot springs, mud pools, steam vents (fumaroles), warm grounds, hot grounds and clay alterations.

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 warm (>15°C) and hot (>50°C) isotherms within which many hot springs, mud pools, steam vents and warm springs occur. The results indicate that tectonic features control geothermal activity in the area. Eight faults, inferred faults and fracture were mapped based on aerial photographs, field studies and alignment of the geothermal manifestations. The trends of the geothermal manifestations are N-S, NE-SW and E-W. Most of hot springs precipitate calcite. The proposed geothermal model of the area shows the geothermal activity associated with active faults and fractures.

1. INTRODUCTION

1.1 Background

The Democratic Republic of Congo is located in the western branch of the East African Rift System, referred to as the Albertine Rift. It is one of those developing countries which suffers from a serious shortage of electricity. Only about 30% of the country has electricity coverage. Frequent power cuts also cause problems. In order to improve the electrical supply, the government wants to utilize its sustainable energy resources by 2030. Geothermal energy is one of the priority energy sources given the volcanic chain presence in the eastern part of the country that contains at least six volcanoes, two of which are active (Nyamulagira and Nyiragongo).

The purpose of this report is to stress the contribution of geothermal mapping in geological exploration. The first step of geothermal resource development is 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.

This study is a part of a six-month training course at the UNU-GTP in Iceland in 2015 which commenced in April. The first 2-3 months were used for course work, field excursions and practical training in various geothermal disciplines. The remaining 3 months were used for practical training in geothermal exploration, the results of which are described in this report. The objective of the study was to provide the author with training in geothermal mapping, using the Middalur field, part of the Hengill volcanic complex in SW-Iceland as a study area. This is a high-temperature geothermal field and the author was trained in exploring such an area and how to analyse, interpret and present the data which were gathered.

1.2 Previous work

Reconnaissance geological mapping (1:25,000 scale) of the Hengill area was carried out in the mid-sixties by Saemundsson (1967). Björnsson and Hersir (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 400 m below sea level, covering 110 km^2, was found to delineate the high-temperature geothermal area. The aeromagnetic map that was produced shows negative anomalies caused by hydrothermal alteration. K. Saemundsson and 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 and faults of the Middalur field were mapped in more detail, as digital mapping and GPS positioning accuracy enables and simplifies the mapping exercise.

2. GENERAL GEOLOGY AND TECTONIC OF ICELAND

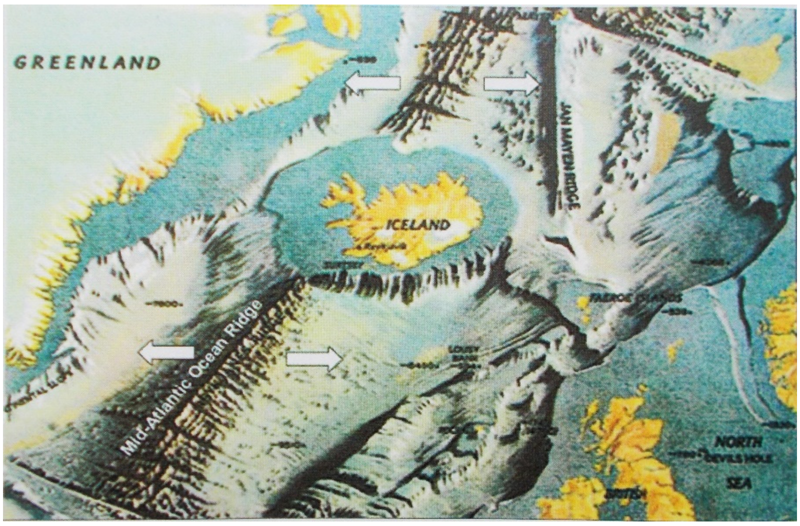

FIGURE 1: Iceland's location in relation to the Mid – Atlantic ridge

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 on the junction of the submarine Mid-Atlantic Ridge and the Greenland-Iceland-Faeroes Ridge. The Mid-Atlantic Ridge defines the constructive plate boundary between the American and the Eurasian plates. From magnetic anomalies to the north and south of Iceland, the spreading rate has been estimated as 2 cm/year symmetrically. The whole region is drifting slowly to the northwest with respect to the Iceland plume (Hardarson et al., 2008) (Figure 1). The Greenland-Iceland-Faeroes Ridge is thought to be the trail of the Icelandic hot spot which has been active from the time of the opening of the North Atlantic Ocean 60 million years ago.

Iceland is a geologically young island, known as the Icelandic basalt plateau, which rises more than 3000 m above the surrounding ocean floor and covers about 350,000 km^2, thereof about 103,000 km^2 being above sea level (Thordarson and Höskuldsson 2002).

Icelandic rocks are mainly composed of Tertiary plateau lavas, 3.3-16 Ma old (Moorbath et al., 1968; Watkins and Walker, 1977; McDougall et al., 1984; Hardarson et al., 1997), Plio-Pleistocene lavas (0.78-3.3 Ma) and hyaloclastites (0.01-0.78 Ma) formed subglacially and Holocene lavas (< 0.01 Ma) (Hardarson et al., 2008) (Figure 2). Approximately 85-90 % of the volume of Iceland above sea level is igneous rocks while some 10-15 % is consolidated sediments. Due to the shallow erosion level of the volcanic pile volcanic rocks predominate. Less than 0.5 % of the surface is intrusive and plutonic rocks (Saemundsson, 1980; Jóhannesson and Saemundsson, 1998).

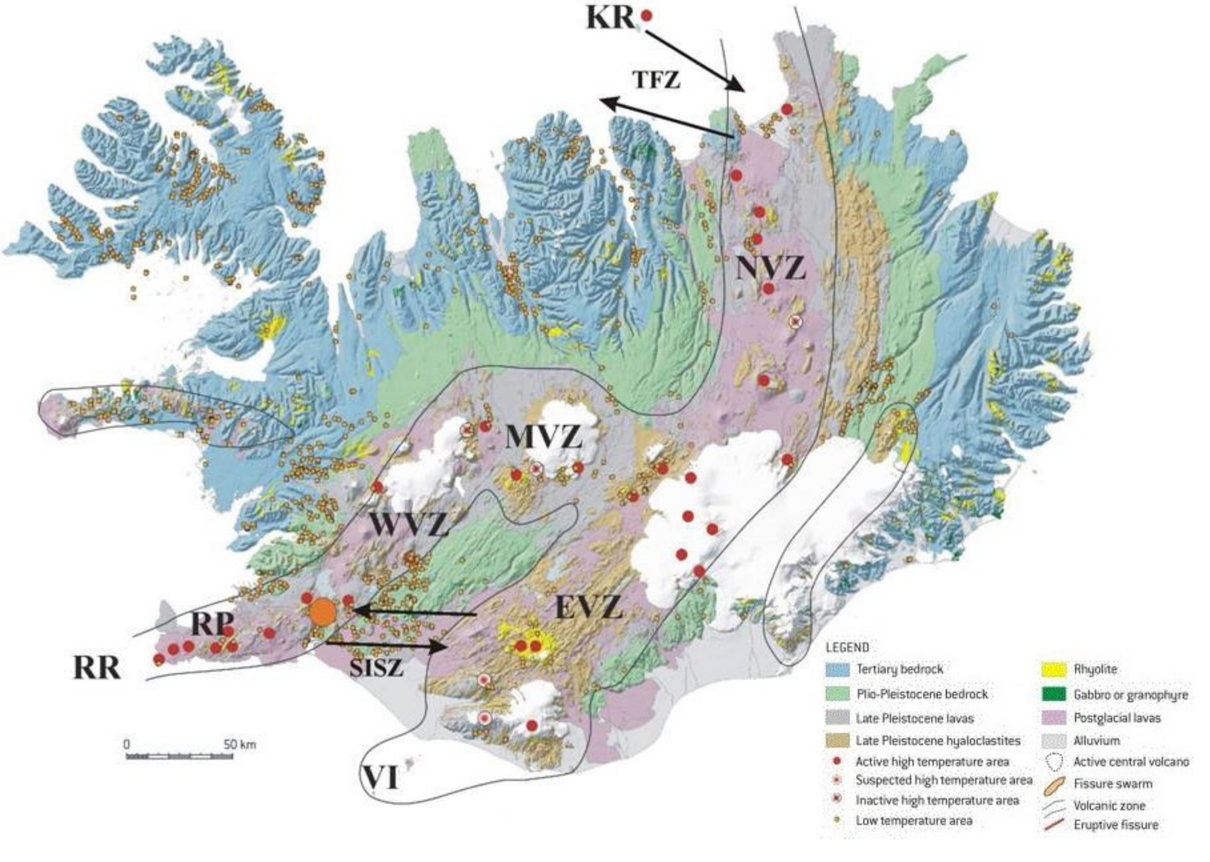

FIGURE 2: Geological map of Iceland showing the location of the active volcanic zones and transforms discussed in this paper. RR = Reykjanes Ridge; RP = Reykjanes Peninsula; WVZ = Western Volcanic Zone; MVZ = Mid-Iceland Volcanic Zone; NVZ = Northern Volcanic Zone; EVZ = Eastern Volcanic Zone; VI = Vestmanna Islands; SISZ = South Iceland Seismic Zone; TFZ = Tjörnes Fracture Zone. Red dots indicate high-temperature areas. Orange circle represents the approximate location of the Hengill volcanic system (from Hardarson et al., 2010)

Iceland owes its existence to the uprising Icelandic mantle plume and crustal accretion at the diverging American and Eurasian lithospheric plates. The movement of the lithospheric plate boundary in relation to the stationary mantle plume is responsible for the complicated tectonic and volcano-stratigraphic structure of Iceland, compared to the Mid Atlantic Ridge to the north and south of the country, and for the eastward shifting of the volcanic belts in Iceland (Ward and Björnsson, 1971; Saemundsson, 1974; Jóhannesson, 1980; Óskarsson et al., 1985; Einarsson, 1989; Hardarson et al., 1997). It is believed that the general tectonic trends in Iceland as seen today have remained the same for at least 24 Ma (Saemundsson, 1980).

According to Vink (1984), the Mid Atlantic Ridge axis moved on top of the mantle plume and then gradually west during Anomaly 6 (24–19 Ma ago). However, as the spreading ridge system in Iceland continues to drift NW with respect to the plume, it is periodically recaptured by the plume through the process of rift relocation or ridge jumping. This plume-ridge interaction has been a dominant process in the formation and tectonic evolution of Iceland (Hardarson et al., 1997, 2008). The volcanic belts in Iceland run SW-NE trending across the country (Figure 2). The plate spreading across the island is accommodated by several volcanic rift zones and two main transcurrent slip zones. In the south of the island, the Reykjanes segment of the Mid Atlantic Ridge comes on shore at the Reykjanes peninsula as an oblique rift zone and branches into the Western Volcanic Zone (WVZ) and the E-W trending South Iceland Seismic Zone (Saemundsson, 1978).

Plate spreading across South Iceland in the WVZ and the Eastern Volcanic Zone (EVZ) is accommodated by left-lateral E-W transform motion across the South Iceland Seismic Zone (SISZ) which connects two volcanic zones. The EVZ extends northward and continues as the Northern Volcanic Zone (NVZ) (Árnadóttir et al., 2008, see Figure 2).

These main fault structures, volcanic zones and belts that lie within these zones are called volcanic rift zones and are characterised by intense volcanic, seismic and high temperature geothermal activity (Gudmundsson and Jacoby, 2007; Thordarson and Larsen, 2007).

2.1 Geothermal aspects of Iceland

Geothermal activity in Iceland, which is related to the tectonic setting of the country, is mainly classified into high- and low-temperature fields and this classification is based on the geological setting and on temperature data from drill holes (Bödvarsson, 1961). Low-temperature areas are classified by their temperatures which are less than 150°C at 1 km depth while the high-temperature areas reach temperatures above 200°C at the same depth (Fridleifsson, 1979). The areas within the active rifting zones (Figure 2) are considered high-temperature fields, characterized by active volcanoes and fissure swarms. Their heat sources are cooling intrusions or other significant magma bodies. Low-temperature areas are mainly found outside the volcanic rift zones, such as in Quaternary and Tertiary formations. They are often fracture dominated systems and derive their heat from the hot crust conducted and pushed upwards along structures such as faults, fractures and dykes. Away from the fractures, the bedrock is less permeable and heat transfer is dominated by conduction. Few Icelandic geothermal fields have reservoir temperatures in the obvious temperature gap in the definition above which are sometimes called medium-temperature fields (Saemundsson et al., 2009).

3. HENGILL AREA

The Hengill area hosts one of the largest high temperature geothermal fields in Iceland. It is located around 30-50 km away from the city of Reykjavik. It hosts three main volcanic centres which are, listed from SE to NW and decreasing age, Graendalur (0.3–0.5 Ma), Hrómundartindur (Ölkelduháls) on the decline and Hengill at the peak of activity.

3.1 Geology and tectonics

The Hengill High-temperature area is located in the southern end of the western volcanic zone (WVZ) of Iceland in the Hengill volcanic complex which rises about 500 m above the surroundings. It is located

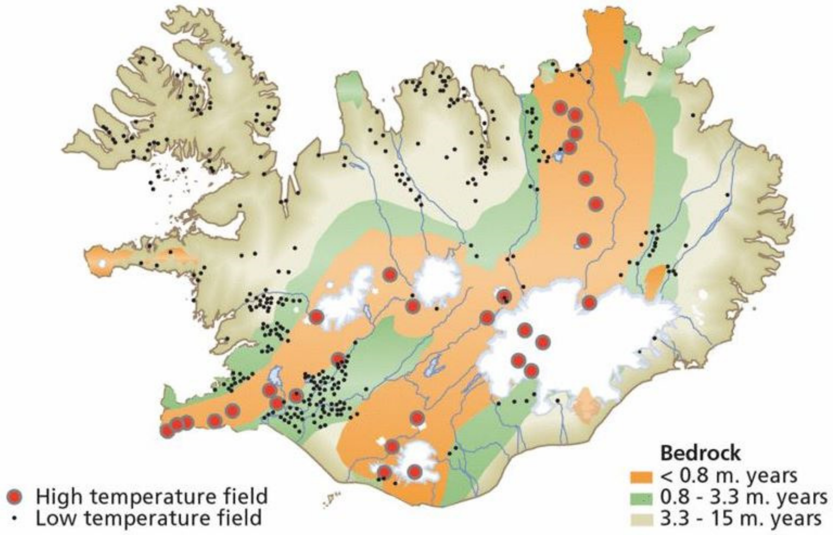

FIGURE 3: Locations of high- and low-temperature geothermal fields in Iceland (Orkustofnun, 2009)

at the triple junction of the WVZ, the Reykjanes Peninsula (RP) which is the landward extension of the Reykjanes spreading ridge and the South Iceland Seismic Zone (SISZ) which is a transform zone, transferring a part of the crustal spreading from the WVZ to the eastern volcanic zone (Figures 2 and 3).

The geology of the Hengill area is intersected by a fissure swarm over 3–5 km wide and 50 km long, trending N 30° E which has a structure of nested grabens. In addition to the major NE-SW fissure swarm and faults, there are some eruptive fissures transecting the centre of Hengill in a NW-SE direction, perpendicular to the main tectonic trend. This area is almost entirely built up of volcanic rocks. Subglacially formed hyaloclastites together with pillow basalts constitute the main rock types (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. Some interglacial and postglacial lava flows are also present, the most recent activity being 2500 and 5500 years old (Saemundsson, 1995a).

3.2 Geothermal activity

Geothermal surface manifestations in the Hengill area are connected to the volcanic system (Figure 3). The main heat source of the Hengill geothermal area is considered to be cooling magma intrusions within the upper crust and deep circulation of groundwater in highly fractured rocks transports the heat upwards (Franzson et al., 2010). The CO_2 gas geothermometer shows three upflow zones and the temperature seems to decrease to the southeast (Ívarsson, 1998) (Figure 4).

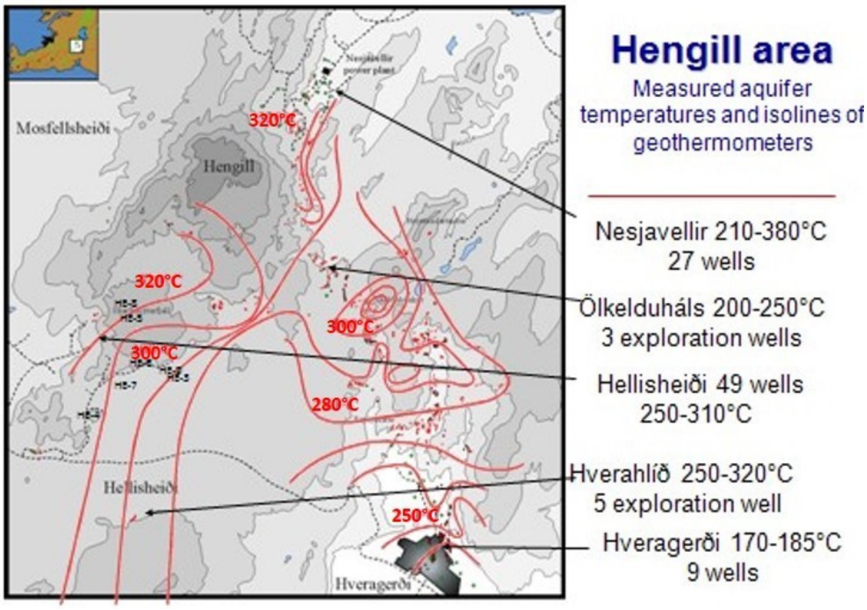

FIGURE 4: Measured aquifer temperatures and isolines of CO_2 gas geothermometers (mod. from Ívarsson, 1998). Geothermal surface manifestations are shown as red dots. Numbers of wells and average temperature in wells for the five known main subfields is shown

3.3 Geophysics

When resistivity surveys conducted in the Hengill area are compared to lithology, alteration mineralogy and temperature they show that the resistivity is high in the surrounding cold unaltered rocks. This high resistivity delineates a 50 km^2 area that represents the hottest central part of the Hengill area (Björnsson and Hersir, 1981). The DC resistivity soundings show a low-resistivity geothermal anomaly at 400 m below sea level which is about 110 km^2 in size. Aeromagnetic measurements carried out in the area indicate negative anomalies, probably caused by hydrothermal breakdown of magnetic minerals within the active high-temperature system (Björnsson and Hesir, 1981). At temperatures of 50-100°C pronounced geothermal alteration sets in with smectite and zeolites as the dominant alteration minerals and the rocks become conductive. At higher temperature in the range of 220-240°C smectite and zeolites are gradually replaced by chlorite as the dominant alteration mineral in the so-called mixed layered clay zone (Kristmannsdóttir, 1979) and the resistivity increases again. At still higher temperatures epidote becomes abundant. The smectite and the zeolites have loosely bound cations that make these minerals conductive, whereas in the chlorites all ions are bound in a crystal lattice (Deer et al., 1962) and are therefore more resistive. Árnason et al., (2000) related the resistivity structures to variations in hydrothermal alteration which appear to be of greater importance than the temperature variation. The low-temperature clay rich outer margin of a high-T reservoir is characterized by low-resistivity and the underlying, higher resistivity is associated with the formation of chlorite and a less water-rich alteration mineral assemblage (Árnason et al., 2000; Árnason and Magnússon, 2001) (Figure 5).

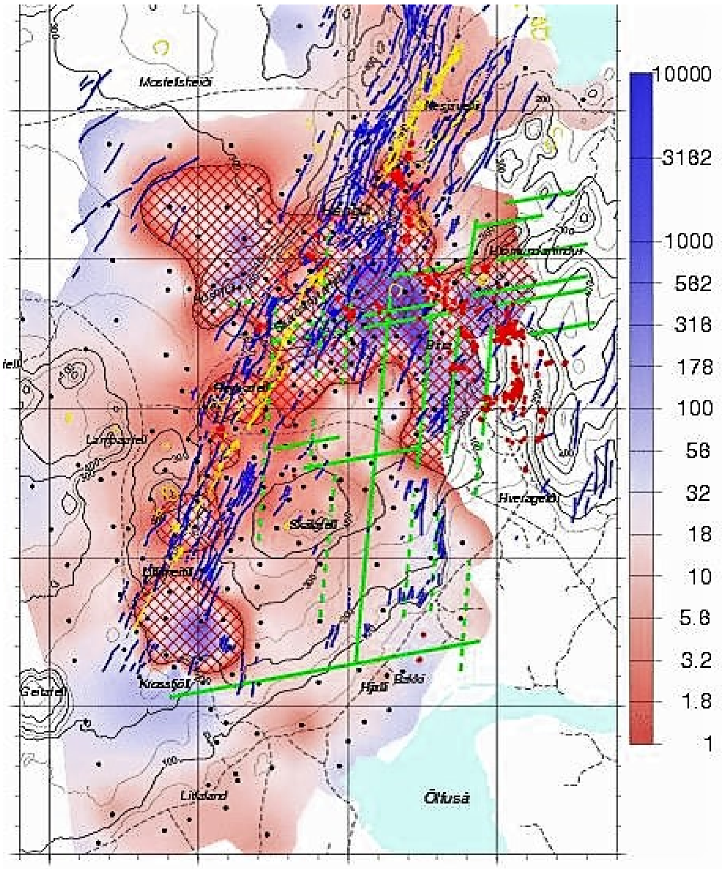

FIGURE 5: A resistivity map of the Hengill central volcano at 850 m b.s.l. showing variations in resistivity. The cross-hatched areas define high resistivity cores below low resistivity and are interpreted as alteration temperatures of over 230°C (Árnason, 2006)

The high temperature from CO_2 might be caused by another system lying deeper, capped by a horizontal dyke (Árnason and Magnússon, 2001).

The Hengill area has been covered with 280 TEM soundings and 148 MT soundings. 1D joint inversion of 148 TEM/MT sounding pairs, correcting for the static shift of the MT curves which can be severe, has revealed the resistivity subsurface structure (Árnason et al., 2009). The inversion showed a conductive cap underlain by a resistive core, both of them being directly related to the geothermal reservoir. At a greater depth (several km) another low resistivity layer was found, the same layer that is found under most of Iceland (Árnason et al., 2010).

The resistive core in Hengill area is trending WNW-ESE, the same orientation as a zone where E-W oriented faults, inferred from seismicity, meet N-S oriented "seismic" faults and indicates alteration temperatures of over 230°C (Árnason et al., 2010) (Figure 5).

The region, where the resistive core rises highest coincides with the area where the seismicity was most intense in the years 1991 to 2001 and where the centre of uplift was located according to InSAR measurements (Feigl et al., 2000).

The MT 3D inversion in this area shows that the low-resistivity ridge to the NW and SE of Hengill extends to the Graendalur central volcano (Figure 5), coinciding with the geothermal surface manifestations and is bordered by high resistivity to the SW and NE (Árnason, 2006). Both inversion approaches of the TEM/MT resistivity soundings reveal a shallow resistivity layer reflecting conductive alteration minerals at temperatures from 100 to 240°C. They also delineate a deep conductor at 3-10 km depth. Deep conductors are believed to reflect hot solidified but ductile magmatic intrusions that are heat sources for geothermal systems (Árnason et al., 2010).

4. GEOTHERMAL EXPLORATION

Geothermal surface exploration invariably entails a multi-geoscientific process which is holistically aimed at defining the geometry and characteristics of the geothermal system prior to drilling. The scientific disciplines commonly involved are geology, geochemistry and geophysics. The geological approach generally aims for understanding the various lithologies, volcanological evolution, structural controls and hydrological regimes of the system. Geochemical exploration relies mostly on sampling and analysis of water, steam and gas from thermal manifestations in order to characterize the fluids, estimate equilibrium reservoir temperature, determine the origin, evaluate mixing scenarios, determine the suitability of the fluids for the intended use and locate recharge areas and direction of fluid flow. Geophysical exploration makes use of methods such as resistivity, gravity and magnetic measurements and help to determine the geometry (shape, size and depth) of the heat sources, reservoir and cap rocks.

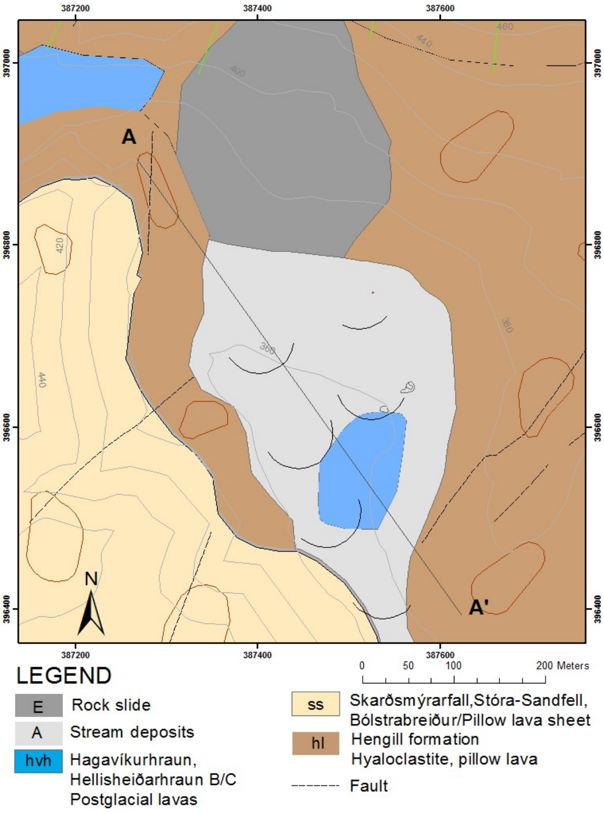

FIGURE 6: A geological map of the Hengill area, modified from Saemundsson (1995a). The volcanic accumulation consists of hyaloclastites from glacial times and interglacial lava flows

Geological studies invariably start at the incipient reconnaissance stage which entails preliminary mapping of the lithologic units and structures, mapping of thermal surface manifestations and possibly relate to the structures and or volcanism in the prospect of interest. This part is the concern of the work presented here.

The Middalur area is composed of surface deposits in the valley, hyaloclastite tuffs and pillow basalts which were probably formed during the second last glacial period (up to 200,000 years old). Part of the geological map is shown in Figure 6. In the map, there is also a section of Hagavikurhraun and Hellisheidarhraum lava which formed about 5500 years ago (Saemundsson, 1995a). The Hagavíkurhraun erupted postglacially in Innstidalur and ran down to Middalur valley. Other bedrock formations shown on the geological map in Figure 6 (and tabulated in Table 1) are mostly composed of hyaloclastite formations of different age.

Tables 1 and 2 (see also Figure 6) show more a detailed description of the lithological units. Beginning with the youngest to the oldest, i.e. from the Hagavíkurhraun lava (hvh) down to Hengill formation (hl) and some superficial deposits such as major landslides (marked E) and major stream deposits (marked A).

TABLE 1: Bedrock lithology of the present study

No.	Unit (acronym)	Name	Description of rock type	Age
3	hvh	Hagavíkurhraun, Hellisheidarhraun B/C	Postglacial lavas	5500 years
2	ss	Skardsmýrarfall, Stóra-Sandfell, Bólstrabreidur	Pillow lava sheet	< 200,000 years
1	hl	Hengill formation	Hyaloclastite, pillow lava	< 200,000 years

TABLE 2: Superficial deposits of Holocene age

No	Unit (acronym)	Name	Description
1	E	Rock slides	Composed of brecciated hyaloclastite and lava blocks
2	A	Stream deposits	River gravels and other steam deposits

4.1 Structures

The characterization of tectonic structures is very important in geothermal exploration because the geothermal manifestations are often directly related to the presence of these structures. One of objectives of this work was to re-evaluate the distribution of tectonic structures such as faults and fractures.

In Middalur area, being located in a valley covered by soil, it is difficult to map tectonically structures but on either side of the valley in the hyaloclastites, the tectonic structures are visible through aerial photographs and in the field. Two fault/fracture patterns, trending NE–SW and N–S, were identified.

Faults: Three N-S faults (Figure 7) and one NE-SW fault are visible in the field. One fracture NE-SW manifests itself with an opening of 13 cm (Figure 8). It is connected perpendicular to the NW-SE fault which lies it outside of the geothermal map.

FIGURE 7: Fault direction N-S

FIGURE 8: Fracture direction N 30°E with around 13 cm opening

Inferred faults: Based on the preferred alignment of the geothermal manifestations, aerial photo line features and the orientation of 50°C isotherms, the author inferred eight faults pattern, trending NE–SW, N-S and E-W (Figure 9 and 10). The alignments of geothermal manifestations in the valley form six lines that could present faults (Figure 10). They all appear to be normal faults cutting through the hill, disappearing towards Middalur valley. They can be traced on aerial photographs covering the area.

Faults, inferred faults and fractures visible on the ground and air photographs were mapped with reasonable accuracy. Most of these structures show a NE-SW trend which is the general direction of tectonic structures in the Hengill area.

5. GEOTHERMAL MAPPING OF THE STUDY AREA

The geothermal mapping takes into account the spatial representation of different types of geothermal manifestations that occur in the study area such as hot springs, steam vent, mud pool, hot ground, warm ground, cold spring and clay alteration.

Soil temperature measurements at 50 cm of depth were executed using a digital thermometer. GPS positioning was used to map different temperature sampling points and geothermal manifestations.

The collected data were downloaded to a computer and edited with the ArcGIS software. The end result is a geothermal map with a scale of 1:2500 showing the temperature distribution in the valley, geothermal manifestations and tectonic structures (Figure 10).

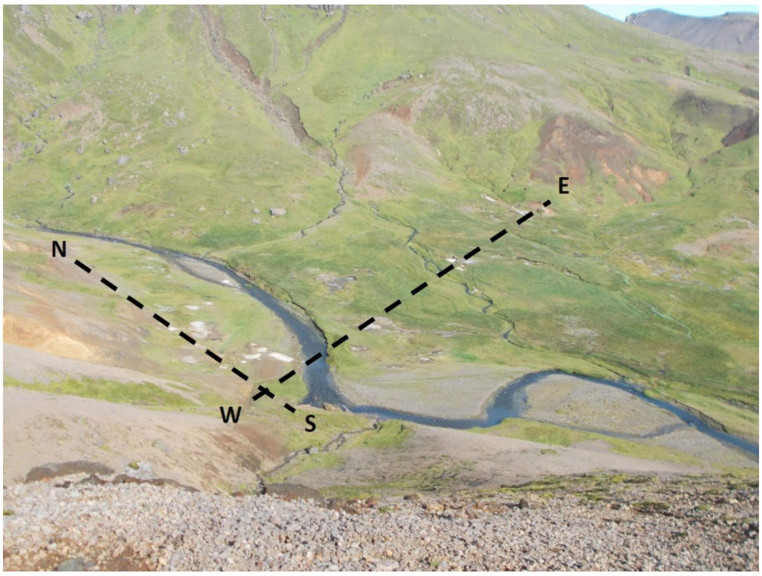

FIGURE 9: Distribution of aligned geothermal manifestations

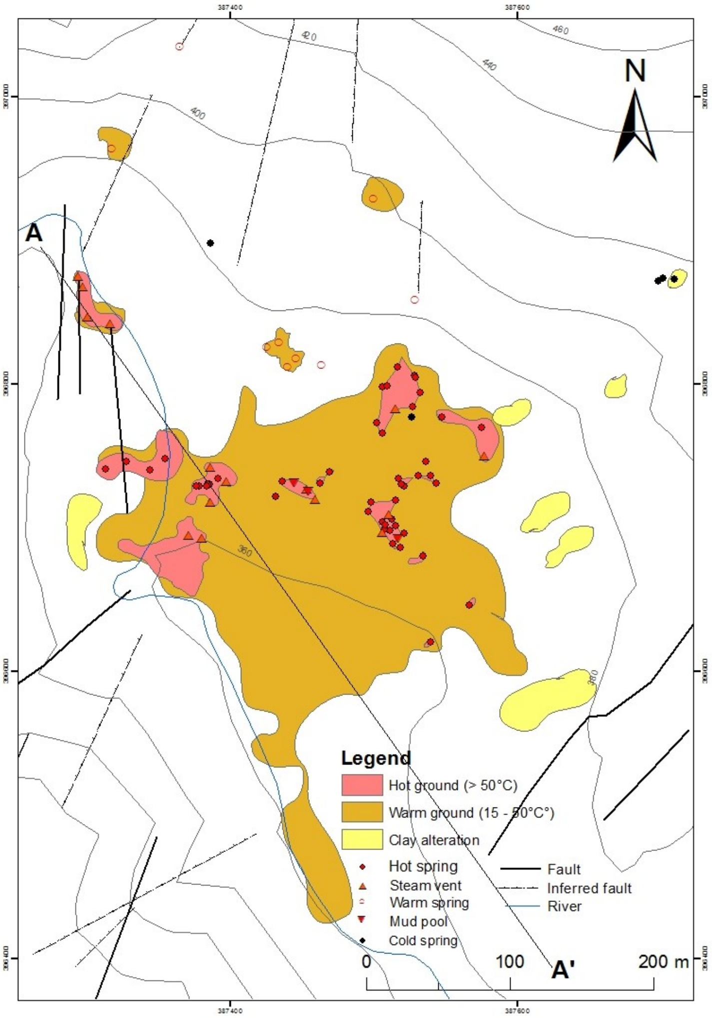

FIGURE 10: Geothermal map of Middalur high–temperature area

5.1 Geothermal manifestations

Geothermal manifestations found in the study area include hot springs, steam vents, mud pools, hot grounds, warm grounds and clay alteration (Table 3). They generally have the characteristics of being highly active.

In the valley (low altitude) one finds manifestations such as hot springs, steam vents, mud pool and hot and warm grounds. At higher altitudes, active geothermal manifestations present are warm and cold springs, steam vents and clay alteration. There appears to be a close relationship between the level of groundwater (water table) and geothermal manifestations in the study area. The cold springs have the same temperature as the groundwater temperatures in Iceland which is about 4°C (Hjartarson and Sigurdsson, 1993).

Figure 10 shows the distribution of geothermal manifestations and temperature in the Middalur area. The manifestations are aligned from east to west, indicating a fault which is, however, not visible on the surface (Figure 9). This possible E-W fault is cut by other faults trending N-S and NE-SW that are also not visible on the surface but can be concluded from the alignment of manifestations (Figure 10). All of these faults are covered with surface deposits.

5.1.1 Hot springs

Hot springs are abundant in the study area (Table 3). In this work, hot springs are classified as having temperatures above 50°C. Most are colourless, brown (due to clay particles) or whitish (due to the abundance of calcite). They can mostly be found on the middle of valley. Most of the springs are boiling but others are simply hot. The temperatures of the hot springs vary between 50 and 97.5°C. Most of these hot springs are surrounded by deposits and dark clay. Some emit CO_2 gas bubbles. Table 3 lists 46 hot springs. The total run off flow was estimated to be about 2-3 l/s.

TABLE 3: Manifestations mapped in Middalur

Manifestation	Total number
Boiling springs	3
Hot springs	46
Warm springs	9
Cold springs	5
Mud pools	3
Steam vents	15
Hot grounds	42

5.1.2 Warm springs

According to the characterization of the springs in this work, those having temperatures between 15°C and 50°C were classified as warm springs. They occur at somewhat higher altitudes than the hot springs. They could be fed by meteoric waters circulating in the faults and fractures where they get heated by circulating steam or cooled maybe by clay alterations and scaling, or by diminishing geothermal activity.

5.1.3 Cold springs

In the present study, cold springs are classified as having temperatures below 15°C. They are colourless and generally have temperatures between 4°C and 5°C. According to Hjartarson and Sigurdsson (1993), the average temperature of groundwater in the SW Iceland is about 4°C. The cold springs found in the area are groundwater fed. The majority of cold springs are located at slightly higher altitudes compared to the valley floor (Figure 10).

5.1.4 Warm grounds

Warm grounds have temperatures between 15 and 50°C. They are widely distributed in the study area (Figure 10). The vegetation colour typically changes from green to yellowish colour with increasing temperature. In areas not covered by vegetation soils, warm grounds are easily identifiable because they have a whitish or cream-white colouration due to calcite precipitation and they have surfaces wet of smooth clay.

5.1.5 Hot grounds

Hot grounds are those with temperatures above 50°C. They are typical manifestation of high geothermal activity. They are isolated, of whitish brown colour with silica, calcite and aragonite deposits that make them easy to recognize from afar. In the study area, the highest temperature measured in the area was 97.7°C.

FIGURE 11: Mud pool

5.1.6 Mud pools

The mud pools usually occur near hot springs (Figure 10). They are formed in high temperature geothermal areas with surface water deficiency. They are characterized by greyish boiling mud in a basin (Figure 11). Only three mud pools were mapped in the research area (Table 3). In the study area, one of the boiling mud pools is at around 1 m depth. The temperatures of the mud pools vary between 94 and 97.3°C.

FIGURE 12: Steam vent with sulphur deposit in the fault N-S

5.1.7 Steam vents

Steam vents mainly occur in hot grounds especially in the valley floor or side hill slopes where the water table is low (Figure 10). Most of them produce a whistling sound indicating that boiling water is at relatively shallow depths below the surface. The steam vents in Middalur valley are silent. Sulphur deposits are visible around them. The temperatures of the steam vents are around 97.5°C (Figure 12).

5.1.8 Clay alterations

Clay alteration patches are formed by surface modification processes and are observed around mud pools areas but also as cold clay ("Extinct clay alterations") in which the clay is altered to different degrees. One can easily see the iron oxide stains and precipitates, mud rich in silica alumina or reddish light colour, usually located close to active manifestations. In the study area, the clay alterations are cold, most clearly visible on the hillsides and they are located outside of the resent active areas (Figure 13).

FIGURE 13: Extinct clay alteration

5.2 Geothermal model of the Middalur field

The geothermal model developed for the study area (Figure 14) is calculated along the cross-section line A-A' on the basis of geological and geothermal maps (Figures 6 and 10). This cross-section is used to show schematically geothermal conduits to surface manifestations.

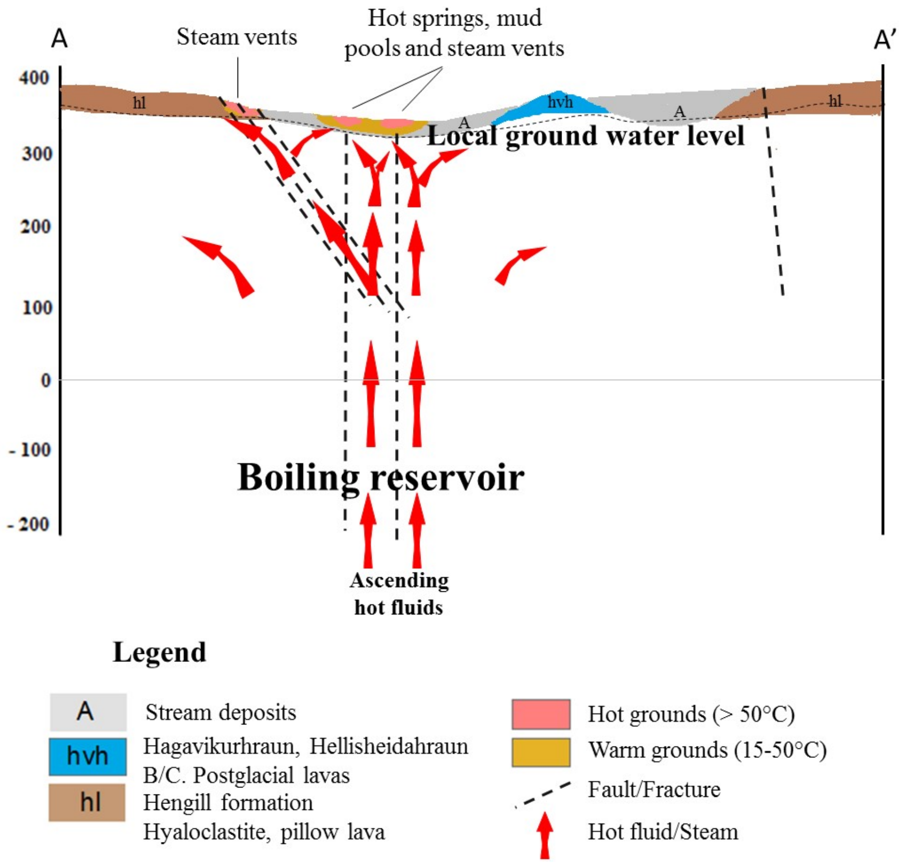

FIGURE 14: Geothermal model of the Middalur area

In the absence of well data to complete the lithology and other in-depth information, we think that the hot water ascends upwards due to buoyancy which offsets further infiltration of cold water from the regional deep-seated groundwater source.

This model assumes a boiling geothermal reservoir at depth. The NE-SW faults and fractures in the region act as upflow zones from which the hot geothermal manifestations emerge to the surface. The N-S striking faults intersect the NE-SW trending faults or fractures which are the principal heat conductors in this area and channel the upward flow.

Local groundwater is heated by steam, subsequently flowing upwards and out through fractures as warm springs. The hot springs and mud baths appear in places where the groundwater reaches the surface through the fault or fractures. The hot grounds and the steam vents occur only at relatively low groundwater levels along the N-S trending faults in the hyaloclastites.

6. CONCLUSIONS

During this work, geothermal mapping was carried out in the Middalur valley. The types of geothermal manifestations found are hot springs, mud pools, steam vents and extinct clay alteration. These manifestations were correlated with tectonic structures in the region. On the map, the manifestations are aligned in the directions E-W, N-S and NE-SW that could represent faults or fractures. The isotherms of >15°C and of >50°C delineate warm and hot ground.

The geothermal model assumes a boiling geothermal reservoir at depth. The upward flow occurs along faults and fractures oriented in NE-SW direction. These faults are connected to the N-S and E-W fault trend, and channel the upward flow which leads to the expression of the thermal manifestations.

This upward flow heats or mixes with local groundwater and the surface water systems.

In summary, this work concludes that:

- Most of the geothermal manifestations are related to structural features like faults indicating that the upflow in the area is mostly controlled by those faults;
- Geothermal manifestations and temperature distribution indicate faults/fractures trending in approximately NE-SW, E-W and N-S directions. These faults are probably controlling the movement of the geothermal water of the area. Heat sources are believed to be cooling intrusions underneath (Hengill central volcano);
- Most of hot springs precipitate deposit and the occurrence of sulphur implies a high-temperature geothermal field;
- 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.

7. RECOMMENDATIONS

For the development of geothermal energy in the Democratic Republic of Congo the following recommendations should be considered:

- The training of more people in various fields of geothermal exploration and development, such as geology, geochemistry, geophysics, drilling and reservoir engineering;
- The awareness of decision makers on the importance of geothermal energy as a clean renewable energy source;
- The mobilization of funds for a detailed geothermal resource assessment in the country.

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