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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 springs, 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 fauld and fracture were mapped based on the airphotos features, field study and alignment of the geothermal manifestations. The trend of geothermal manifestations are N-S, NE-SW and E-W. Most of the 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

Democratic Republic of Congo is in western branch of the East African Rift System, referred to as the Albertine Rift. It is one of developing countries which suffer from a serious shortage of electricity. 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 use 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 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.

This study is a part of a six month training course at the UNU-GTP in Iceland in 2015 which commenced in April. 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 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 and faults of the Middalur field was mapped in more detail, as digital mapping and GPS positioning accuracy enables and simplifies the mapping exercise.

2. GENERAL GEOLOGY AND TECTONIC OF 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. 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). 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 of the North Atlantic Ocean 60 million years ago to the present.

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, 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 (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 1).

The volcanic belts in Iceland run SW-NE across the country (Figure 1). 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 by 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 1).

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

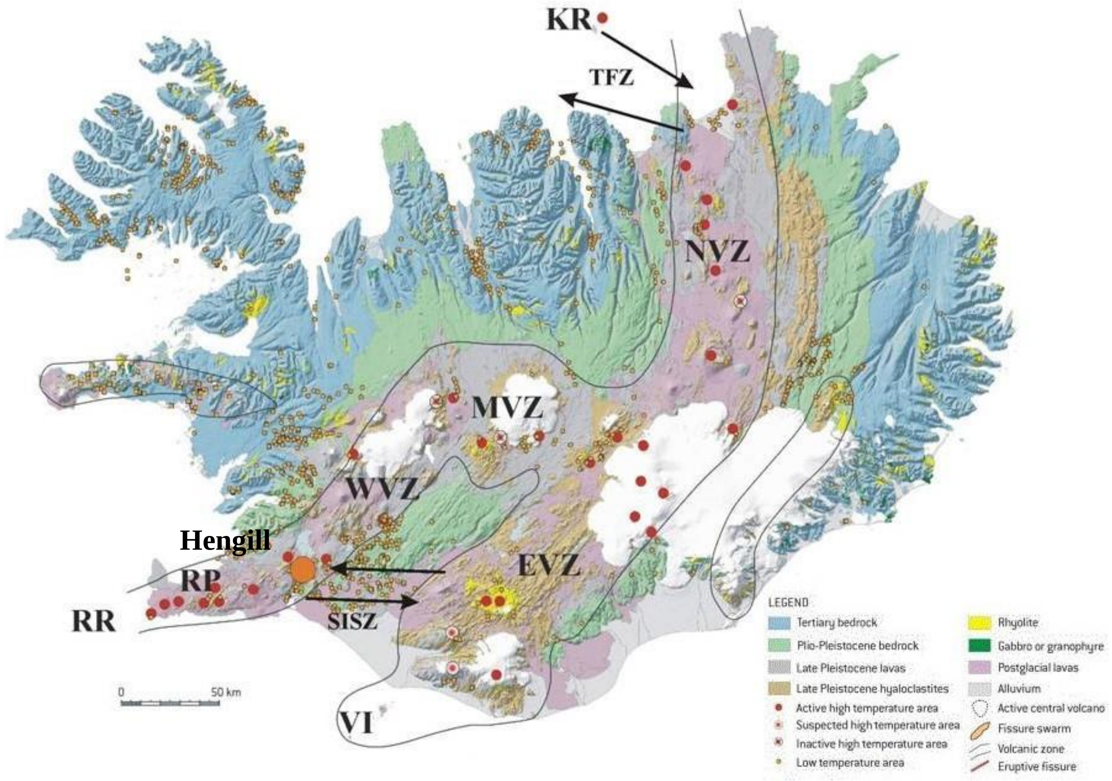

Figure 1: Geological map of Iceland showing the location of the active volcanic zones and transforms discussed in this paper. RR = Reykjanes Ridge; RP = Reykjanes Peninsula; WVZ = Western Volcanic Zone; MVZ = Mid-Iceland Volcanic Zone; NVZ = Northern Volcanic Zone; EVZ = Eastern Volcanic Zone; VI = Vestmanna 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 (Hardarson et al., 2010)

2.1 Geothermal aspects of Iceland

Geothermal activity in Iceland is common due 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). At present, it is considered that low-temperature areas show temperatures of less than 150°C at 1 km depth, but above 200°C in the high-temperature areas (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 but those 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 from the city of Reykjavik. It hosts three main volcanic centres, which are, listed from SE to NW and decreasing age, Grændalur (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 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 1 and 2).
The geology of the Hengill area is intersected by a fissure swarm over 3–5km wide and 50 km long, trending N 30° E and 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.

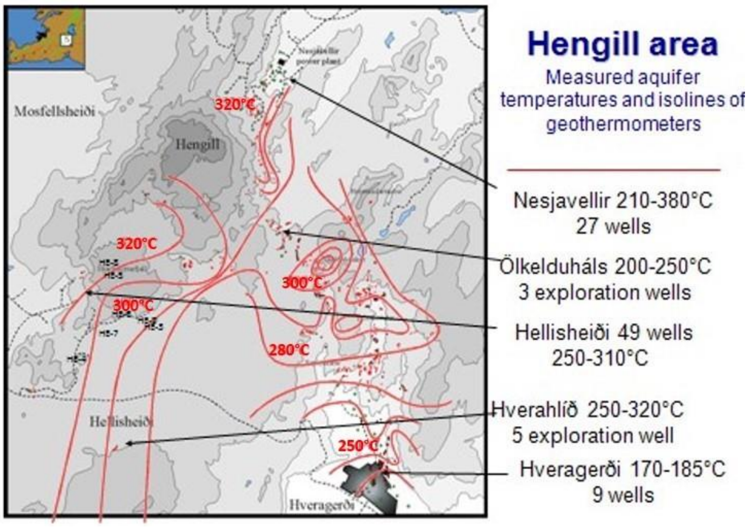

Figure 2: Measured aquifer temperatures and isolines of CO_2 gas geothermometers (modified from Ívarsson, 1998). Geothermal surface manifestations are shown as red dots. Numbers of wells and average temperature in the wells for the five known main subfields is given as well

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, 1995).

3.2 Geothermal activity

Geothermal surface manifestations in the Hengill area are connected to the volcanic system (Figure 1). 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. The CO_2 gas geothermometer shows three upflow zones and the temperature seems to decrease to the southeast (Hesir and al., 2009) (Figure 2).

3.3 Geophysics

When resistivity surveys conducted in the Hengill area 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 Hesir, 1981). The DC resistivity soundings showed a low-resistivity geothermal anomaly at 400 m depth of about 120 km^2. 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 less water-rich alteration mineral assemblage (Hardarson, 2014).

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

The resistive core in Hengill area shows the direction WNW-ESE, the same as that of 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).

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. Geological approach generally aims at 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 using methods such as resistivity, gravity and magnetics helps in determining the geometry (shape, size and depth) of the heat sources, reservoir and cap rocks.

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 in the lower part and pillow basalts at higher levels, and was probably formed during the second last glacial period (up to 200,000 years old). Part of the geological map is shown in Figure 3. In the map, there is also a piece of Hagavikurhraun and Hellisheiðarhraum lava which formed about 5500 years ago (Saemundsson, 1995).

The Hagavíkurhraun postglacially lava is formed in the Hengill formation (Hyaloclastite and pillow lava) and the Skarðsmýrarfall Pillow lava sheet. Other bedrock formations shown on the geological map in Figure 3 (and tabulated in Table 1) are mostly composed of hyaloclastite formations of different age.

Tables 1 and 2 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).

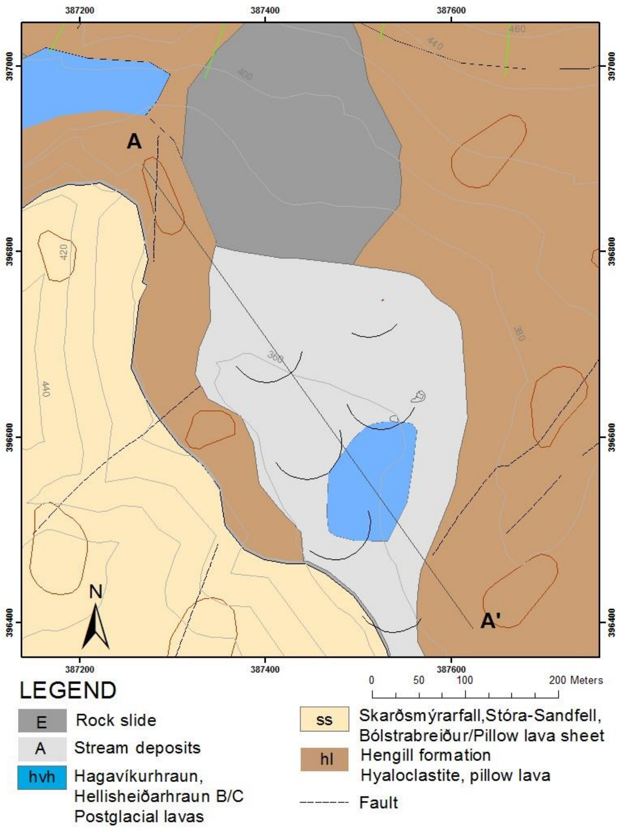

Figure 3: A geological map of the Hengill area, modified from Saemundsson (1995). The volcanic accumulation consists of hyaloclastites from glacial times and interglacial lava flows.

Table 1: Bedrock lithology of the present study are

No.	Unit (Acronym)	Name	Description of rock type	Age
3	hvh	Hagavíkurhraun, Hellisheiðarhraun B/C	Postglacial lavas	5500 years
2	ss	Skarðsmýrarfall, Stóra-Sandfell, Bólstrabreiður	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 reevaluate the distribution of tectonic structures such as faults and fractures.

Middalur area, being in a valley covered by soil 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 (Figure 4).

Inferred faults: Based on the preferred alignment of the geothermal manifestations, air photo lines features and the orientation of 50°C isotherms, the author inferred eight faults pattern, trending NE–SW, N-S and E-W. The alignments of geothermal manifestations in the valley form six lines that could present faults (Figure 5). They all appear to be normal faults cutting through the hill, disappearing towards Middalur valley. They can be traced on air photographs covering the area.

Figure 4: Fault direction N-S

Faults: Three N-S faults and one NE-SW fault are visible in the field. One fracture NE-SW manifests itself with opening of 13 cm to the hill, it is connected perpendicular to the fault NW-SE.

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 after field work and edited by ArcGis software. The end result is a geothermal map on a scale of 1: 2500 showing the temperature distribution in the valley, geothermal manifestations and tectonic structures.

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 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 are characterized by warm springs, 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, about 4°C (Hjartarson and Sigurdsson, 1993).

Figure 10 shows the distribution of geothermal manifestations and temperature in the Middalur area. This distribution shows an alignment of manifestations from east to west indicating, a fault which is, however, not visible on the surface. This fault E-W is cut by other faults N-S and NE-SW that are also not visible on the surface, just by the alignment of manifestations (Figure 5). All of these faults are covered with surface deposits. This condition shows that these faults have been formed before the surface deposits.

5.1.1 Hot springs

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

5.1.2 Warm springs

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

5.1.3 Cold springs

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

5.1.4 Warm grounds

Warm grounds are with temperatures between 15 and 50°C. They are widely distributed in the study area (Figure 5). 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 clayey.

5.1.5 Hot grounds

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

5.1.6 Mud pools

The mud pools usually occur near hot springs (Figure 5). They are formed in high temperature geothermal areas with surface water deficiency. They are characterized by greyish boiling mud in a basin. Only three mud pools were mapped in the research area (Table 3). In the study area, one of boiling mud pools is at around 1 m depth. The temperatures of the mud pools vary between 94 and 97.3°C.

5.1.7 Steam vents

Steam vents mainly occur in hot grounds especially in high altitudes or side hill slopes where the water table is low (Figure 5). Generally most produce a whistling sound indicating that boiling water is at relatively shallow depths below the surface. The steam vents in Middalur valley are silent the sulphur deposits are visible around them. The temperatures of the steam vents range from 71 to 97.5°C.

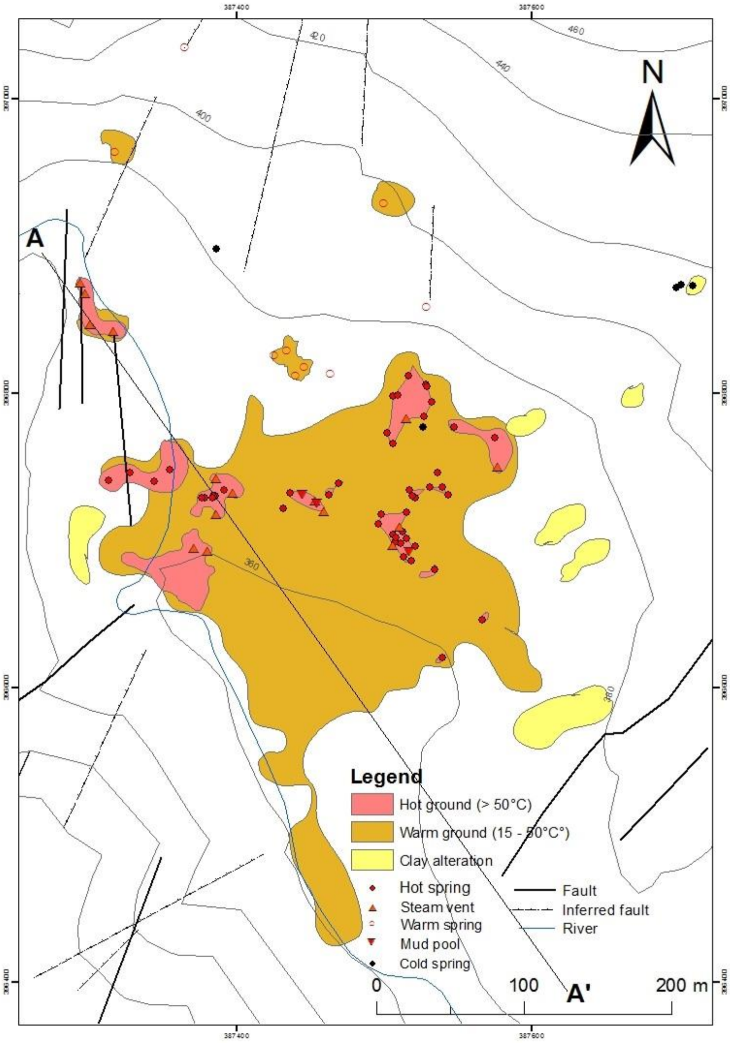

FIGURE 5: Geothermal map of Middalur high – temperature area

5.1.8 Clay Alterations

The clay alteration patches are formed by surface modification processes and are observed in the hot spring and mud pool areas, 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 most clearly visible on the hillsides.

5.2 Geothermal model of the Middalur field

The geothermal model developed for the study area (Figure 6) is taken through the cross-section line A-A' on the basis of geological and geothermal maps (Figures 3 and 5). This cross-section is used to show schematically geothermal conduits to surface manifestations.In the absence of well data to complete the lithology and other in-depth information, we think that the hot water lower density 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 faults N-S intersect the faults or fractures NE-SW, which are the principals conducted heat in this area share together the upward flow.

Some run-off local groundwater is heated by steam, subsequently flowing upwards and out through fractures as warm springs. The hot springs and mud baths occur in places where the groundwater intersects the surface in the fault or fractures NE-SW in the stream deposits. While the hot grounds and the steam vents occur only at relatively low groundwater levels, along the faults N-S in the hyaloclastites.

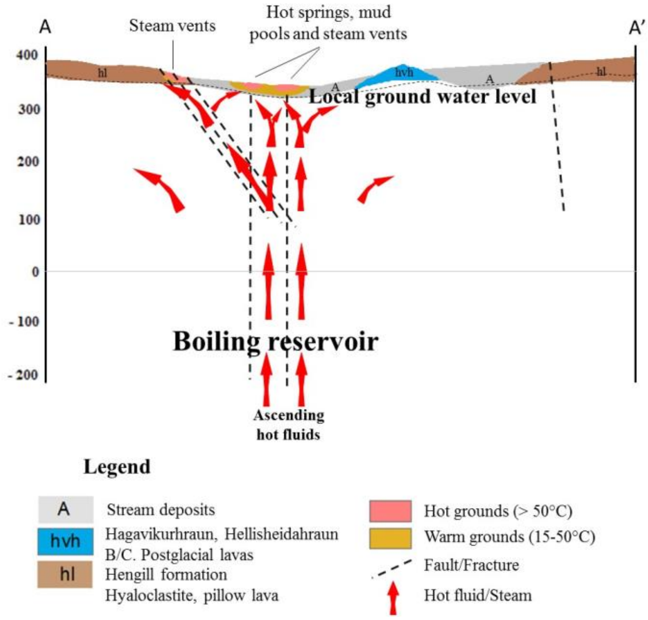

Figure 6: Geothermal model of the Middalur area

6. CONCLUSIONS

In this work, geothermal mapping was carried out in the Middalur valley. The types of geothermal manifestations found are the hot springs, the mud pools, steam vents and clay alteration. These manifestations were correlated with tectonic structures in the region.

On the map, the manifestations are aligned to the directions E-W, N-S and NE-SW that could present faults or fractures. The isotherms of > 15°C and of > 50°C delineate warm and hot ground.

The model assumes a boiling geothermal reservoir at depth. The upward flow occurs along faults and fractures NE-SW. The faults or fractures NE-SW are connected to the faults N-S and share together the upward flow.
These upward flow to shallow depths mixes with and heats up the local groundwater and surface water systems.

For this work, in a few lines, we can retain :

- Most of the geothermal manifestations are related to structural features like faults indicating that the upflow in the area is mostly controlled by them.

- Geothermal manifestations and temperature distribution indicate faults/ fractures trending approx. NE-SW, E-W and N-S.

  These are probably faults controlling the movement of the geothermal water of the area. Heat sources are believed to be cooling intrusions underneath (Hengill central volcano).

- Calcite precipitation in hot springs and hot grounds imply a diminishing geothermal activity. However, 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

The development of geothermal energy in Democratic Republic of Congo requires some recommendations:

- 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 the detailed geothermal resource assessment.

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