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# GEOTHERMAL EXPLORATION IN GUFUDALUR, HVERAGERDI, SW-ICELAND

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## ABSTRACT

The Hveragerdi geothermal field is located on the eastern margin of the western rift zone and the western margin of the South Iceland Seismic Zone (SISZ). Earthquakes with epicentres in the Hveragerdi central volcano are quite common; most of these are smaller than 4 on the Richter scale. The most recent earthquakes in the SISZ occurred on the 29$^{th}$ of May 2008 with two major earthquakes with magnitudes of 6.3 and 5.5 between the towns of Selfoss and Hveragerdi. It is believed that the first earthquake triggered the second one. These major earthquakes affected the Hveragerdi geothermal field. Many sudden changes regarding surface manifestations were observed. Visible fractures on the surface, the appearance of new fumaroles, hot springs, and many surface manifestations in the Hveragerdi geothermal field changed due to these earthquakes. The main purpose of this study on the valley of Gufudalur, Hveragerdi, is to map the surface manifestations, alteration and soil temperatures and correlate the manifestations with structures such as faults, fractures and lineaments. In addition, the results are compared with previous geothermal maps from the same area to pinpoint any changes caused by the earthquakes in 2008. More than 450 GPS locations of geothermal manifestations were taken and divided into 12 separate active areas. Present geothermal activity was compared with studies done in 1995 and soon after the earthquakes in 2008.

The present study reveals that the earthquakes which occurred in 2008 created new geothermal manifestations and the geothermal activity increased. New surface manifestations are still forming in the Gufudalur, Hveragerdi area. Alignment of geothermal manifestations along preferred directions indicates structural features, like lineament expression of underlying geological structures such as faults/ fractures/lineaments. The major structural trends that control the geothermal manifestations are oriented NE-SW, although N-S and NW-SE oriented faults and fractures are also present. On the basis of geothermal mapping, it was concluded that the geothermal manifestations are controlled by the geological structures and topography.

# 1. INTRODUCTION

## 1.1 Study area and background

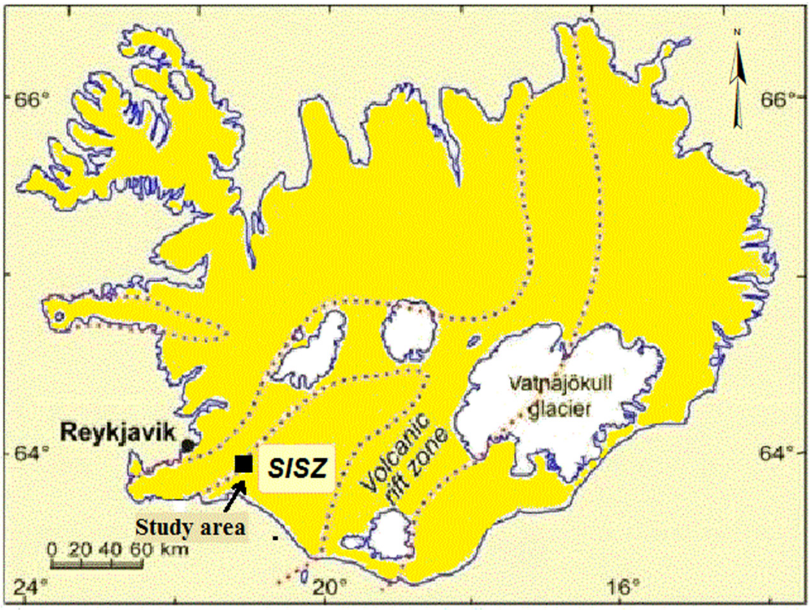


FIGURE 1: Location of the study area

Hveragerdi geothermal field is located on the eastern margin of the western volcanic (rift) zone (Figure 1), With respect to the tectonic setting of Iceland, seismic activity is common. The study area of Gufudalur valley in the Hveragerdi district is located in the South Iceland Seismic Zone (SISZ). The area is geothermally highly active and surface manifestations such as fumaroles, hot springs, mud spots and hot ground are common. Fumaroles and hot ground dominate in the northern part of the system and hot springs are common below 100 m elevation in the southern part (Geirsson and Arnórsson, 1995).

With the occurrence of an earthquake in southern Iceland, of magnetite 6.3 on the Richter scale, on the 29th May 2008, the geothermal activity in the area changed overnight. The epicentre was located 8 km west-northwest of the town of Selfoss. The impact of the earthquake affected the Hveragerdi geothermal field and many sudden changes in the system were observed. Visible fractures on the surface and the appearance of new fumaroles and hot springs were observed; many surface manifestations in the Hveragerdi geothermal field changed due to the earthquake. Even sudden pressure drops or increases in the wells in the area caused changes in the water levels of geothermal wells in the area (Thorbjörnsson et al., 2009).

With respect to the location of the Hveragerdi geothermal field relative to the active volcanic belt of Iceland (Figure 1), and in conjunction with it drifting out of the volcanic belt, the field is probably in the process of changing from a high- into a low- temperature geothermal system (Arnórsson, 1995a and b).

Since the major earthquake in 2008, several studies have been done in the surrounding area to identify changes in the region, but few detailed geothermal mapping projects have been executed to identify changes in the Gufudalur, Hveragerdi valley. The main purpose of this study is to map all surface manifestations, alteration and soil temperatures, and correlate the manifestations with structures such as faults, fractures and lineaments. In addition, the results are compared to older geothermal maps from the same area in order to pinpoint any changes caused by the earthquakes in 2008.

## 1.2 South Iceland Seismic Zone (SISZ)

The active volcanic rift zone which lies across Iceland is the surface expression of the Mid Atlantic Ridge and it is divided into two parallel branches in South Iceland (Figure 1). The block between does not show evidence of active deformation or volcanism and earthquake epicentres are completely lacking (Einarsson, 2008). This block appears to fulfil the criteria of a micro plate and has been termed the Hreppar microplate. The southern boundary of the Hreppar Microplate is marked by the South Iceland

Seismic Zone (SISZ), where large strike-slip earthquakes occur (Einarsson, 2008). These fracture zones and faults are seismically very active and earthquakes are experienced regularly (Figure 2). Accumulated strain in the SISZ is released during strike-slip earthquakes and such a type of earthquakes, as large as magnitude 7, take place at intervals of decades to centuries (Einarsson, 1991).

The SISZ shows widespread evidence of Holocene fracturing. Glaciated surfaces, alluvial plains and postglacial lava flows are fractured along the 15 km wide, 70 km long, E-W trending seismic zone (Einarsson and Eiríksson, 1982; Einarsson et al., 1981, 2002; Clifton and Einarsson, 2005). A map of all detectible Holocene fault structures is shown in Figure 2a.

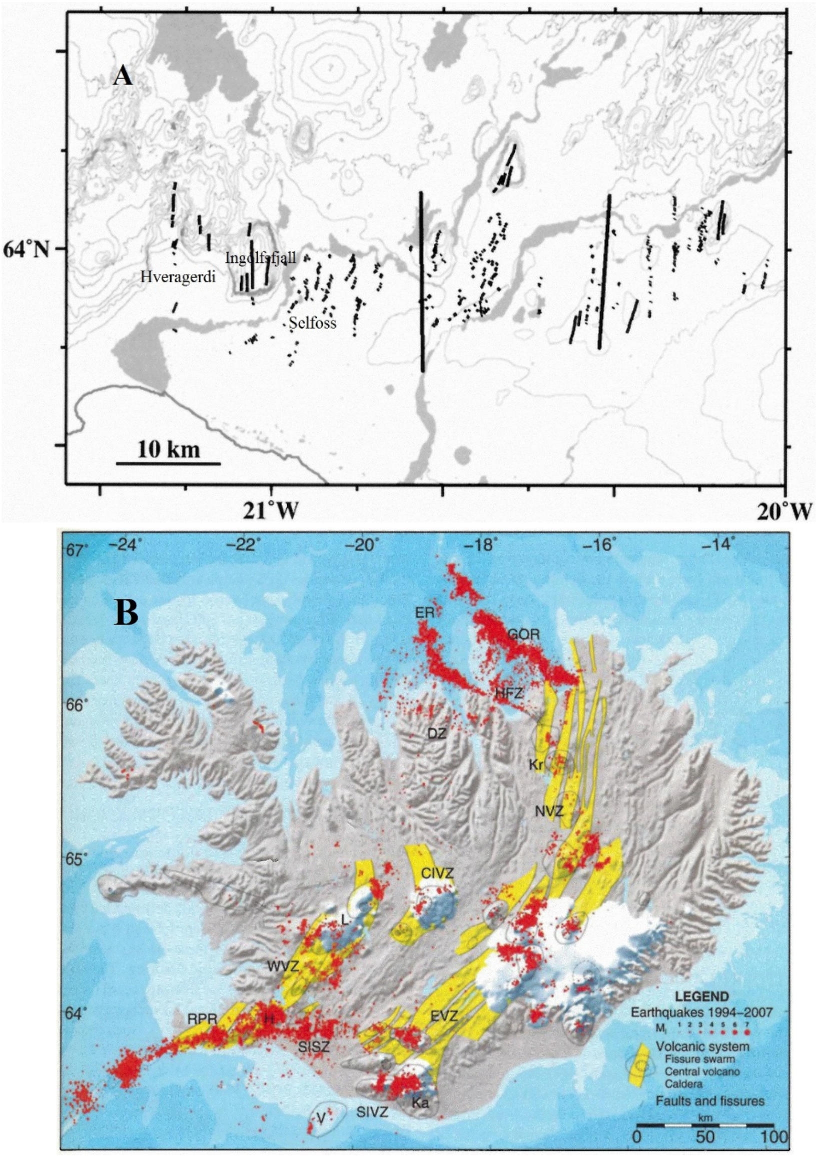


FIGURE 2: a) Mapped Holocene faults in South Iceland Seismic Zone; The heavy N-S lines show the source faults of the June 17 and 21, 2000 earthquakes; b) Red dots on the map shows earthquake epicentres 1994-2007 (Einarsson, 2008)

Earthquakes with epicentres in the Hveragerdi central volcano are fairly common. Most of these are smaller than 4 on the Richter scale, like in 1991 and in 1995, involving episodes of intense seismic activity. Many such earthquake episodes are known from this century and, in two of these, significant changes in surface hydrothermal activity took place, i.e. in 1915 or 1916 and in 1947. (Saemundsson and Fridleifsson, 1992). The SISZ was hit by a series of earthquakes in June 2000, two of which caused considerable damage (Stefánsson et al., 2003). The earthquakes followed a pattern previously observed in large historical earthquakes in this zone. The activity began on June 17 with a magnitude 6.5 event in the eastern part of the zone. This immediately triggered activity along about a 90 km long stretch of the plate boundary to the west, including three events with magnitudes larger than 5 on the Reykjanes peninsula oblique rift (Clifton et al., 2003; Pagli et al., 2003; Árnadóttir et al., 2004). The pattern of faulting during the 2000 earthquake sequence is compatible with the model of ‘‘bookshelf faulting’’ for the SISZ. It was furthermore demonstrated that bookshelf faulting continued to the west, along the Reykjanes peninsula oblique rift (Árnadóttir et al., 2004).

The most recent major earthquake in the SISZ occurred on the 29th of May 2008, with a magnitude of 6.3. Its location was between the towns of Selfoss and Hveragerdi (Figures 2a and 3). The epicentre of the first earthquake was by the southwest end of Mt. Ingólfsfjall (Figures 2 and 3) and immediately afterwards, another earthquake occurred, about 5 km west of the first earthquake. The epicentre of the second earthquake was on a N-S fault about 8 km west-northwest of Selfoss, and about 2 km southeast of Hveragerdi. It is believed that the first earthquake of 5.5, triggered the second one of 6.3 (Figure 3) (Icelandic Meteorological Office, 2008; Thorbjörnsson et al., 2009; Brandsdóttir, et al., 2010).

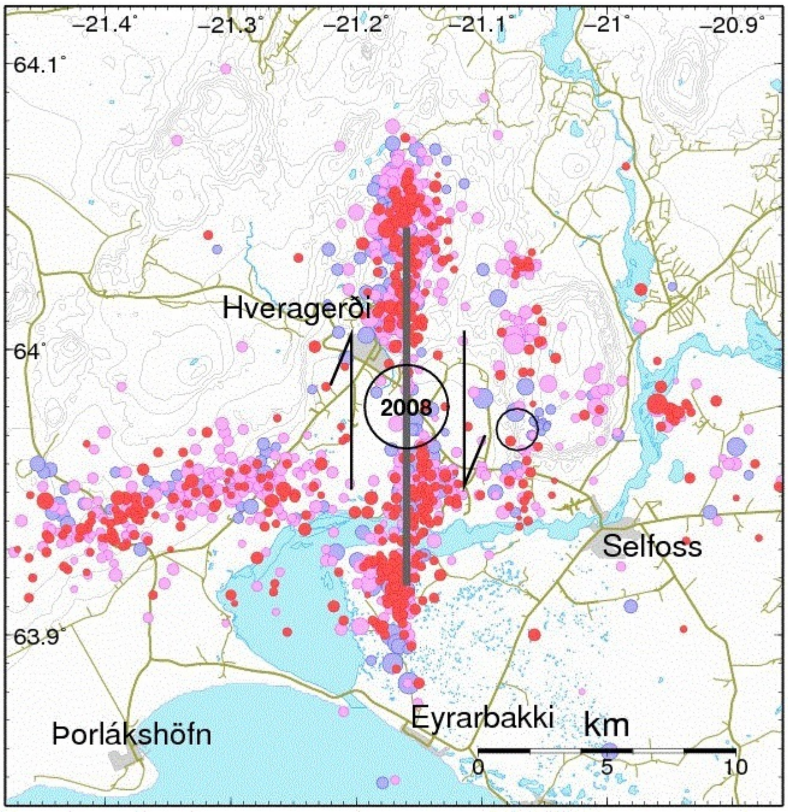


FIGURE 3: The epicenters of the earthquakes which occurred 29th May 2008; Rings represent the two major earthquake epicenters and small dots indicate minor earthquakes that occurred during the following three days (Icelandic Meteorological office, 2008)

### 1.3 Previous studies

The first systematic mapping of the Hengill area, including Hveragerdi and Gufudalur, was published in 1967 (Saemundsson, 1967). In the 1970s, the area was mapped in relation to drilling activities at Hveragerdi. Later, by combining previous work, the Hveragerdi central volcano was outlined and many of the formations from which it is composed were established. Jónsson (1989) undertook some research in the area, mostly on Upper Pleistocene and Holocene lavas. During 1989 and 1990, the geological mapping of this area was finalized, the emphasis being on the lithostratigraphy, tectonics, the geothermal activity and alteration of the area (Saemundsson and Fridleifsson, 1992, 1996). The Hveragerdi central volcano was mapped in detail some years ago by Orkustofnun, in co-operation with Hitaveita Reykjavíkur (Reykjavik District Heating) (Saemundsson and Fridleifsson, 1992). The maps were later combined with maps of the Hengill central volcano and published (Saemundsson, 1995a and b). Walker (1992) mapped the volcano with respect to its eruptive units and their petrology. A conceptual model of the Hveragerdi geothermal reservoir, based on chemical data, was published by Geirsson and Arnórsson in 1995. All this work was combined in a map of the Hengill central volcano in a scale of 1:50,000 (Saemundsson, 1995). Geothermal exploration of the Hveragerdi-Graendalur area was also done by the UNU-GTP fellow Kyagulanyi (1996) and, the same year, geothermal exploration of the Saudá valley north of Hveragerdi was carried out by UNU-GTP fellow Malik (1996). Kristjánsson and Fridriksson (2003) published a geothermal map of the Ölfus area, partly based on research done by Saemundsson (1993a and b). Heat measurements in the soil and fractures in Hveragerdi were completed by Saemundsson and Kristinsson in 2005. Thorbjörnsson et al. (2009) investigated the effects of the earthquakes of 29th May 2008 on the groundwater level, geothermal activity, fractures and pressure in boreholes in the Hveragerdi area.

## 2. GEOLOGY, TECTONIC SETTING AND GEOTHERMAL ACTIVITY IN ICELAND

### 2.1 Geology and tectonic setting of Iceland

Iceland is a geologically young island and owes its existence to the uprising Icelandic mantle plume and crustal accretion at the diverging American and Eurasian lithospheric plates. The relative 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). Even though the American and Eurasian lithospheric plates of the NorthAtlantic Ocean are spreading (2 cm/yr.) symmetrically, the whole region is drifting slowly to the northwest with respect to the Iceland plume (Hardarson et al., 2008). During Anomaly 6 (24–19 Ma ago), the Mid Atlantic Ridge axis moved on top of the mantle plume and then gradually west of it (Vink, 1984). 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 across the country (Figure 4). 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 oblique rift zone and branches into the Western Volcanic Zone (WVZ).

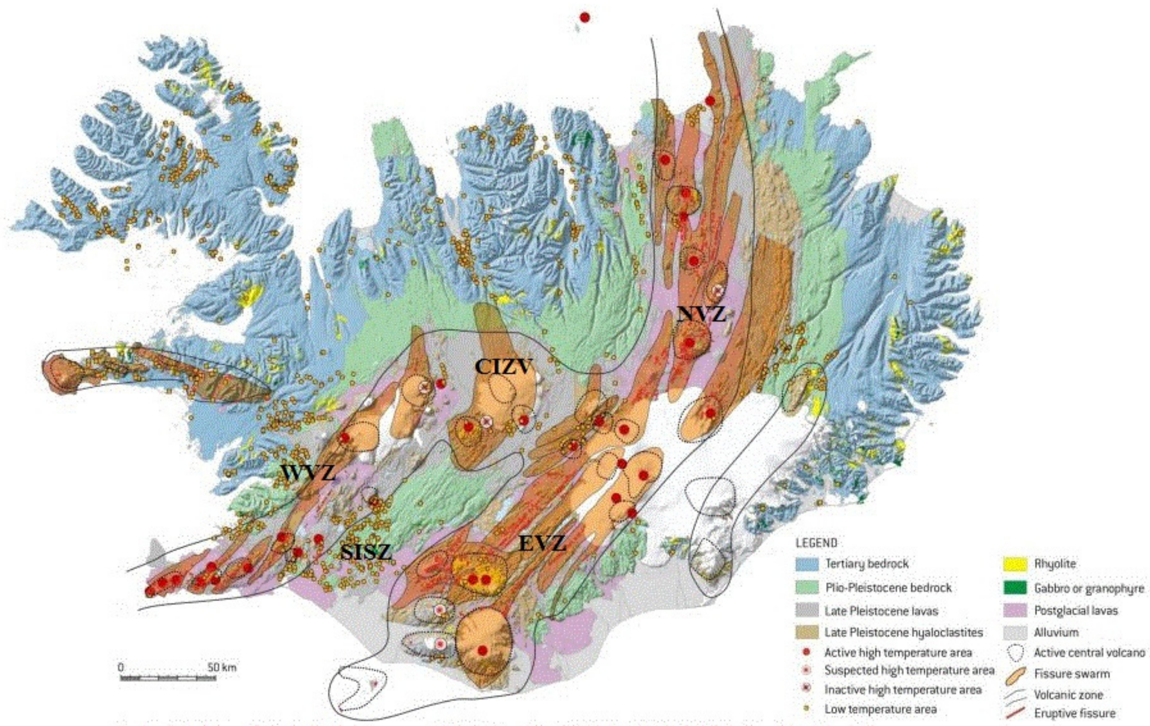


FIGURE 4: Geological map of Iceland showing the main rock formations, the volcanic zones and the geothermal areas; WVZ=Western Volcanic Zone, EVZ=Eastern Volcanic Zone, CIZV=Central Iceland Volcanic Zone, NVZ=Northern Volcanic Zone, SISZ=South Iceland Seismic Zone (Jóhannesson and Saemundsson, 1999)

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 (Figure 4). The EVZ extends northward and continues as the Northern Volcanic Zone (NVZ) (Árnadóttir et al., 2008). 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).

Icelandic rocks are mainly composed of Tertiary plateau lavas, Plio-Pleistocene lavas and hyaloclastites, formed subglacially, and Holocene lavas (Figure 4). 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). The geological formations in Iceland have conveniently been divided into four formations (Saemundsson, 1980): Holocene (< 0.01 Ma); Late-Pleistocene (0.01-0.78 Ma); Plio-Pleistocene (0.78-3.3 Ma); and Tertiary (3.3-16 Ma) (Hardarson et al., 2008).

Icelandic rocks are predominantly of basaltic composition. About 75% of the rocks are basalt, 14% intermediate rocks and 11% silicic rocks, which is close to a recent estimate of the production of volcanic rocks during the last 1100 years in Iceland (Jakobsson et al., 2008). The oldest rocks exposed on land in Iceland are only about 16 million years old (Moorbath et al., 1968; Watkins and Walker, 1977; McDougall et al., 1984; Hardarson et al., 1997).

### 2.2 Geothermal activity

Geothermal activity in Iceland is common due to the tectonic setting of the country as it is located on the Mid Atlantic spreading ridge, making the island a natural laboratory for geothermal research. Geothermal areas can be identified by surface manifestations such as hot springs, fumaroles, etc. while some areas may show no surface indications. Depending on their temperature, geothermal fields can be utilized in many ways from direct use to electricity generation.

Geothermal activity 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 in the 1000 m depth, but above 200°C in the 1000 m depth are high-temperature areas (Fridleifsson, 1979). The areas within the active rifting zones (Figure 4) 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. MAPPING OF GEOTHERMAL MANIFESTATIONS

### 3.1 Methodology

The main objective of this project is mapping the surface geothermal manifestations in the Gufudalur area north of the village of Hveragerdi (Figures 2 and 3). The mapping of surface manifestations involves determining the surface characteristics of the manifestations and plotting their GPS locations on a map. The aim is to compare the data with results obtained before and soon after the 2008 earthquake episode and map any observable changes in geothermal activities which were caused by the quakes. In addition, an effort is made to correlate any changes with structures formed during this seismic event.

Geothermal phenomena in the research area are manifested in the form of warm, hot or boiling springs, fumaroles steam vents, solfataras, and warm and hot ground, mud pools, silica and other encrustations and hydrothermal alteration (altered ground). The temperatures of individual surface manifestations were measured using a digital thermometer and their locations were plotted on a basemap using specific symbols for each phenomenon. The areas, where geothermal activity was observed as being clustered, are marked as zones of active geothermal area by giving a location number and are discussed briefly.

The springs were classified according to their temperature and any surface effects caused by the springs, such as precipitates or deposits, where noted. In addition, if a spring was located near a larger stream or river, the stream or river temperature was measured.

Altered grounds were identified and mapped. Several temperature measurements were performed to determine the temperature distribution within the hot or altered ground. Special notice was given to the colour of the altered ground and its form. The form of the precipitates and taste was noted to try to distinguish between silica and some form of mineral salt; samples were collected and analysed using XRD.

### 3.2 Characteristics of geothermal manifestations

#### 3.2.1 Springs

Springs are the most common hydrothermal manifestations in the study area and they have a wide range of temperatures. Based on their temperature, the springs were divided into four categories: (i) cold springs with temperatures below 10°C; (ii) moderately warm (tepid) springs with temperatures between 10 and 30°C; (iii) warm springs with temperatures between 30 and 70°C; and (iv) hot springs with temperatures above 70°C.

A hot spring is a spring that is produced by the emergence of geothermally heated groundwater from the Earth's crust. There are geothermal hot springs in many locations and silica and other mineral coatings can be observed in the rocks along the flow paths.

#### 3.2.2 Fumaroles/steam vents, mud pools and boiling hot springs

These forms of geothermal manifestations are grouped together and, in many cases, they are found interlinked in the same location. Fumarole/steam vents are often found in active geothermal areas, emitting steam and gases such as carbon dioxide, sulphur dioxide, hydrogen chloride and hydrogen sulphide (Figure 5). The steam is created when hot water turns to steam as pressure drops and subsequently emerges from the ground. The term solfatara, from the Italian solfo, meaning sulphur, is given to fumaroles that emit sulphurous gases. Fumaroles may occur along tiny cracks or long fissures, in unsystematic clusters or fields, and on the surfaces of lava flows and thick deposits of pyroclastic flows. A fumarole field is an area of thermal springs and gas vents where magma or hot igneous rocks at shallow depth release gases or interact with groundwater. From the perspective of groundwater, fumaroles could be described as hot springs that boiled off all water and the resultant steam reaches to the surface.

FIGURE 5: Fumarole found in the study area

FIGURE 6: Mud pool found in the study area

Mud pools and mud pots form in high-temperature geothermal areas where water is in short supply (Figure 6). The little water that is available rises to the surface at a spot where the soil becomes rich in grey coloured clay and other fine particulates. The viscosity of the mud usually changes with seasonal changes of the water table.

#### 3.2.3 Hydrothermal alteration, minerals, salt precipitation and warm grounds

Rock alteration due to hydrothermal fluids basically means changing the mineralogy of the rock by passing hot water through the rocks and changing their composition by adding, removing or redistributing the components of the rocks. The fluids carry metals in solution, either from a nearby igneous source, or by leaching nearby rocks. The primary minerals are replaced by secondary minerals because of changes in the prevailing conditions subjected to the rock. These changes could be changes in temperature, pressure, or chemical conditions or any combination of these factors.

FIGURE 7: Steaming ground with white precipitates and mineral salts

Extinct alteration is much more widespread and is expressed by grey clays of kaolinitic, smectitic and chloritic types. Silica and mineral salt precipitations are actively formed in areas of present geothermal activity (Figure 7). In some of these areas, alteration and precipitation mostly occurs along fractures within the rock mass. The process of sintering is sometimes manifested in the form of a thin crust of mineral salts and silica, accompanied by sulphur deposition.

FIGURE 8: Yellowish green moss in the warm ground

Yellowish green moss characterizes warm grounds (Figure 8). This is the only vegetation which can thrive above 35°C in this climate and soil type but, below 27°C, grass will grow. Rising temperature is usually manifested in dying or drying-away of the thick green grass. Typically, black soil is observed in the hot grounds or where progressively increasing heat is being transferred to the surface.

## 4. TECTONIC SETTINGS AND CONNECTIONS TO THE THERMAL ACTIVITY OF HVERAGERDI

### 4.1 The relationship between surface manifestations and the geology and tectonics

Geothermal manifestations are surface indications of geothermal activity in the subsurface. Geothermal manifestations such as hot springs, fumaroles/steam vents, altered or hot ground, steaming grounds, steam jets and sulphur depositions, must be mapped and their extent measured and correlated to geological structures.

Faults and fractures always indicate movements within the earth's crust. Faults can be distinguished from each other by lateral or vertical displacement; open fissures are common in most rock formations, but some are covered by erosional material. Therefore, they are often difficult to ascertain. Geological structures like fracture zones, shear zones, faults, fractures and fissures may not always be obvious on the surface. Rock slides, landslides, avalanches and erosional material can cover the surface geological features. However, in some situations, geothermal manifestations may indicate subsurface conditions, even though they are not apparent on the surface. For example, such manifestations may be oriented in a linear direction which only becomes obvious once a map is compiled. Alignment of geothermal manifestations along preferred directions indicates structural features like lineament expression of an underlying geological structure such as faults and fractures. These lineaments may indicate fracture zones, shear zones or intrusions such as dykes.

Tectonic movements within the Hveragerdi central volcano and its immediate surroundings are chiefly of four types: 1) tilting towards NW; 2) faulting; 3) formation of open seismic fissures and hot spring fissures; and 4) fracturing of rocks with little or no displacement (Saemundsson and Fridleifsson, 1992). The tilting is most intense furthest to the northwest, up to 8°, decreasing eastwards, only being 1-2° east of the volcano. The progressive increase in tilting towards the NW, towards the Hrómundartindur- and Hengill volcanic centres, and the relatively young age of the tilting, indicates that the tilting is caused by progressively increased burial of the younger volcanics in the rift zone to the west. Most commonly, faults in the area strike NE-SW or N-S and show 10 to 20 m displacement. A well-known seismic fissure striking N20°E extends from Hveragerdi across the Varmá river, towards Badstofuhver and the extinct hot spring, Svadi. After the 1947 earthquake, a narrow open fissure was seen in the terrace above Hverahvammur. The banks of the Varmá river (Figure 9) are scree covered but, just east of it, several NE-SW fissures with hot water are exposed. A N-S fissure is found west of Saudá (on the east side of Klóarmelar) in the centre of the valley. It is characterized by a long line of hot springs distributed along the fissure. The third open fissure is found in Folaldaháls, several tens of m long with a line of depressions occurring along it. The longest seismic fissures of this type, all of which relate to present day activity of the South Iceland Seismic zone, extend about 1 km. NE-SW striking fractures are common as are NW-SE. N-S trends are also seen in the Hveragerdi central volcano area (Saemundsson and Fridleifsson, 1992). According to the conceptual model of the Hveragerdi high-temperature geothermal field, a stream of geothermal water enters the Hveragerdi field from the north and the temperature of the water is 240-250°C. The water flows south and, on the way, the water cools due to mixing with cold groundwater (Geirsson and Arnórsson, 1995).

### 4.2 General geology of the Gufudalur area

The Gufudalur valley area is located in the extinct Hveragerdi volcano, which drifted about 5 km away from the rift axis to the west during the last 500,000 to 1 million years (Fridleifsson, 1979). The extinct Hveragerdi volcano and the presently active Hengill volcanic system developed on the western branch of the volcanic rift zone in SW-Iceland, which is characterized by tensional stress parallel to the spreading direction. The Hengill central volcano is intersected by a fracture system trending N30-35°W, forming geothermal manifestations such as fumaroles and hot springs, which are distributed in a zone from Hveragerdi centre to the Hengill centre, transecting the main fissure swarms (Fridleifsson, 1979). The main heat source of the Hveragerdi system is from the volcanic rift zone through the faults and fissure swarms connecting to the Hengill central volcano (Fridleifsson, 1979). Fissures/faults and the hydrothermal activity are interconnected with the seismic activity. Rock slides are a prominent surface feature in the study area, mostly caused by large earthquakes related to the South Iceland Seismic Zone since the Holocene.

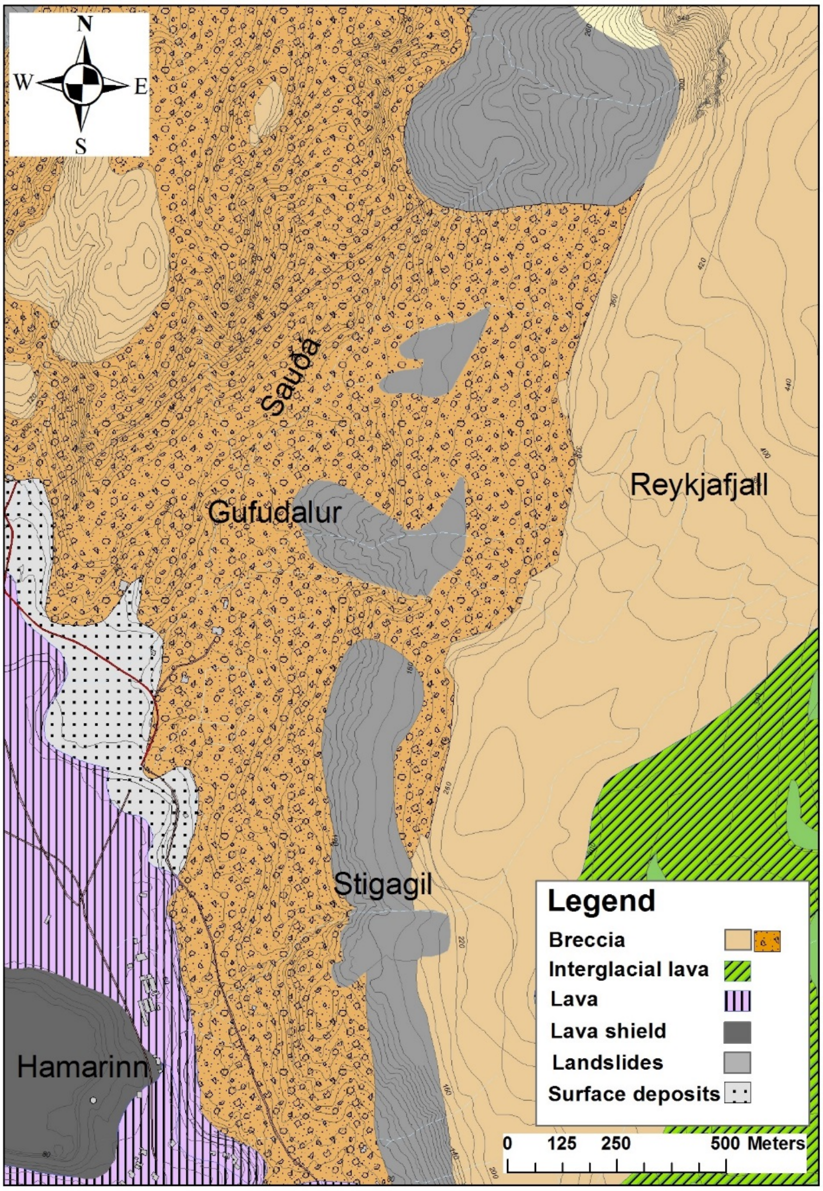


FIGURE 9: Map showing the general geology of the Gufudalur area

The volcanic rocks in the area are mostly of basaltic composition and are mainly composed of various lithofacies of subglacially formed hyaloclastites and interglacial lava flows (Figure 9). They range from olivine tholeiite to tholeiite; some basaltic andesites also occur. The hyaloc1astites range from glassy fine grained tuffs to coarse breccias and pillow lavas. Sometimes these pass into lava flows. The units have textures ranging from aphyric, fine or coarse grained to variably porphyritic. The hyaloclastites in the volcano form NE-SW striking ridges; the younger ones also show N-S strikes. The rocks are slightly tilted towards WNW or NW, and the maximum tilt reaches up to 8° in Dalaskard in the northwest. The tilt is much less in the south and east. Numerous dykes are found in the centre, some of these forming dyke swarms, and most of them are of the same composition as the extrusive rocks (Saemundsson and Fridleifsson, 1996).

Rocks in this area can be divided into two main rock series. The rocks that have been affected by strong hydrothermal alteration are considered as being the older series and the main units are hyaloclastite of quartz tholeiite composition, termed the Varmá formation, and of olivine tholeiite composition, termed the Tindar and Saudá formations (Saemundsson and Fridleifsson, 1992). The alteration degree reaches the smectite/chlorite alteration zone locally (indicated by the pale green colour of the rocks) in the stratigraphically lower Varmá formation. The regional blackish to brownish colouring of the Tindar and Saudá units suggests a smectite alteration-zone (Saemundsson and Fridleifsson, 1992). The less altered rock units are categorized by younger rock series that occurred at higher levels in the hills north and east of the Saudá valley. The main units are a group of lavas termed the Kvíar basalts and a group of hyaloclastites higher up, extending to Mt. Reykjafjall (Figure 9), east of Saudi (Saemundsson and Fridleifsson, 1992).

### 4.3 Details of geothermal manifestations

East of the Gufudalur valley area (Figure 9), geothermal manifestations consist mainly of steaming grounds, steam vents/ fumaroles, hot springs, and warm and hot grounds. It was seen that several manifestations were noticeable after the earthquakes in 2008 and it was also observed that activity had increased since the earthquakes in 2008. The map in Figure 10 shows the location of old and present geothermal manifestations in the Hveragerdi central area and the areas containing a large number of manifestations can be observed as clusters of points on the map. They were divided into 12 localities which are described briefly. The map also shows previous geothermal exploration/ mapping carried out in the area by Saemundsson (1995b), and soon after the earthquakes in 2008 by Thorbjörnsson et al. (2009). Among the twelve locations on the map, localities No. 13-04 and 13-07 are new geothermal manifestations; they were not identified in previous studies. Increased geothermal activity was observed in areas shown at locations No. 13-01, 13-02, 13-05, 13-06, 13-10, 13-11 and 13-12, while areas shown at locations No. 13-03, 13-08 and 13-09 appear stable when compared to the geothermal activity in 1995 and 2008. The alignment of geothermal manifestations striking NE-SW are also shown on the map.

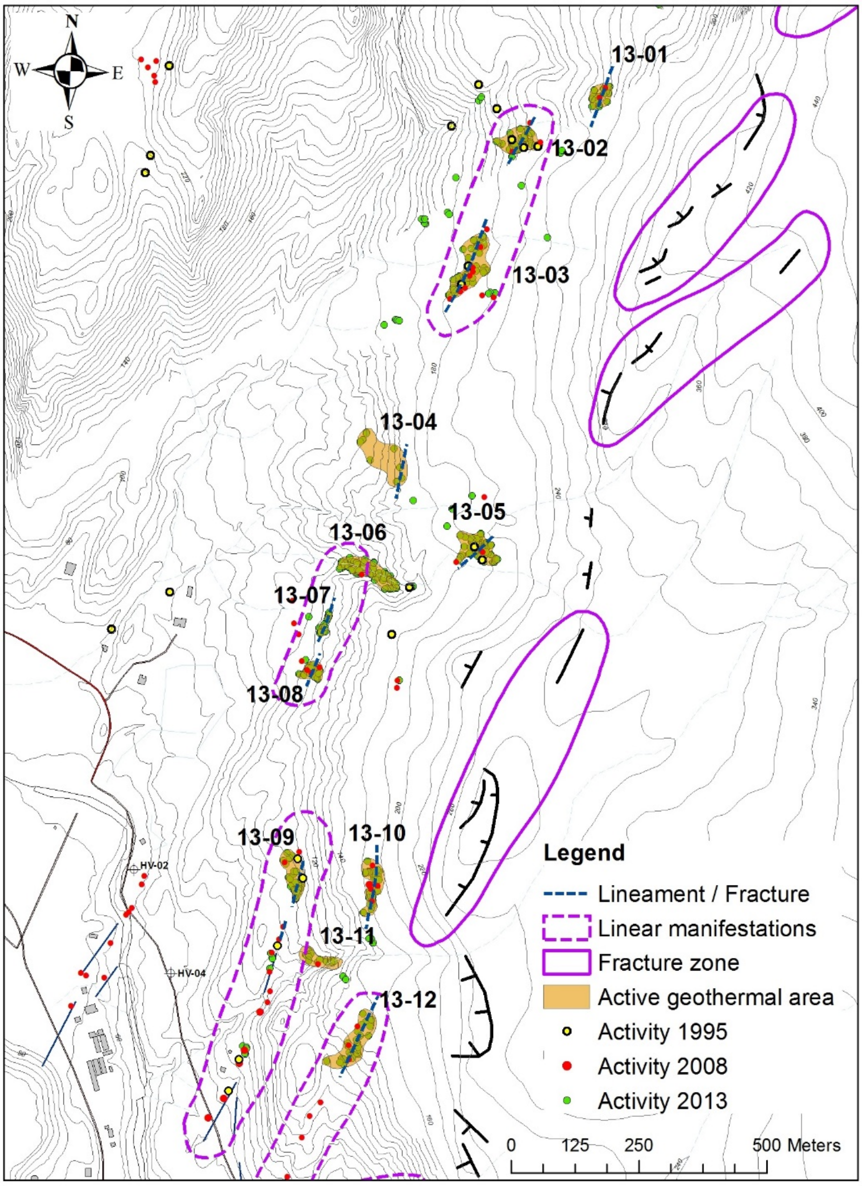


FIGURE 10: Map showing the location of geothermal manifestations and geological structures in the Gufudalur, Hveragerdi area; the geothermal activity in 1995, 2008 and 2013 is shown in different colours; active geothermal areas are shown in 12 location zones; linear manifestations and fracture/lineament in NE-SW direction are also shown on the map; geothermal activity mapped in 1995 and 2008 was completed by Saemundsson (1995) and Thorbjörnsson et al (2009); activity in 2013 refers to the present study

FIGURE 11: Warm and steaming grounds in Location No. 13-01

FIGURE 12: The intense geothermal activity in the area of Location No. 13-02

FIGURE 13: The geothermal activity in the area at Location No. 13-03

Location No. 13-01: The geothermal activity is recent and centred in a 2 x 2 m size steaming ground at temperatures of about 97°C, surrounded by warm grounds covered by yellowish green moss (Figure 11). The steaming ground is covered with white and yellow mineral precipitates. The total area is about 25 × 10 m in size and extends NE-SW.

Location No. 13-02: Intense geothermal activity is present in this area (13 x 20 m) and consists mainly of a large area of steaming ground with steam vents with temperatures greater than 90°C. White, yellow precipitates and mineral salts are present and give off $H_2S$ (sulphur) smells. Also found was a combined 2 × 2 m size boiling mud pool and fumarole. Steaming and hot grounds in the active area are circled by yellowish green moss (Figure 12).

Location No. 13-03: Highly altered steaming ground covered with white and yellow mineral precipitates (Figure 13). Seven fumaroles were identified while a 1 x1 m size grey colour clay filled boiling mud pool was located in this gently sloping area; their temperatures exceed 97°C. A small hot spring is located in the same area.

Location No. 13-04: This area is mostly warm ground (>20°C) covered by rock slide gravel in a 40 x 10 m area and contains several warm and hot springs (up to 82°C) having <5 l/s flow. Run-off water in the area is in the temperature range of 27-55°C.

Location No. 13-05: This area is on a steep slope having six moderately warm springs with very low flow rates and three boiling springs (98°C) with low flow rates. Two mud pools and one fumarole are located in the steaming ground. $H_2S$ odour is noticeable and the vegetation is spoiled due to the hot and steaming grounds. Yellowish green moss covers most of the warm grounds (see Figure 14). One sample of precipitates in the warm spring area (Sample No. 6) was analysed by XRD and identified the presence of calcite.

Location No. 13-06: The area is in a gully with a large number of geothermal manifestations aligned along the gully (Figure 15), mostly composed of steaming grounds with mineral precipitates such as silica and calcite. Five fumaroles with temperatures exceeding 97°C were found. $H_2S$ odour is noticeable. Also, a number of hot springs with low flow rates were seen running into the stream running through the gully. Most of the hot and warm grounds are located on the slopes inside the gully.

FIGURE 14: Geothermal activity in Location No. 13-05

The extent of the geothermal activity in Locations No. 13-05, 13-06 and No. 13-07 are shown in Figure 16. Also shown are the types of manifestations found in the zones. Location No. 13-06 had several sites of activity before the earthquakes in 2008, but the geothermal activity has increased, extending in a NW direction. Location No. 05 increased activity compared to activity in 1995 and 2008. The area shown in Location No. 13-07 is new activity, not yet identified after the earthquakes in 2008 by the mapping done by Thorbjörnsson et al. in 2009. The direction of the lineament/fracture is NE-SW and the direction of the activity in location No. 13-06 is controlled by the topography.

FIGURE 15: The geothermal activity along the gully area of Location No. 13-06

Location No. 13-07: Two patches of yellowish green moss could be observed with a temperature range of 20-69°C. The warm grounds are 15 x 10 m and 9 x 5 m, extending N10°E. This is fresh activity, not recorded in previous studies (Figure 17).

Location No. 13-08: Steaming ground with two hot springs and one fumarole on a steep slope near abandoned Well SP-01 (Figure 18). The area also shows layers of precipitates of an extinct geyser (Spýtir); two samples (Samples No. 1 and 7) of mineral salts and precipitates were tested by XRD and identified the presence of gypsum and anhydrite.

Location No. 13-09: Evidence of an extinct geyser and a combination of large boiling springs, boiling mud pools, and fumaroles were found at this location, shown on the map in Figure 21, along with steaming grounds, hot and warm grounds shown in Figure 19. A boiling spring with about a 3 x 4 m size pool and water rising in a geyser for about 20-50 cm were seen. Seven boiling mud pools are distributed in this area surrounded by brownish and grey coloured clay, the largest one extending 5 x 5

m. 25 x 25 m; hot and warm ground with hot, warm springs and a warm water pool are located a few metres to the north of the old geyser area.

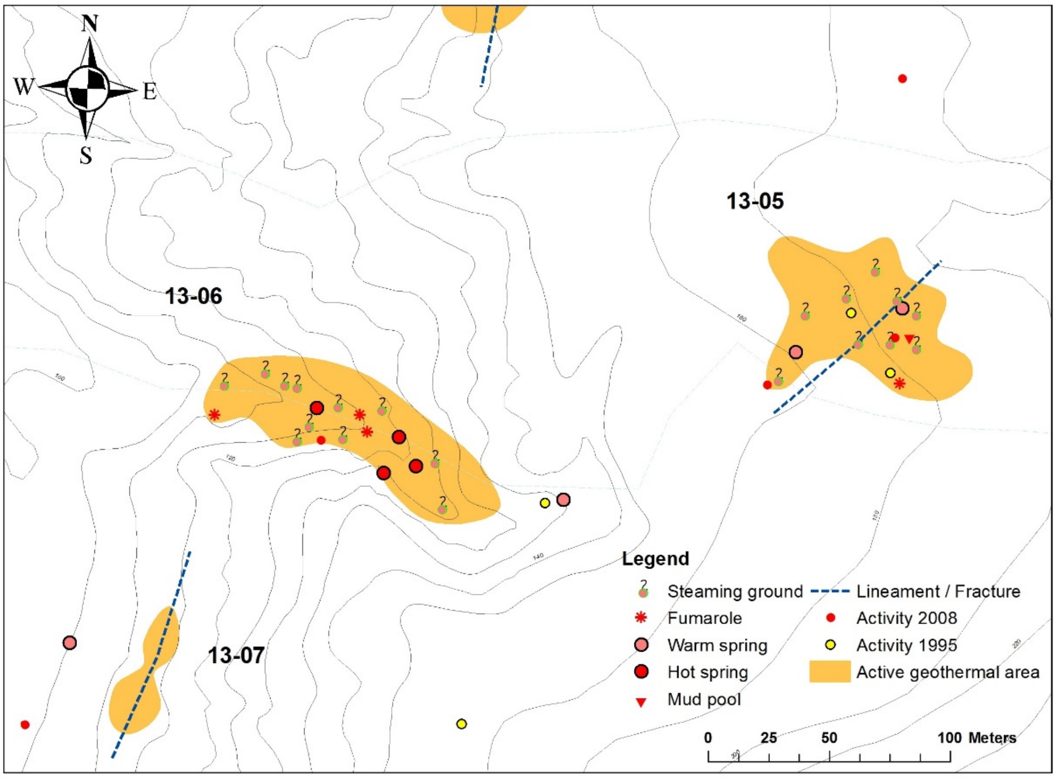


FIGURE 16: Map showing Locations No. 13-05, 13-06 and 13-07

FIGURE 17: The yellowish green moss in the warm ground at Location No. 13-07

Location No. 13-10: This recently active area is located in the rock fall area; steaming grounds are about 10 m in width and extend several tens of metres to the south, as shown in Figure 21. The steaming grounds contain white and yellow precipitates and three samples were tested (Samples No. 2, 3 and 4) in the laboratory using XRD which identified the presence of amorphous silica (opal), gypsum and anhydrite. One fumarole and one small mud pool are present and steaming ground gives rise to $H_2S$ odour. Although the subsurface structures are covered by a rock fall/surface deposits, geothermal activity at the surface indicates a sub-surface structure with a lineament/fracture striking NE-SW.

Location No. 13-11: The area contains 20 x10 m size warm ground (temperatures up to 70°C) covered with yellowish green moss and several warm springs with temperatures ranging from 50-60°C, including a warm spring (38°C) having a flow-rate of 1 l/s. Another 10 × 10 m size warm ground is located close to the major spring area and the activity of this area started after the earthquakes in 2008 and has increased since then. The area is presented in Figure 21 and shows a NW-SE trend. A sample collected by the spring (Sample No. 5) for XRD analysis indicates the presence of calcite.

Location No. 13-12: A number of steaming grounds with temperatures greater than 95°C are scattered in this area. A large area of warm grounds is observed surrounding the steaming grounds (Figure 20). The activity in this area started after the earthquakes in 2008 and currently geothermal activity in the area is increasing, trending N10°E.

The map shown in Figure 21 shows the geothermal manifestations representing the areas of geothermal activity. The general trend of the manifestations is aligned in the direction of NE-SW. The geothermal activity in the areas of Locations No. 13-10, 13-11 and 13-12 was new and started soon after the earthquakes in 2008, and activity is still increasing. In 1995, no geothermal activity in this area was reported. Location No. 13-09 shows old geothermal activity and has evidence of an extinct geyser.

FIGURE 18: The geothermal activity at Location No. 13-08

FIGURE 19: At Location No. 13-09 there is an extinct geyser area having several mud pools, boiling spring/geyser and steaming grounds

FIGURE 20: Steaming grounds and warm grounds in the area of Location No. 13-12

## 5. DISCUSSION

Mapping of surface manifestations on the east side of Gufudalur valley, Hveragerdi, has revealed new manifestations which were created after major earthquakes struck in 2008. When comparing the author's study to previous studies carried out in 1995 by Saemundsson, and soon after the earthquakes (Thorbjörnsson et al., 2009), new manifestations are revealed in the area and there has been an increase in geothermal activity from 2008 to 2013. New surface manifestations such as fumaroles/steam vents, hot springs, boiling springs, warm grounds, hot grounds and steaming grounds were identified towards the high elevated areas on the east slopes of the valley, indicating that new lineaments/fractures had opened, virtually parallel to the old fractures.

Some parts of the study area are covered by landslides and rock slides and, therefore, most of the geological features are covered by surface deposits, but in some locations geothermal activity has been powerful enough to manifest itself at the surface, revealing the subsurface conditions, and the manifestations indicate a pattern of alignment striking NE-SW and NNE-SSW.

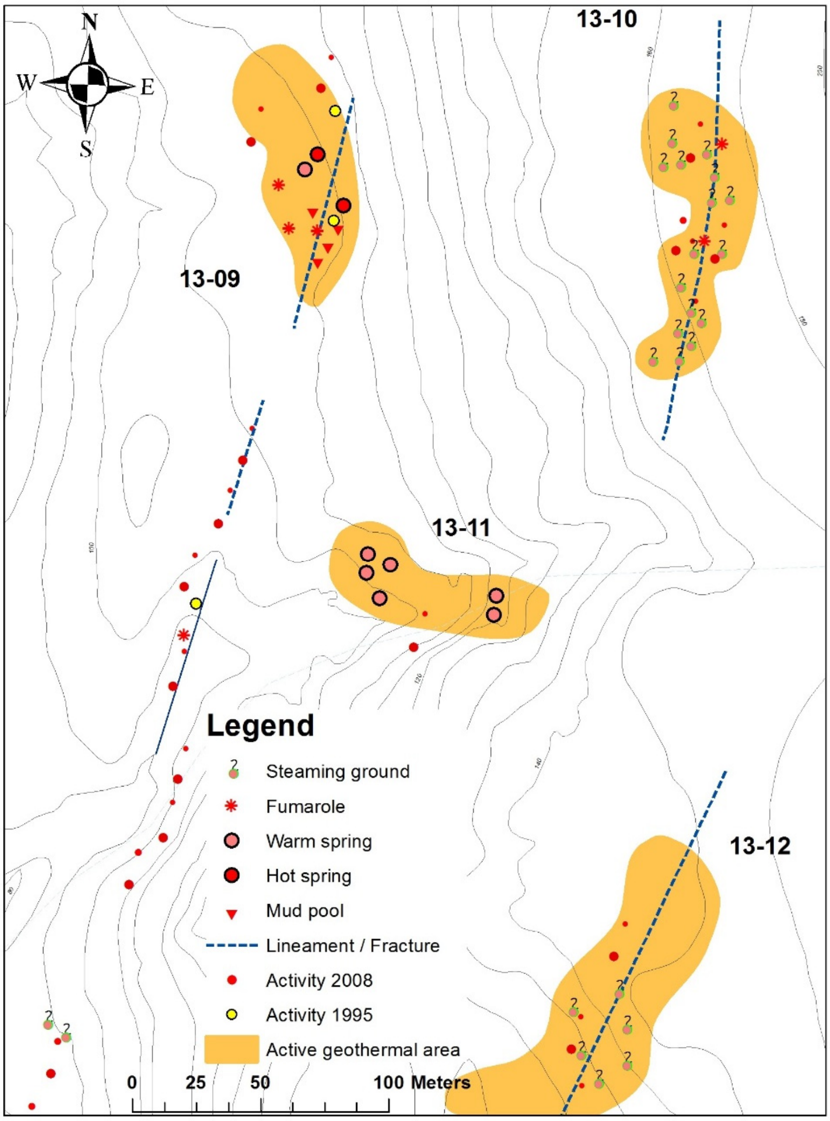


FIGURE 21: Map showing the extent of geothermal activities at Locations No. 13-09, 13-10, 13-11 and 13-12

## 6. CONCLUSIONS

Detailed geothermal mapping of surface manifestations was carried out in the Gufudalur valley, Hveragerdi geothermal field, which indicated that the geothermal manifestations are the result of large earthquakes affecting tectonic structures.

The east side of the Gufudalur valley area is characterized by widespread geothermal manifestations having variable temperatures, and variable degrees of alteration, controlled by structural elements such as faults and fractures. The alignment of geothermal manifestations is in preferred directions indicating geological structures derived from tectonic activity and structural control. The major faults represent several fractures on the surface while the fractures unite in the sub surface.

By investigating the new geothermal surface manifestations, new lineaments/fractures were identified on the eastern side of the valley, trending N-S and NE-SW, which were formed by two earthquakes which occurred in Hveragerdi and Selfoss on 29th May 2008. The major structural trends that control the geothermal manifestations are oriented NE-SW, but NW-SE and N-S oriented lineament/fractures and faults are also present. The earthquakes in 2008 created new, or renewed, geothermal activity; the geothermal activity has intensified and new surface manifestations are still appearing in the Gufudalur, Hveragerdi area.

On the basis of geothermal mapping, the geothermal manifestations are controlled by the tectonics and topography. Some parts of the study area are covered by rock falls, landslides or avalanche deposits. Therefore, the presence at the surface of geothermal phenomena may be heavily dependent on the individual sizes of the rock falls, landslide blocks and their thickness. Consequently, the faults and fractures that control the flow of the hydrothermal fluids may be hidden underneath major landslides and rock falls.

The local groundwater level can change seasonally, affecting the appearance of geothermal manifestations like hot springs, mud pools and steam vents in such a way that when the groundwater table is high, it forms boiling/hot springs, but they can change to mud pits and eventually to steam vents when the ground water level is low.

Colour changes in the vegetation in warm grounds, such as yellow to green moss and grass, reflect temperature distribution and vegetation over the dyed vegetation, indicating changes of the phenomena due to heating or cooling.

Seven samples were tested in the XRD to identify the mineral precipitates and salts found in the steaming grounds (Samples No. 1, 2, 3, and 4), warm springs (Samples No. 5 and 6), and extinct geyser deposits (Sample No. 7). The laboratory results indicate the presence of amorphous silica (opal) in Samples No. 3, 4 and 7; calcite was found in Samples No. 5 and 6; gypsum and anhydrite minerals were found in Samples No. 1 and 2. The results are shown in Appendix I.

## 7. RECOMMENDATIONS

- Geothermal manifestations indicate that new faults/fractures were formed by the two major earthquakes in 2008, showing that geological structures such as faults, shear zones, fissures and lineaments are derived from active tectonic activities.
- The type of geothermal mapping for geothermal exploration completed in this study can be applied in the prospect for utilizing geothermal energy for small scale, binary power generation in Sri Lanka.
- It is essential to create and increase awareness amongst decision makers and politicians on the importance of geothermal energy as a clean renewable energy source, as opposed to fossil fuel burning power stations.
- More people should undergo training in various disciplines relevant to geothermal development for the purpose of increasing the number of qualified geothermal personnel in Sri Lanka.
- The mobilization of funds for detailed geothermal resource assessments in potential geothermal areas of Sri Lanka is highly recommended.

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**APPENDIX I: XRD results of seven samples of mineral precipitates**

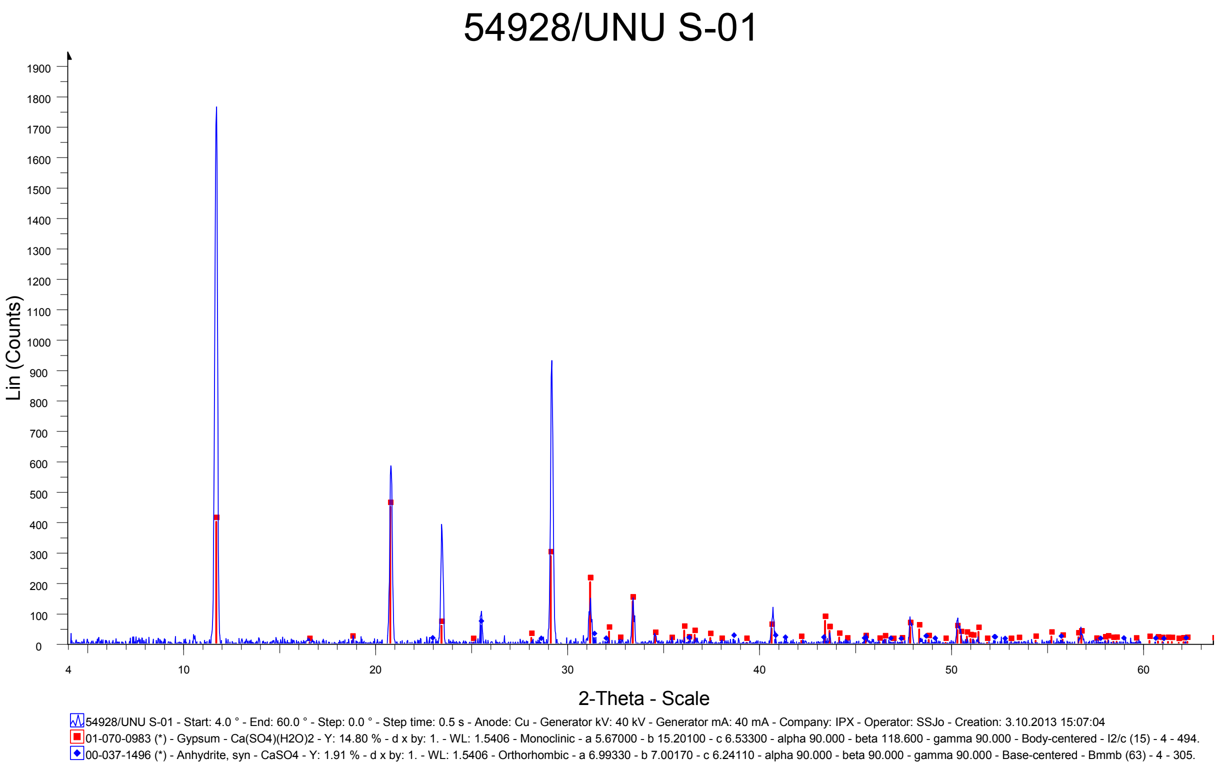


FIGURE 1: XRD graph showing the presence of gypsum and anhydrite minerals in Sample No. 1 collected in steaming ground at Location No. 13-8

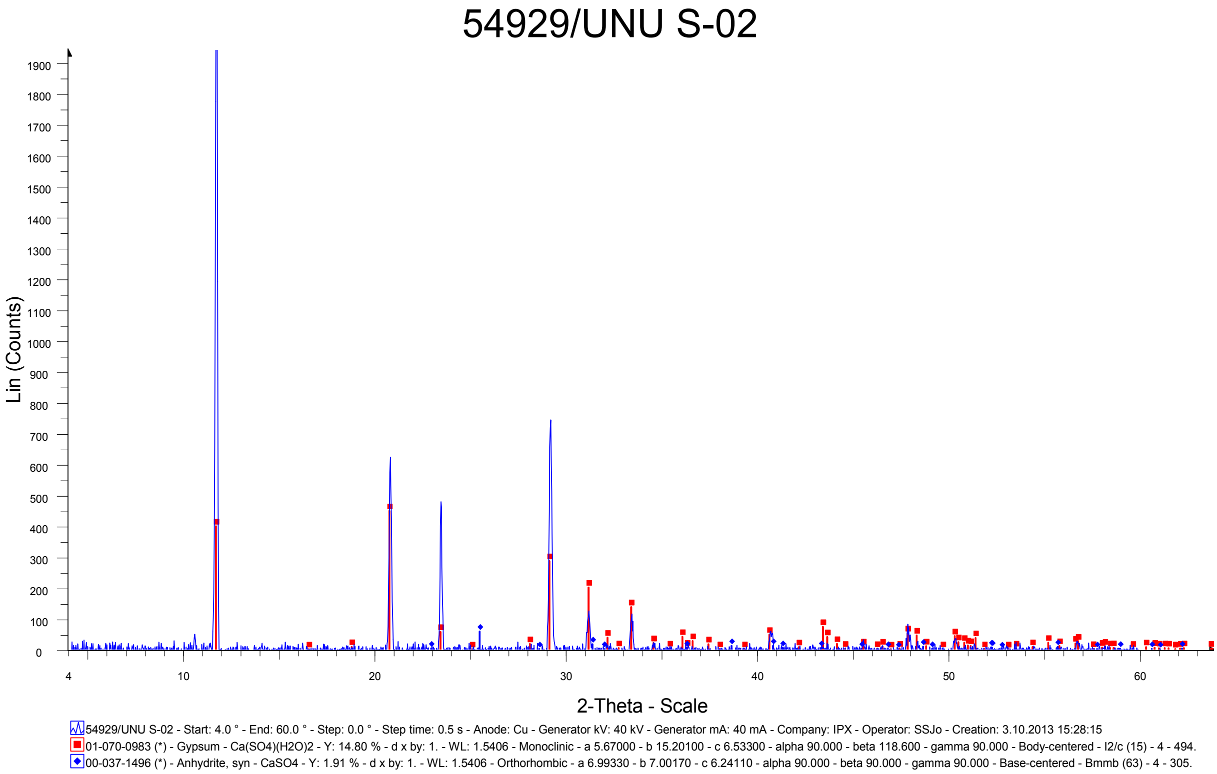


FIGURE 2: XRD graph showing the presence of gypsum and anhydrite minerals in Sample No. 2 collected in steaming ground at Location No. 13-10

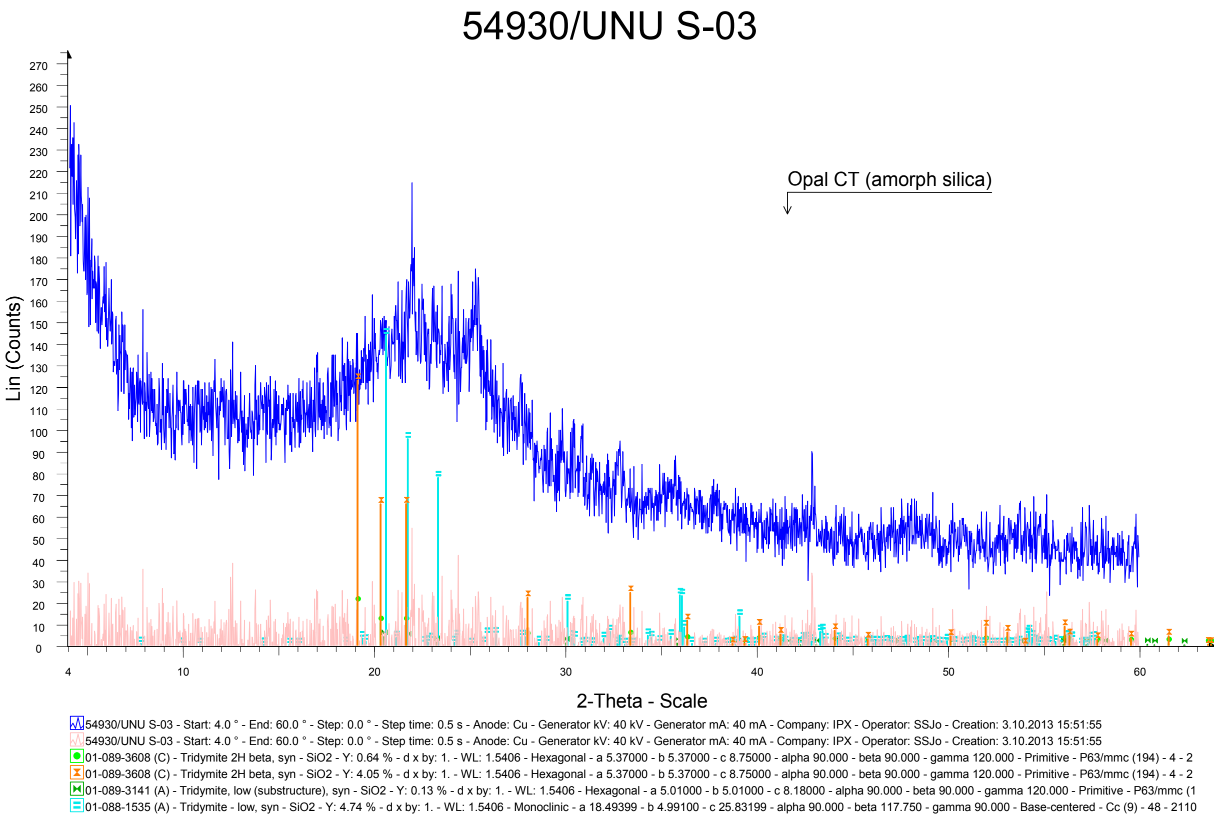


FIGURE 3: XRD graph showing the presence of amorphous silica (opal) in Sample No. 3 collected in steaming ground at Location No. 13-10

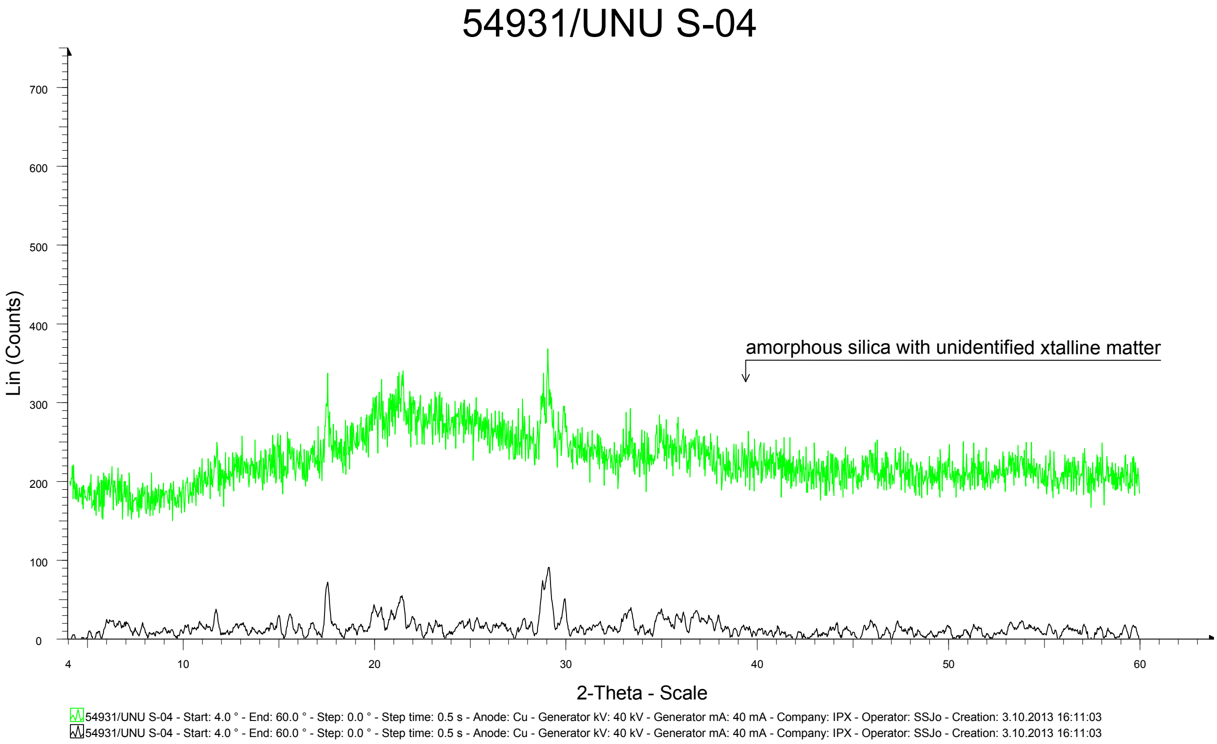


FIGURE 4: XRD graph showing the presence of amorphous silica (opal) in Sample No. 4 collected in steaming ground at Location No. 13-10

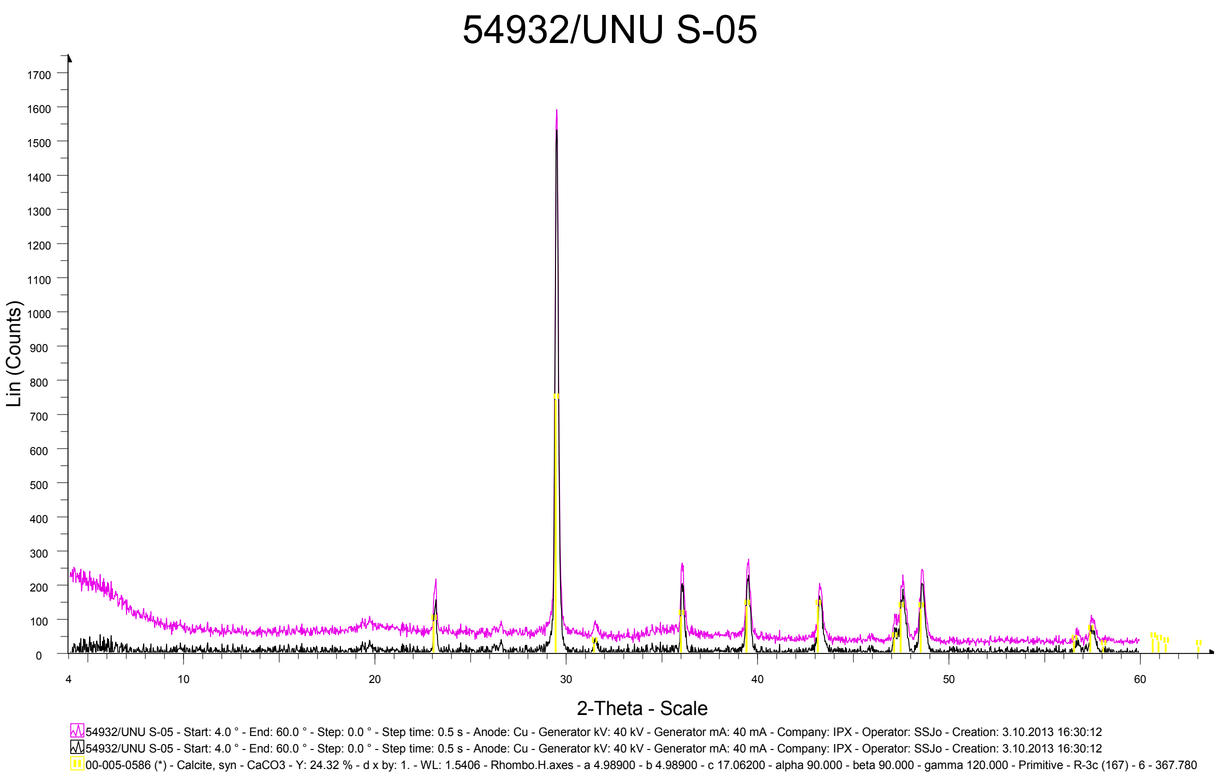


FIGURE 5: XRD graph showing the presence of calcite in Sample No. 5 collected in warm spring at Location No. 13-11

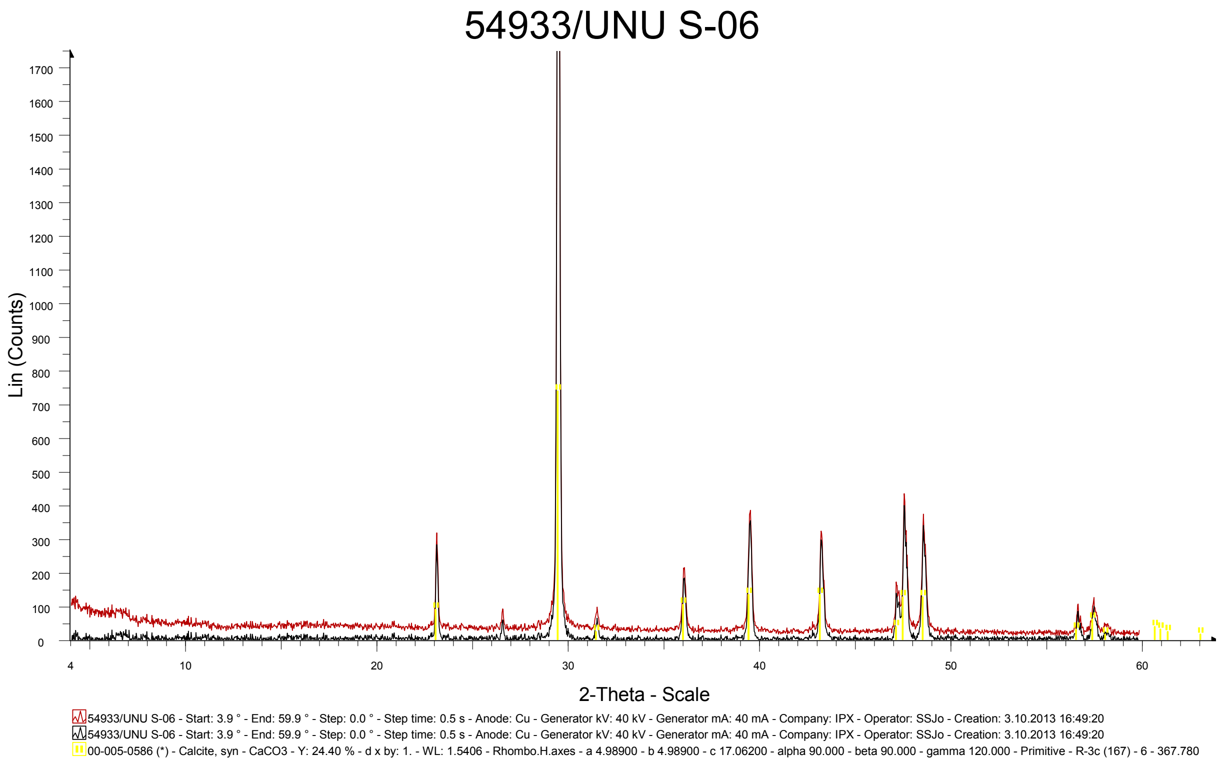


FIGURE 6: XRD graph showing the presence of calcite in Sample No. 6 collected in warm spring at Location No. 13-05

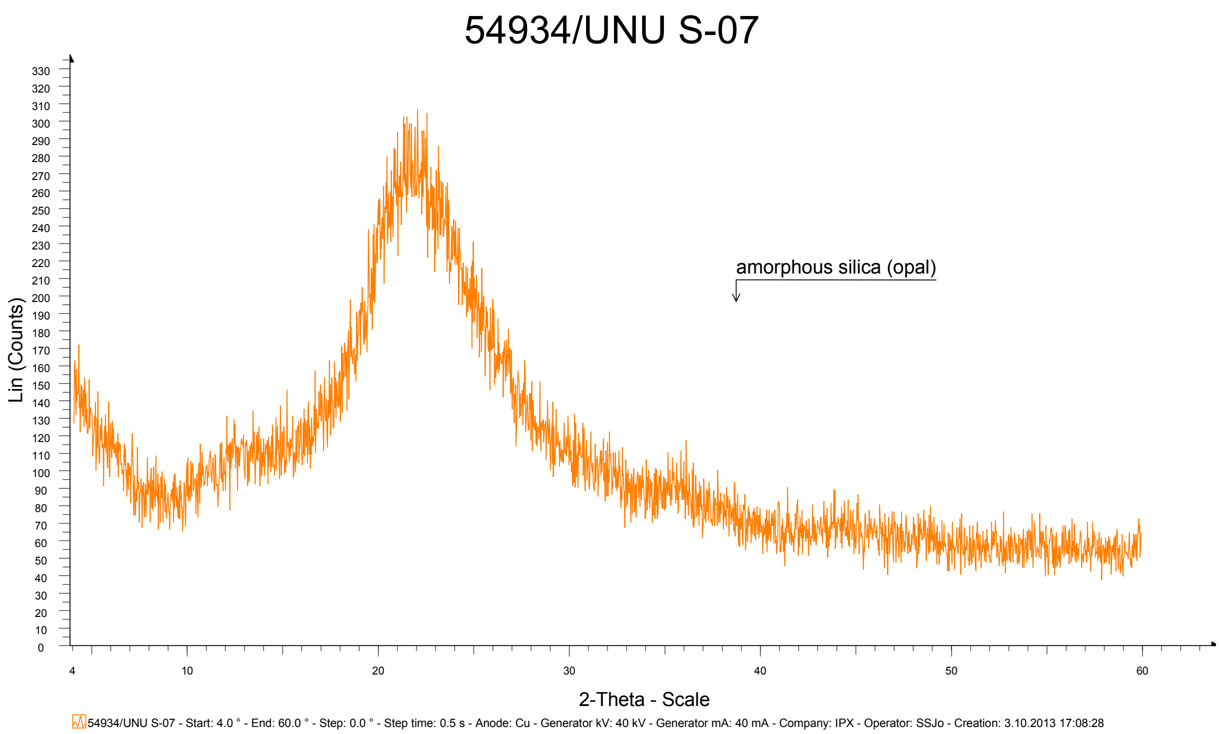


FIGURE 7: XRD graph showing the presence of amorphous silica (opal) in Sample No. 7 collected in extinct geyser deposit at Location No. 13-8