



GEOTHERMAL GRADIENT AND GEOLOGY OF HOFFELL LOW-TEMPERATURE FIELD, SE-ICELAND

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ABSTRACT

The study area is a part of the Geitafell central volcano in southeast Iceland. This area has been studied extensively for the exploration of geothermal resources, in particular low-temperature, as well as for research purposes. A geological map is the foundation on which a geothermal exploration is based. All other data need to be interpreted in view of the observed or known geological features. During geothermal exploration, geothermal maps should emphasize on young igneous rocks that could act as heat sources at depth. They also show the distribution and nature of fractures and faults, and the distribution and type of hydrothermal alteration. This report describes the results of a geothermal and geological mapping project in a low-temperature geothermal field in SE-Iceland. The aim of the study was to familiarize the author with geothermal gradient mapping, interpretation of geological information, including tectonic structures and low-temperature geothermal manifestations, as well as to study the site selection for production/exploration well drilling. Another goal of this study was to make geological and geothermal maps of a volcanic field and to analyse whether some relationship could be established between the tectonic setting and the geothermal alteration of the study area. The geothermal model of the drilled area is consistent with the existence of a structurally controlled low-temperature geothermal reservoir at various depths ranging from 50 to 600 m. Televiewer data showed that Wells ASK-29, ASK-50, ASK-56, ASK-82, and ASK-83 drilled in the area have open fractures and show a comparatively high geothermal gradient, indicating that further drilling for exploration/production should be executed. A geothermal map is presented on which possible drilling targets for a production well are suggested.

1. INTRODUCTION

1.1 Location, topography and climate of the study area

The study area, located in SE-Iceland (Figures 1 and 2), is home to a low-temperature geothermal field, which is about 400 km east of Reykjavik, the capital city of Iceland. It is located at 64°42'20''N – 64°44'20''N and 15°04'20''E – 15°06'30''E. Within the region the extinct central volcano of Geitafell is found, but it was active five million years ago (Fridleifsson, 1983a).



FIGURE 1: Map showing the location of the study area

Today the roots of the volcano can be seen, due to glacial erosion. The topography comprises mountains of volcanic rocks and a valley mostly covered by alluvium and vegetation. The altitude is between 30 and 500 m above sea level. Since the study area is close to the Atlantic Ocean, it is affected by the Irminger current, which greatly moderates the climate along Iceland's southern and western coasts. The climate of the area is characterized by a fairly cold winter and a moderate summer. The area receives a relatively high mean annual precipitation, between 1100 and 2100 mm per year. Winter is cold with a mean daily temperature in the range between -2 and -4°C . Summers are fairly warm, with a mean monthly temperature of about $8-10^{\circ}\text{C}$ (Einarsson, 1991). The weather is highly unpredictable since rainfall may occur at any time, and snowfall can prevail in the winter. There are two glacial rivers, Austurfljót and Sudurfljót, draining the area. These are braided river systems which flow across a sandur plain, known as Hoffellssandur, on which the mountain of Svínafell (323 m) is located.

1.2 Background and objectives

Bangladesh is one of the poor and developing countries which suffer from a serious shortage of electricity. About 40% of the country has electricity coverage. Frequent power cuts also cause severe problems. In order to improve the electrical supply, the Geological Survey of Bangladesh (GSB) initiated a drilling programme in 2010, exploring possible geothermal resources in the north-western part of the country. During the exploration phase of geothermal prospects, geological mapping of surface geothermal manifestations and low-temperature surveys are essential for evaluating geothermal resources. Therefore, on the request of GSB, The Geothermal Training Programme of the United Nations University (UNU-GTP) in Iceland kindly approved the present author to attend the programme in the specialized field of geological exploration in 2013. This study is a part of a six month training course at the UNU-GTP in Iceland in 2013 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 volcanic field at Hoffell in SE-Iceland as a study area. This is a low-temperature geothermal field and the author was trained in exploring such an area and how to analyse, interpret and present the data which was gathered.

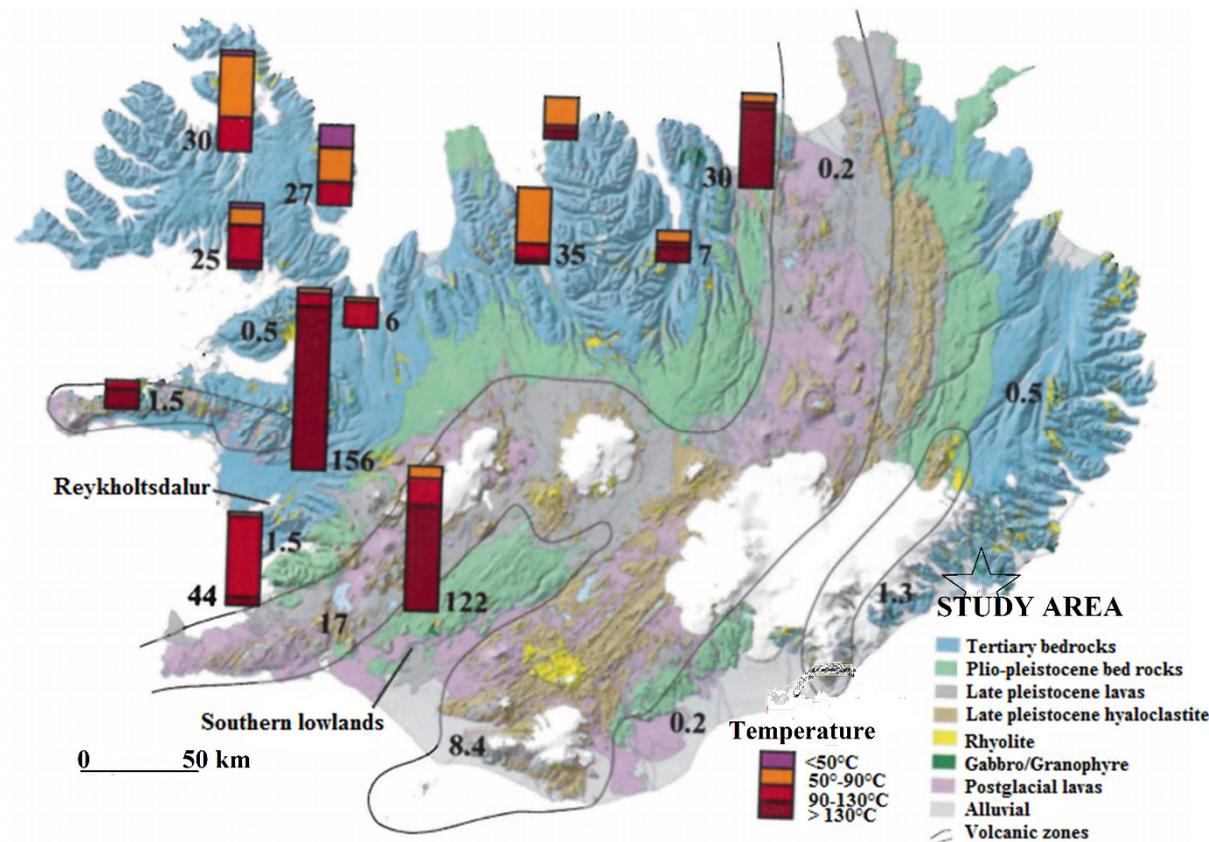


FIGURE 2: Geological map of Iceland (modified from Jóhannesson and Saemundsson, 1999)

1.3 Previous work

The geothermal area is mentioned in several reports but the first comprehensive study of the geology of the area appeared in the PhD thesis of Gudmundur Ómar Fridleifsson (1983a). The field was explored for geothermal applications in 1992 when the first wells were drilled. Later Stapi- Geological Services (1993, 1994, 2002, 2005, and 2006) did geothermal studies in the area on the basis of the temperature gradients of the region. Hjartarson et al. (2012) went through all existing data and made suggestions regarding further work in the area. Árnadóttir et al. (2013) used a televiewer in order to better acquire indications of the direction and angle of fissures and faults in 7 wells. Also, temperature, dimensional, neutron and gamma measurements were completed in the same research. Based on these results, exploration/production Well HF-01 was sited and drilled. The results from that well confirm the existence of an 80°C geothermal field (Kristinsson et al., 2013). Besides these, some studies were also completed about the surrounding study area. Burchardt and Gudmundsson (2009) worked on the infrastructure of Geitafell volcano, southeast Iceland. Three-dimensional modelling of Geitafell volcano was done by Burchardt et al. (2011).

2. GEOLOGY AND TECTONIC SETTING OF ICELAND

2.1 Geology

Iceland is geologically a young country. It is located on the spreading boundary of the Mid-Atlantic Ridge, where the American and Eurasian tectonic plates are diverging at an average rate of 2 cm per year (Figure 3). Iceland is formed by the coincidence of the spreading boundary of these plates and a

hotspot or mantle plume. As the plates move apart, excessive volcanism caused by the mantle plume construct the island. Iceland is the largest island on the Mid-Atlantic Ridge because of the additional volcanism caused by the plume, which is stationary. However, the NW movement of the plate system as a whole, relative to the plume, has caused several rift jumps to the east throughout the geological history of the island (Hardarson et al., 1997). The oldest rock formations date back to the late Tertiary basaltic lava pile, which is predominantly exposed in the eastern and northwest quadrants of the island (Figure 2). The oldest rocks are dated at approximately 16 Ma in the extreme northwest region (Hardarson et al., 1997). The Quaternary rocks are composed of sequences of basalt lavas and hyaloclastites that are exposed along the volcanic zones. The nature of the volcanic products during this period was strongly controlled by climatic conditions. The volcanism is divided into interglacial (ice-free) volcanism and subglacial (glacial) volcanism (Saemundsson, 1979, 1980). The ice free volcanism is categorized into inter- and post-glacial volcanism, and the rock types erupted under this climatic condition are represented by subaerial eruptions forming lava flows, pyroclastic scorias and welded lavas. The glacial volcanism is divided into sub- and supraglacial volcanism, and eruptions are characterised by phreato-magmatic deposits and the formation of hyaloclastites. The surface geology is entirely made up of volcanic rocks with basalts being 80-85% of the volcanic pile, and acid and intermediate rocks 10%. The amount of sediments of volcanic origin is 5-10% in a typical Tertiary lava pile, but may locally be higher in Quaternary rocks (Saemundsson, 1979; Jakobsson and Gudmundsson, 2008).

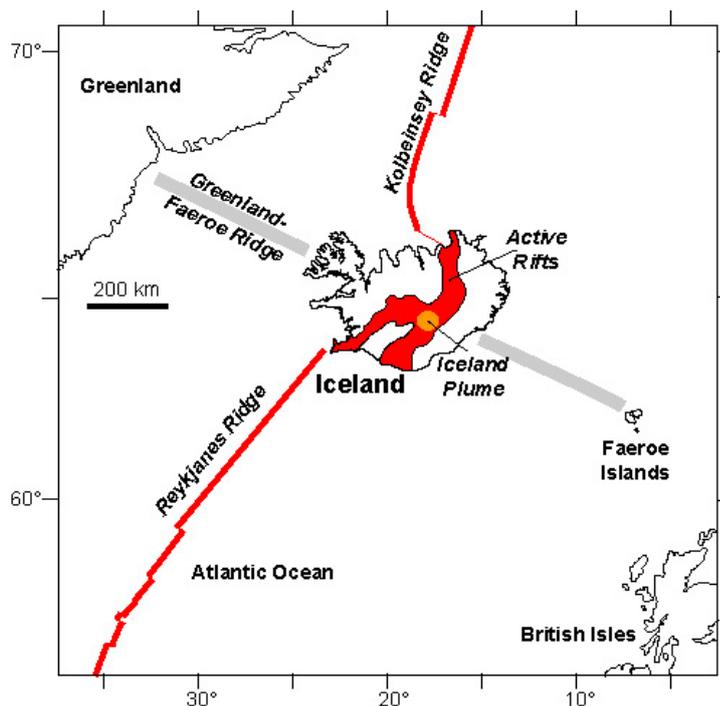


FIGURE 3: Tectonic systems of Iceland (modified after Keck Junior Research Project, 2004)

2.2 Tectonic setting

Iceland lies astride the Mid Atlantic Ridge on the diverging North American and Eurasian Plates (Figure 3). The tectonic plates move apart, towards southeast and northwest, and both the North American and the Eurasian systems move to the northwest across the stationary hot spot. On top of hot spots, generally a 20-100% molten layer is found at a depth of 5-20 km, which supplies sufficient material for eruptions (Bjarnason, 2008). Iceland is home to more than 100 volcanoes, over 25 of which have erupted in recent history (Jakobsson and Gudmundsson, 2008). Eruptions occur about every 5-10 years and primarily consist of basaltic lava and tephra. A few long-lived centres, such as Mt. Hekla, erupt more silicic magmas (Blake, 1970). Iceland is by

far the biggest subaerial part of the Mid Atlantic Ridge and, while the North Atlantic is spreading symmetrically away from the mid-ocean ridge (Hjartarson, 2009), the ridge itself migrates over the plume and repeatedly shifts its spreading axis through rift jumping (Hardarson et al., 1997). The Mid Atlantic Ridge is a constructive plate boundary while the Greenland-Iceland-Faeroes Ridge is thought to be the trail of the Icelandic mantle plume, which has been active from the time of the opening of the North Atlantic Ocean 60 million years ago to the present (Sigmundsson and Saemundsson, 2008). The mantle plume is seen to be located below Central East Iceland (Figure 3), close to the volcanic rift zone which crosses Iceland from southwest to northeast (Figures 2 and 4) and is divided into two parallel branches in South Iceland (Pálmason and Saemundsson, 1974). In South and North Iceland, the Mid

Atlantic Ridge has been displaced to the east by transform faults which are defined as fracture zones (Óskarsson et al., 1985). The southern fracture zone is called the South Iceland Seismic Zone (SISZ) while the northern one is called the Tjörnes Fracture Zone (TFZ), shown in Figure 4. The volcanic rift zone is about one-third of the area of Iceland. The volcanic rift zone is a zone of active rifting and volcanism and is characterised by well-developed extensional structures such as tension fractures, normal faults and grabens with dykes and normal faults occurring at deeper levels (Gudmundsson, 1998). According to Gudmundsson (1992), a fissure swarm associated with a central volcano may be up to 5-10 km wide and 40-80 km long and make up most of the volcanic rift zone.

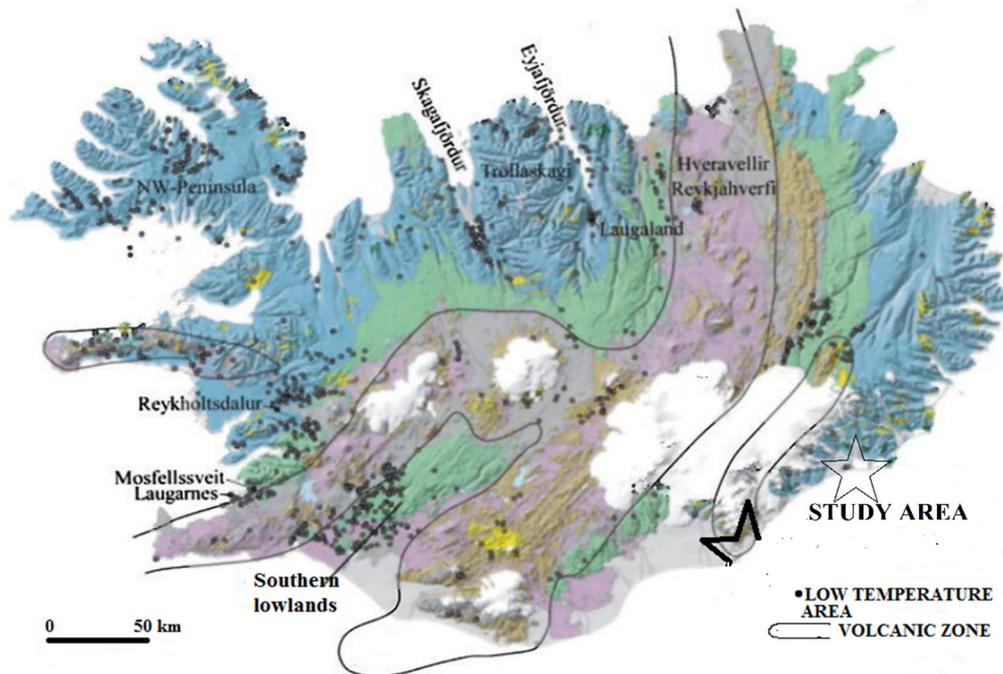


FIGURE 4: Map showing the distribution of low-temperature areas in Iceland; the volcanic zones are enclosed by a dark line (modified from Jóhannesson and Saemundsson, 1999)

3. GEOTHERMAL ACTIVITY IN ICELAND

Iceland is one of the most volcanically active places on earth, resulting in a large number of volcanoes and hot springs. Earthquakes are frequent, but rarely cause serious damage. More than 200 volcanoes are located within the active volcanic zone stretching through the country from the southwest to the northeast, and at least 30 of them have erupted since the country was settled (Arnórsson et al., 2008). It is characterised by high heat flow due to its geological location on a divergent plate boundary. The regional heat flow ranges from 80 to 200 mw/m^2 , furthest away from and near the spreading zone, respectively (Neuhoff et al., 1999). Geothermal activity in Iceland has been classified as high-temperature and low-temperature fields. Surface activity in the low-temperature geothermal areas is distinctly different from that of the high-temperature areas as described below.

3.1 High-temperature activity

The high-temperature fields are defined by temperatures above 200°C at 1 km depth in the crust and they are located in the belts of active volcanism within the rift zone (Figure 4). The heat sources of high-temperature geothermal fields are high level magma chambers and magmatic intrusions. Most of the high-temperature geothermal fields lie astride active fissure swarms where the fissures intersect the

lithospheric plate boundary. Central volcanic complexes have formed at some of these points and calderas have developed in several of them. Geothermal manifestations of high-temperature fields are characterised by the occurrence of fumaroles, mud pools, hot springs, and geysers. They are mainly used for the production of electricity but also for hot water.

3.2 Low-temperature activity

The low-temperature areas are fracture and fault dominated deriving their heat from convection within the cooling lithospheric plate. According to Arnórsson and Gíslason (1991) low-temperature geothermal activity in Iceland is the consequence of one or more of the four following scenarios:

- a) Deep circulation of groundwater from higher to lower elevation along fractures or other permeable structures, driven by a hydraulic head.
- b) Convection in young fractures formed by deformation of older crust.
- c) Drift of high-temperature geothermal systems out of the active volcanic belts, accompanied by cooling due to displacement from the magmatic heat source.
- d) Intrusion of magma into fractures or other permeable formations by the margins or outside the volcanic belts.

The heat-source for low-temperature activity in Iceland is believed to be the island's abnormally hot crust, but faults and fractures, which are kept open by on-going tectonic activity, also play an essential role by providing channels for the water that circulates through the systems and mines the heat. Outside the volcanic zones, the temperature gradient varies from about 150°C/km near the margin to about 50°C/km farther away (Arnórsson et al., 2008). There are more than 250 separate low-temperature areas with temperatures, not exceeding 150°C in the uppermost 1,000 m, mostly in the areas away from and flanking the active volcanic zones (Figure 4) (Burchardt and Gudmundsson, 2009).

3.3 Utilization of low-temperature geothermal energy

Low-temperature geothermal energy has been utilized for many purposes, both for direct use and for binary power plants. Initially in Iceland it was used for bathing and washing. The first trials to use geothermal energy for space heating were made in the middle of the 18th century in Iceland. Direct heating in all its forms is far more efficient than electricity generation and places less demanding temperature requirements on the heat resource. Heat may come from co-generation with a geothermal electrical plant or from smaller wells or heat exchangers buried in shallow ground. As a result, geothermal heating is economical over a much greater geographical range than geothermal electricity. Where natural hot springs are available, the heated water can be piped directly into radiators. Low-temperature geothermal heat is also used for swimming pools, fish farming, to heat greenhouses and by many companies to dry products like fish heads and wood. The study area at Hoffell in SE-Iceland is home to low-temperature geothermal energy. The main use of this energy is for space heating and bathing (Figure 5) in the adjoining region.



FIGURE 5: Low-temperature geothermal water being used for bathing at Hoffell

4. GEOTHERMAL AREA OF THE GEITAFELL CENTRAL VOLCANO, SE ICELAND

4.1 Introduction

The study area is partly related to the extinct Geitafell central volcano. The total thickness of strata from the volcano is 2700 m which indicates that the volcano was a high mountain. The volcano has two major structural elements: 1) a caldera fault and 2) a flexure zone. It was active about 5 million years ago but glacial erosion has since exposed its core (Fridleifsson, 1983a). The study area by Hoffell (Figure 6) is outside the caldera fault as can be seen on the geological map in Figure 7. The volcano is located northwest of the town Höfn (Figure 1) and has been deeply carved and eroded by the glaciers of the last glaciation.



FIGURE 6: Photograph showing the study area around the Hoffell farm

4.2 Geology and tectonic setting of the study area

The Geitafell central volcano was formed within a rift zone (Saemundsson, 1979). The study area is located within this volcanic complex. It was active five to six million years ago and activity lasted for about a million years (Fridleifsson, 1983a). The area consists mostly of tholeiitic rocks of which 60% are basaltic lavas and 30% hyaloclastites (Figure 7). Several gabbro bodies are exposed in its core, representing the uppermost part of an extinct crustal magma chamber surrounded by a dense swarm of inclined sheets. Intrusive rocks of the Geitafell volcano are composed of several gabbro, granophyre and felsite intrusions, together with dyke and sheet swarms. A dense swarm of inclined (cone) sheets is in direct contact with the chamber (Fridleifsson, 1983a). The sheets and basaltic dykes range from aphyric porphyritic dolerites to aphyric and fine grained, porphyritic basalt. The overall pattern of the tectonics relates to divergent movement of crustal plates and is accompanied by inflow of magma to all crustal levels. The general characteristics of the dilation tectonics involved are open fissures and grabens at the surface but normal faulting at depth (Fridleifsson, 1983a).

4.3 Stratigraphic units of this volcanic area

The research area is separated into 7 major stratigraphic units. The stratigraphic division is described below (Fridleifsson, 1983a):

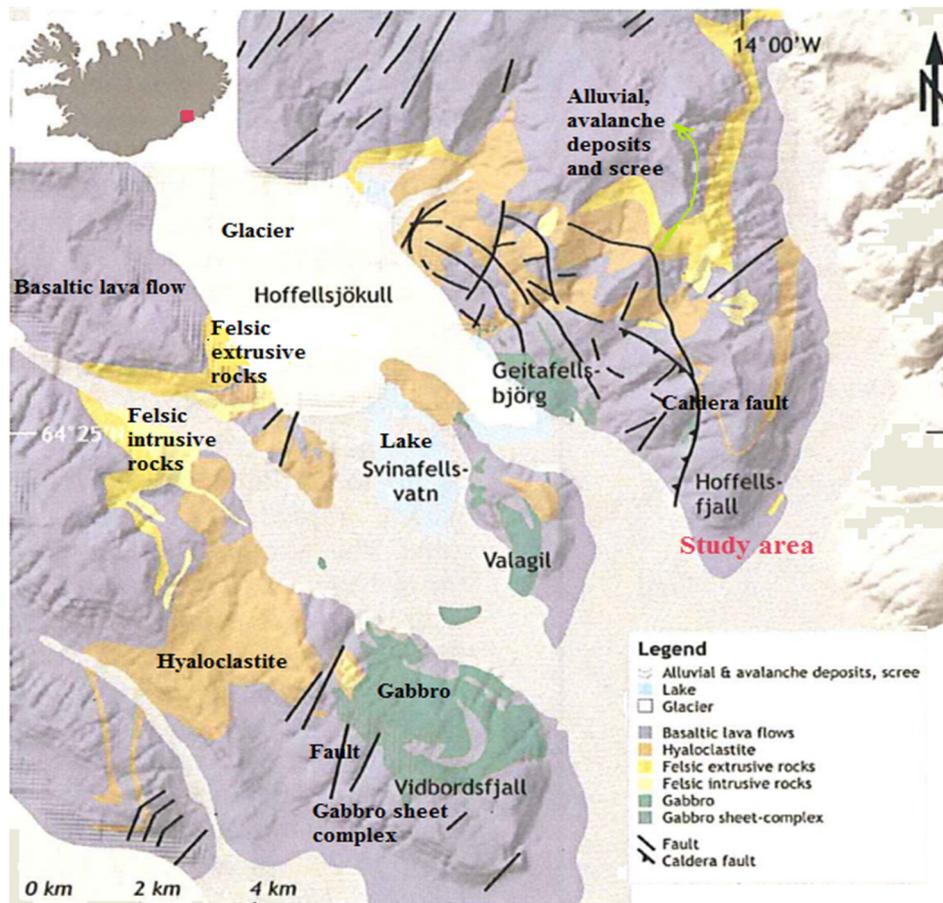


FIGURE 7: Geological map of the study area (modified from Fridleifsson, 1983a)

Basaltic lava unit-I (B-I): This unit is mainly composed of tholeiitic lavas. The unit is divided into three sub-units. B-I unit thickens towards the centre of a hypothetical NE-SW striking fissure-swarm crossing the Geitafell central volcano. The maximum thickness of this unit is 750 m.

Rhyolite unit-I (R-I): This unit is located within the basaltic lava unit-I the volcano which comprises mixed composition. An altered pitchstone layer, granophyric intrusion and acid tuff are found in this unit. Maximum thickness of this unit is 50 m.

Hyaloclastite unit-I (H-I): Mainly composed of aphyric basalt clasts, but acid clasts also occur in some locations. Basic pillow lava is not found within this unit but pillow fragments occur in many places. This unit is heavily intruded and highly brecciated by sheets.

Basaltic lava unit-II (B-II): This unit comprises thick tholeiite, olivine tholeiite, feldspar tholeiite, and feldspar porphyritic basalt flows. Most of the lavas are believed to have been erupted outside the Geitafell central volcano. The maximum thickness of this unit is 700 m.

Hyaloclastite unit-II (H-II): This unit consists mainly of aphyric basalt fragments and reworked, porphyritic, boulder beds as well as feldsparphyric tuff. In addition, some highly vesicular interbedded lava flows may be found. This unit is maximum 300 m thick.

Rhyolite unit-II (R-II): The unit comprises three rhyolitic lavas. Acid tuff beds with two thinner rhyolitic lavas are interbedded in the base of lava unit III.

Basaltic lava unit-III (B-III): The unit comprises thick tholeiite, olivine tholeiite and feldspar porphyritic basalt flows, some of which also contain phenocrysts of pyroxene and olivine. Most of the lavas are regarded as having been erupted outside the Geitafell central volcano.

4.4 Stratigraphy of the study area

The study area is mainly composed of tholeiitic lavas which lie under the basaltic unit-I (B-I). Heavily intruded and highly brecciated by sheets as well as aphyric basalt clasts and acid clasts bearing older hyaloclastite units are included in this area. Feldsparphyric basalt lava under the unit of basaltic lava unit-II (B-II) is also found in the study area (Figure 7). According to Fridleifsson (1983a), the intrusive rocks of this volcanic area have been divided into 12 phases which are described below:

Intrusive phase-1: This phase is regarded as a feeder dyke system to basaltic lava units I and II, rhyolite unit I and hyaloclastite unit II. Acid intrusives are regarded as belonging to intrusive phase I and are only found within rhyolite unit I on the east side of Mt. Hoffellsfjall.

Intrusive phase-2: The Geitafell central volcano, as well as contemporaneous gabbros, constitutes the phase. The gabbro has hypidiomorphic granular texture in which mineral phases are bytownite-labradorite, calcite, augite, and titanomagnetite. Olivine and orthopyroxene are most often completely pseudomorphed, mainly to talc, chlorite and magnetite.

Intrusive phase-3: Feldsparphyric dykes are common in this phase and they are slightly younger than the Geitafell gabbro and apparently related to the same intrusive episode. Only a few members are found to belong to phase-3.

Intrusive phase-4: Acid veins crosscut the pegmatite veins in the gabbro and brecciate the gabbro near the southern end.

Intrusive phase-5: This phase consists of a doleritic cone-sheet swarm, the sheets being 0.5-1.5 m thick. The doleritic sheet swarm is characteristically greyish green and thus differs from all other intrusive phases except intrusive phase-7.

Intrusive phase-6: A Feldsparphyric dolerite sheet swarm is dominant in this phase. The feldspar phenocrysts are bytownite, zoned to labradorite, and a dolerite matrix which is slightly finer grained than in intrusive phase-5.

Intrusive phase-7: It is characterized by a dyke swarm, sometimes feldsparphyric with thickness commonly less than 1 m. The grain size of this phase is similar to that of phase-5.

Intrusive phase-8: A fine grained basaltic sheet swarm forms this phase. The thickness of these sheets varies from 0.3 m to 1 m and is most common in Efstafellsnes, Efstafell area.

Intrusive phase-9: The dykes of this phase are thicker than the sheets. This phase is petrographically similar to phase-8.

Intrusive phase-10: This phase is characterized by highly feldspar porphyritic dykes and sheet swarms which are found with apparently contemporaneous gabbro intrusions in Vidbordsfjall, Kráksgil and Litla Dímon. Phase-10 is believed to have occurred during the caldera formation.

Intrusive phase-11: Large felsitic intrusions, rhyolite or pitchstone dykes and veins constitute the phase. Rhyolite unit-II was probably fed by intrusive phase-11. A close association is seen between intrusive phases 10 and 11.

Intrusive phase-12: Thick dolerite dykes characterize phase-12 with thicknesses varying from 0.5 to 6 m but most of the dykes are close to 2 m across. Unlike the other intrusive phases, the dykes are commonly columnar jointed and relatively fresh but develop characteristic brown weathered surfaces.

5. MINERALOGICAL EVOLUTION AND TECTONICS OF THE GEITAFELL AREA

5.1 Mineralogical evolution

The mineralogical distribution within the Geitafell hydrothermal system is represented by the five mineralogical zones (Figure 8). The five mineral zones all relate to the formerly active high-temperature geothermal system (Fridleifsson, 1983a, 1983b). They are:

- 1) Chlorite zone (Chl)
- 2) Epidote zone (Ep)
- 3) Androdite zone (Gr)
- 4) Actinolite zone (Act)
- 5) Sulphide zone

In particular, four of these zones (chlorite→epidote→garnet→actinolite) show the progressive appearance of the index minerals within both the host rocks and the intrusive rocks (including phase-11). Four to six major mineral vein systems were formed in the volcano. Upon progressive rise in the geothermal gradient within the volcano, the vein mineral deposition changed to silica precipitates (jasper→chalcedony→quartz) and smectite→chlorite. A high-temperature system then became active upon the emplacement of the central gabbros (IP-2) at shallow depths and a sharp change in vein deposits took place. The veins, formed after the IP-2 emplacement, show distinctive depth and spatially related variation, generally involving higher temperature mineral assemblages at depths and towards the volcanic centre. The types of minerals formed in veins related to the high-temperature system within the actinolite zone include epidote, quartz, calcite, actinolite, androditite, and albite (see photo in Figure 9). In the overlying mineral zones, actinolite, quartz, albite, and wairakite sequentially disappear from the vein system, while within the upper part of the epidote zone, epidote and prehnite are more or less restricted to mineral veins and wall rock zones within and in the vicinity of some members of a particular intrusive phase-10 (IP-10) and or in the vicinity of the caldera fault. The last vein systems invariably contain zeolites, chiefly, stilbite and heulandite, related to cooling of the high-temperature system (Fridleifsson, 1983b).

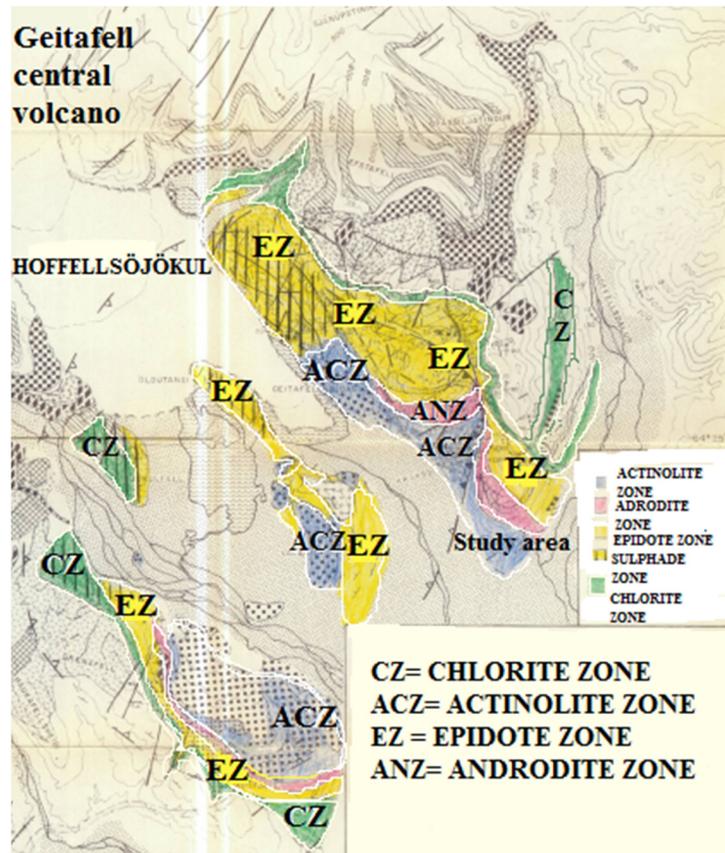


FIGURE 8: Map showing the mineralogical alteration zones around the study area (modified from Fridleifsson, 1983b)

5.2 Intrusive phases

The study area is mainly composed of tholeiitic lavas and dykes but sheets and faults are also found (see photo in Figure 10). The strike direction is north-west and the dip direction is north-east (65-80°NE). According to the description of several intrusive phases, it may be suggested that the study area of Hoffell is under the intrusive phase-5. Dolerite sheets are most common in intrusive phase-5 which is also found randomly near the Hoffell farm area (Fridleifsson, 1983a). Three main mineral zones are found in the study area. Epidote, androdite and actinolite are most common; chlorite zone is also found but scarcely. The study area is mainly composed of a gabbro sheet complex with some felsic extrusives. Dykes and cone sheets, which sometimes cut each other, are also to be noted in this area. This area also forms part of intrusive phases 6, 10 and 12 (Fridleifsson, 1983a).

5.3 Fractures and veins

Fracture systems act as conduits for fluids and play an important role in the extraction of geothermal energy in both liquid- and vapour-dominated fields. Several types of fractures can developed in a rock formation. Several types of vein fillings were observed in the study area which are directly related to the low-temperature geothermal field.

5.4 The hydrothermal system of the Geitafell central volcanic complex

Low-temperature geothermal areas are fed by regional groundwater systems and withdraw heat from a large volume of warm country rocks. The state of any hydrothermal system through time depends upon the interactions of different lithologies, moving fluids, transfer and availabilities of heat and the tectonic scenario within the systems. The way in which these parameters interact with one another is shown in Figure 11. The origin of hydrothermal fluids may be juvenile, magmatic, meteoric, connate, metamorphic, and oceanic; in the Geitafell hydrothermal system, most of the fluids are meteoric or oceanic or a mixture of the two (Fridleifsson, 1983b).

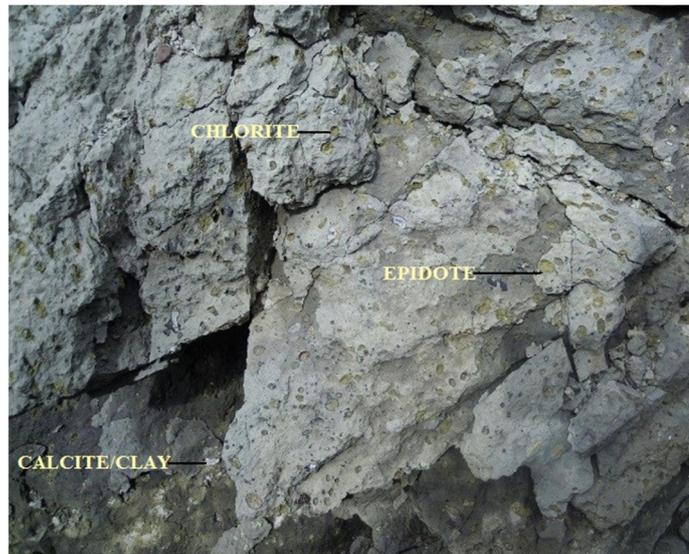


FIGURE 9: Photograph showing vein fillings in a rock found in the study area by Hoffell; green colours indicate chlorite, yellowish green is epidote and white colour indicates calcite or clay mineral



FIGURE 10: Photograph showing dykes in the Hoffell farm area

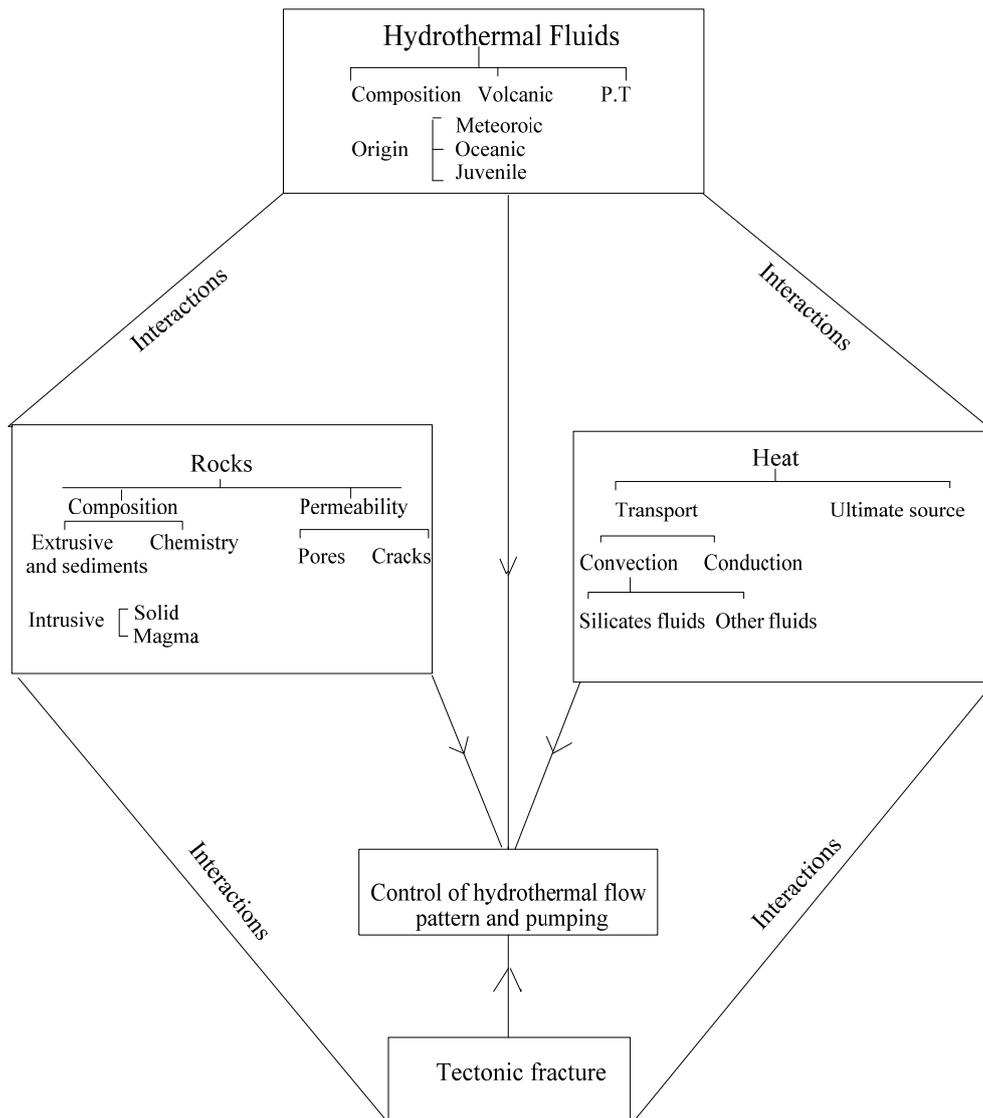


FIGURE 11: Diagram showing the hydrothermal system of the Geitafell central volcano and the adjoining study area (after Fridleifsson, 1983b)

6. WELL HF-1

6.1 Stratigraphy of Well HF-1

Iceland GeoSurvey (ÍSOR) conducted a drilling programme for a deep exploration well in the study area near the farm of Hoffell. The well (HF-1) was drilled down to 1608 m, the main purpose being to confirm the existence of an 80°C hydrothermal system. A detailed lithological description of Well HF-1 is presented below and shown in Figure 12, according to Kristinsson et al. (2013).

Gravel (0-18 m): This layer acts as an aquifer in the area. Mixed rock fragments, basaltic, and acidic, of different grain sizes. The unit represents river deltas and coastal environments.

Lava pile (18-90 m): Eight to nine tholeiitic lava flows separated by scoria.

Sediments (90-92 m): Slightly rounded basalt and glass fragments.

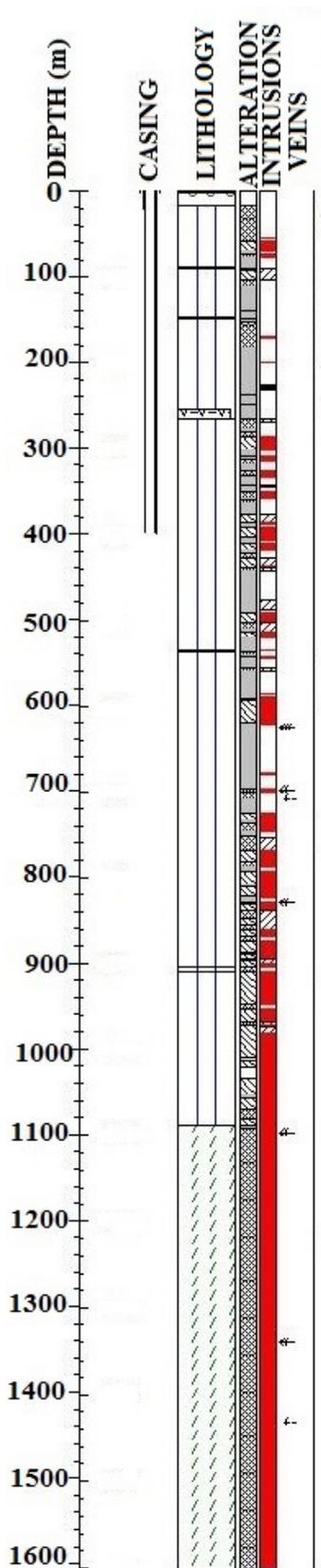


FIGURE 12: Lithology and their description of Well HF-1 at Hoffell farm area, SE-Iceland (modif. from Kristinsson et al., 2013)

Lava pile (92-147 m): The top part is porous and includes some scoria. The pile becomes less porous with depth. Five separated tholeiitic lava flows were observed. Red interlayers are present in between the lavas. The rocks are mainly fine-medium grained and aphyric.

Sediments (147-150 m): Basalt rock fragments and sedimentary grains.

Lava pile (150-256 m): Tholeiitic lava flows (10-12 in number), usually aphyric but plagioclase is found at 204-213 m depth.

Tuff (256-267 m): Oxidized tuff mixed with ash and scoria.

Lava pile (267-537 m): Mostly fine grain tholeiitic lavas. Plagioclase and pyroxene are observed at 315-320 m but otherwise the lavas are mostly aphyric. Pyroxene is found at 359-366 m, and at 420-428 m olivine tholeiite is observed.

Lava pile (537-904 m): The top layer is plagioclase aphyric. At 554-565 m plagioclase and pyroxene are found but it is inconclusive if this is lava or an intrusion. Otherwise, this is mostly a fine to medium grained basalt pile of tholeiites and olivine tholeiites. The largest feed-zone in the well is at 626 m depth which also shows significant washout. Some plagioclase is observed at 680-685 m but otherwise the pile is mostly aphyric. Scoria is found between the lava flows. Below 720 m intrusions seem to become common, indicated by NN and resistivity loggings.

Sediments (904-905 m): The nature of this sediment is unclear. It is very fine grained, darkish with glassy crystals which seem to be pore fillings or rounded phenocrysts, in disequilibrium with the magma. The rock is fairly porous.

Intrusions (905-1608 m): Below 905 m the lithology consists almost entirely of intrusive rocks, even though occasionally lavas may be observed. Below 905 m a granophyre intrusion is encountered which extends to the bottom of the well (1608 m).

6.2 Intrusions

In the study area, several types of intrusions are found. These are mainly gabbro intrusions associated with a large number of intrusive sheets.

Gabbro intrusions: The intrusion has a diapiric form with a steeply plunging feeder and pronounced tabular jointing. This gabbro is the most extensively studied where it rises from the sandur plain. Seven main mineral vein systems were emplaced within the Geitafell gabbro (Fridleifsson, 1983b).

Dykes: The ratio of dykes in the area is high, in some areas they make up to 40% of the strata. The strike is 55°-70°NW and they

dip steeply to the southwest (65-80°SW). There are two main types of dykes, regional dykes, usually 1.5-2 m thick, and steeply dipping cone sheets, usually about 0.6 m thick (Fridleifsson, 1983a). Cone sheets and dykes (Figure 10) are fine-grained basalt to coarse dolerite (Annels, 1967).

Cone sheets: The cone-sheet swarm is of doleritic composition, the dykes usually being 0.5-0.7 m thick but sometimes up to 1.5 m (Annels, 1967). They are greyish green in colour and are readily distinguished from other cone sheets of other intrusive phases. The sheet swarm is widely distributed in the area dipping towards the southwest or northwest. Some sheets are almost vertical as they intrude through the lava pile.

7. GEOTHERMAL MAPPING USING GRADIENT WELLS

A geothermal or temperature gradient is a physical property that describes in which direction and at what rate the temperature changes in units of degrees (on a particular temperature scale) per unit length. The rate of change in temperature in a given direction, especially in altitude, is a temperature gradient of the change of temperature with depth. Geothermal energy is heat from underground or is the energy stored in the form of heat beneath the earth's surface. In this energy, the temperature gradient is the most important and common element. Heat flow is directly related to the temperature gradient. There are no surface manifestations in this area, so the gradient method was applied to locate geothermal anomalies and prepare a geothermal map. Drilling a gradient well is a method used in exploration of both high- and low-temperature geothermal fields. Low permeability is a prerequisite for the method to give reliable results. It is important to avoid disturbances from the internal flow inside the well. In fracture controlled low-temperature fields, shallow wells give the best results. The regional geothermal gradient (Figure 13) must also be known as a baseline for recognizing thermal anomalies (Saemundsson 2007).

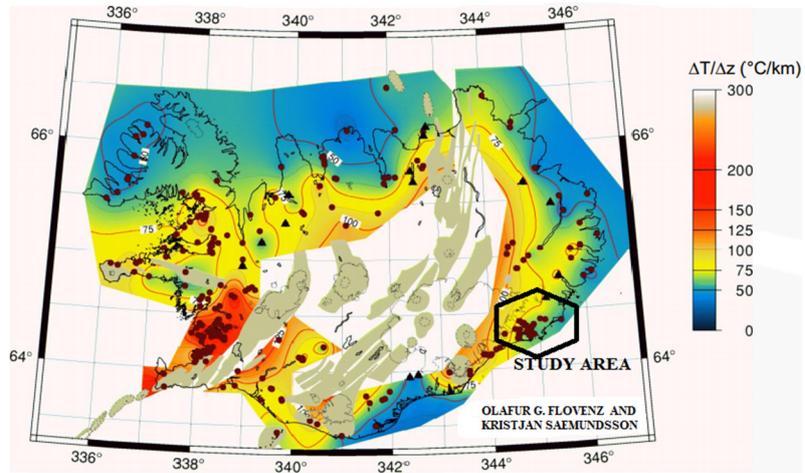


FIGURE 13: Geothermal gradient map of Iceland showing the regional gradient 40-60°C/km in the study area (Flóvenz and Saemundsson, 1993)

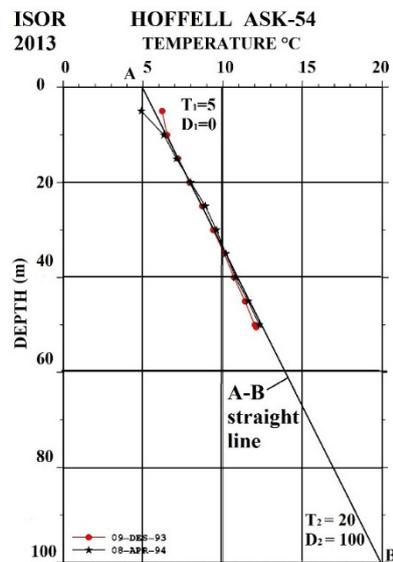


FIGURE 14: Temperature versus depth relationship

There are no surface manifestations in this area, so the gradient method was applied to locate geothermal anomalies and prepare a geothermal map. Drilling a gradient well is a method used in exploration of both high- and low-temperature geothermal fields. Low permeability is a prerequisite for the method to give reliable results. It is important to avoid disturbances from the internal flow inside the well. In fracture controlled low-temperature fields, shallow wells give the best results. The regional geothermal gradient (Figure 13) must also be known as a baseline for recognizing thermal anomalies (Saemundsson 2007).

7.1 Gradient calculation

The gradient calculation was conducted based on Equation 1 as well as with the help of Figure 14, clearly described below. In Figure 14 the relationship between temperature and depth is shown. An A-B straight line was drawn which cuts the maximum points of temperature versus depth points. Then the dt and dz were calculated from Figure 14.

$$G = \frac{dt}{dz} = \frac{T2 - T1}{D2 - D1} \tag{1}$$

where G = Temperature gradient ($^{\circ}\text{C}/\text{km}$)
 T_1 = Starting temperature of straight line ($^{\circ}\text{C}$);
 T_2 = Ending temperature of straight line ($^{\circ}\text{C}$);
 D_1 = Starting depth of straight line (m);
 D_2 = Ending depth of straight line (m);

With: $T_1 = 5^{\circ}\text{C}$; $T_2 = 20^{\circ}\text{C}$; $D_1 = 0$ m; $D_2 = 100$ m, Equation 1 yields:

$$G = \frac{20 - 5}{100 - 0} = 0.15^{\circ} \frac{\text{C}}{\text{m}} = 150^{\circ}\text{C}/\text{km}$$

The temperature gradient of ASK-54 is $150^{\circ}\text{C}/\text{km}$ as calculated by the above formula. The temperature gradient was calculated for several wells in the Hoffell area, using the same formulas. After the calculation, the gradient was plotted for a certain well location on a map and isotherm lines were drawn, resulting in a gradient map.

7.2 Geothermal gradient map of the study area

Figure 15 shows the location of all the wells in the area. The depth of the wells varies from 50 to 600 m and the temperature gradient varies from 100 to $210^{\circ}\text{C}/\text{km}$ (Well ASK-29). The contour lines were drawn with respect to certain temperature intervals, creating the geothermal gradient map in Figure 16. In addition, a heat map was made based on the measurements of the same gradient wells at Hoffell. The heat map shows temperature conditions at 50 m depth (Figure 17). Three different temperature zones are shown in the two maps. The red colour-bounded zones represent the highest temperature gradient, $>200^{\circ}\text{C}/\text{km}$ (Figure 16) and the highest temperature, $>15^{\circ}\text{C}$ (Figure 17).

Figure 18 illustrates a comparison between the temperature map and the gradient map. It shows that the highest gradient zone (dark colour bounded) is within the larger highest temperature zone (red colour bounded). It clearly shows the N-S trend of maximum heat, while on a more regional scale, the anomaly is more east or southeast trending indicating flow towards these directions.

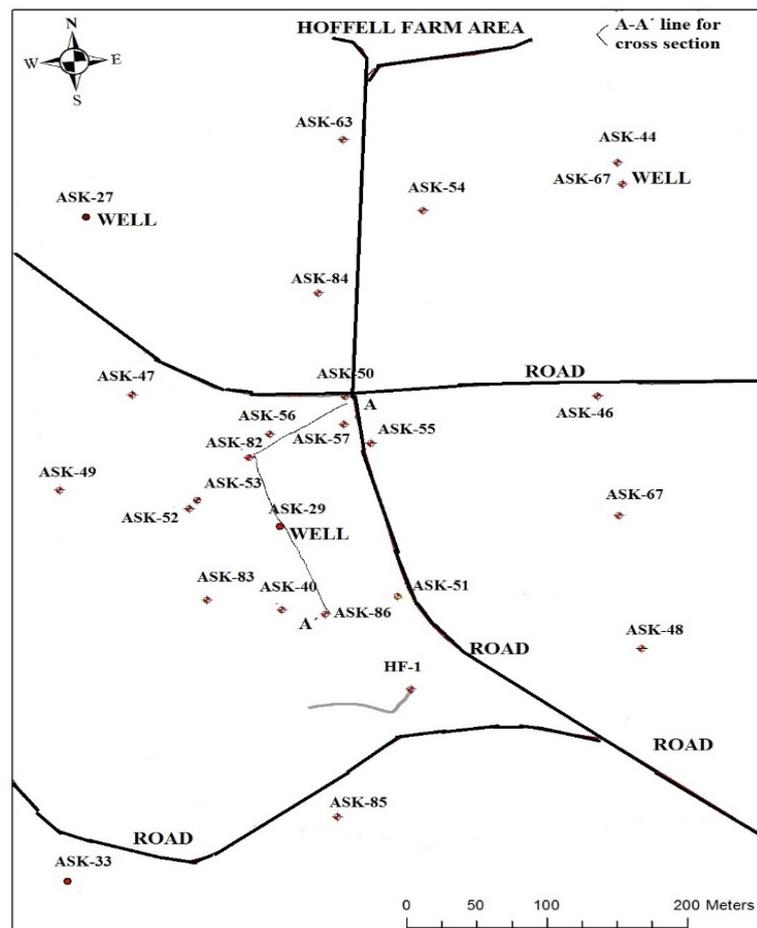


FIGURE 15: Map showing the location of different wells and roads in the study area

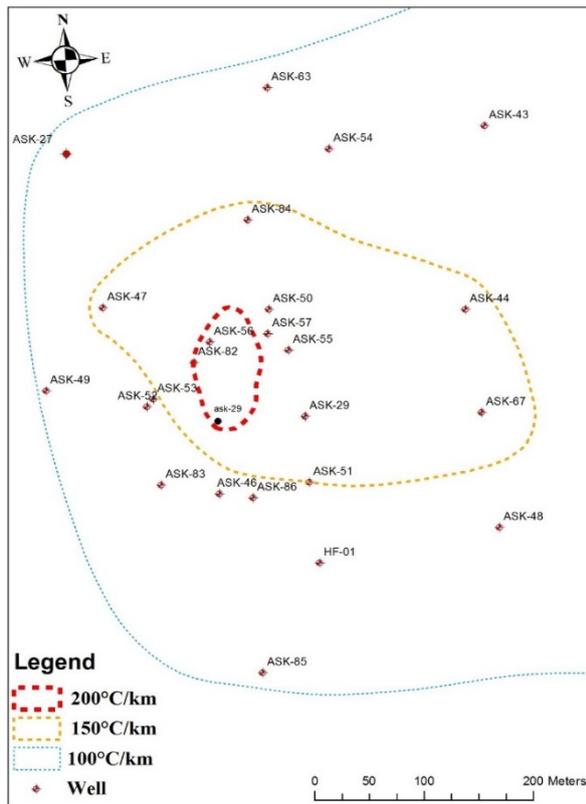


FIGURE 16: Map showing the temperature gradient in the wells of the Hoffell area

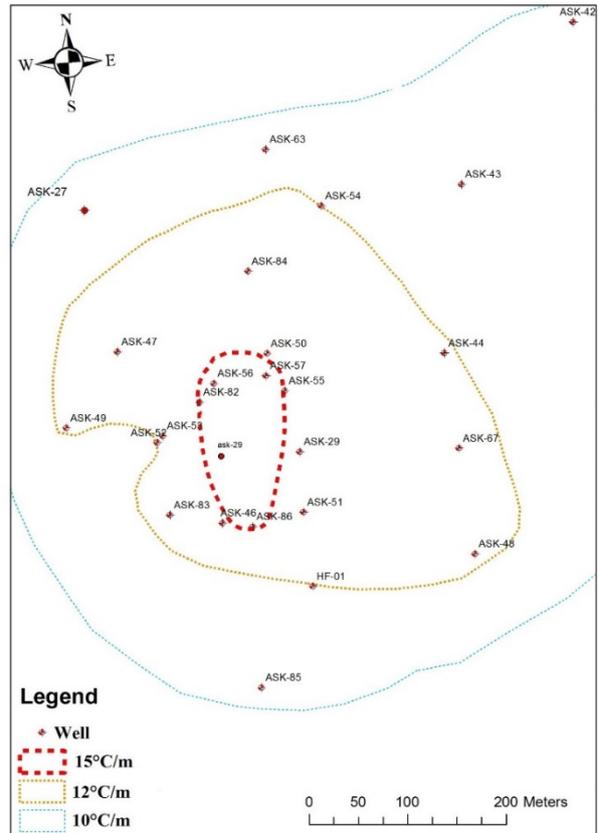


FIGURE 17: Map showing the temperature in the wells of the Hoffell area at 50 m depth

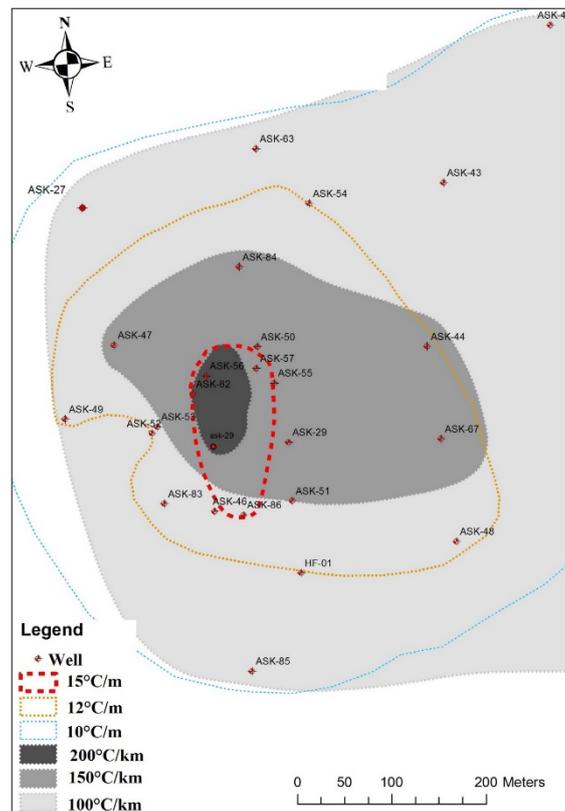


FIGURE 18: Comparison between temperature and gradient maps of the Hoffell area

8. INTERPRETATION OF FRACTURES AND VEINS IN SEVERAL WELLS

In all, the temperature gradients of 23 wells in the study area were measured, and in some of them open veins as well as open fractures could be seen in televiewer measurements, which indicates a good reservoir. Figure 19 shows the main structural trends and directions of open fractures in the measured wells. Grouping these, the open fractures-fault zones trend in NNE-SSW and W-E WSW-ENE directions (Figure 19). Also seen are four main structural trends, NE-SW to NNE-SSW, W-E and NW-SE (Figure 19). The wells within the area of maximum temperature have been demarcated (Wells ASK-29, ASK-50, ASK-57, ASK-82 and ASK-86). Some of these are described below regarding open fractures (Table 1). Only in Wells ASK-29 and ASK-85 insufficient data was collected with televiewer.

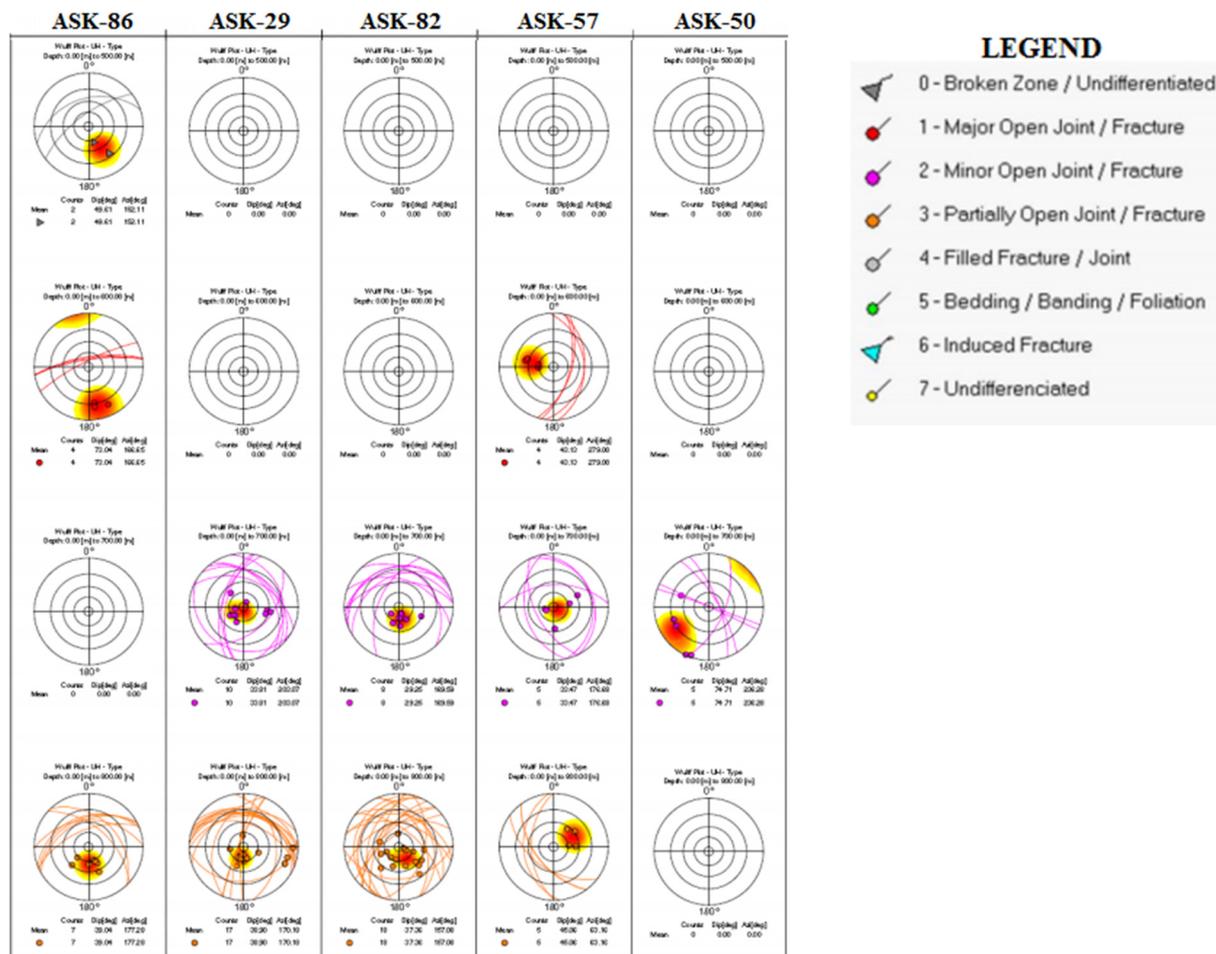


FIGURE 19: Map showing the main structural trends and direction of open fractures in the measured wells (modified from Árnadóttir, 2013)

TABLE 1: Short summary of veins seen in Wells ASK-29, ASK-50, ASK-57, ASK-82, ASK-85 and ASK-86 that appeared in the televiewer measurements at Hoffell study area, and other veins in the same wells (modified from Árnadóttir, 2013)

Well no.	Veins appearing in televiewer measurement		Other veins defined but above the teleview. measurements
ASK-29			126 m, 129 m
ASK-50	74 m	Viewed as open fractures	
ASK-57	465 m	Viewed as large open fractures at the depth of 458 m	113 m, 121 m, 296 m
ASK-82	180 m	Viewed as open fractures	
ASK-86	485 m	Viewed as large open fractures at a depth of 486.35 m	228 m, 300 m

Well ASK-29. The temperature gradient of this hole is 210°C/km hole. Ten large open fractures and their dip direction S33°W were seen. Seventeen partially open fractures were also found with a dip direction of almost 40°S (Figure 19). The highest temperature gradient (210°C/km) was calculated for this well. This well and the adjoining area may be a high-temperature prospect zone. The well is 150 m deep with a feed zone at shallow depth, clearly seen in the well’s cross-section. This well is the shallowest well among all the measured wells.

Well ASK-50. The temperature gradient of this well is 150°C/km. This well is also in the high-temperature region. From the televiewer data (Figure 20), the vein is at 74 m depth, where an open fracture is seen. Five major open fractures were counted, with an average dip direction of S 74°W, and no minor/partially open fractures were found in this well. Feed zones were found at shallow depth. This is a 150 m depth well and the shallowest open fracture well.

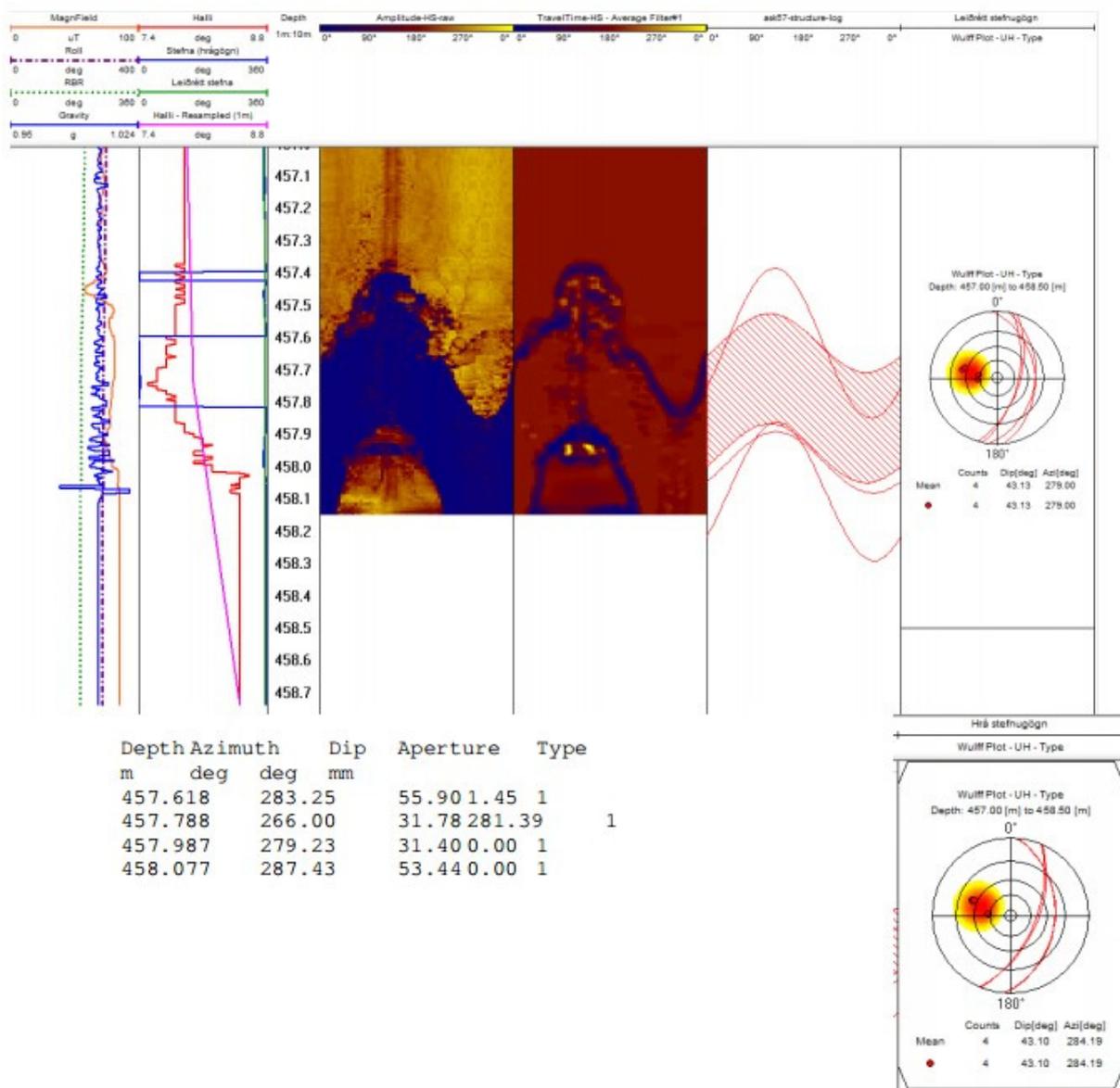


FIGURE 20: Televiewer measurement data of Well ASK-50 showing veins, open fractures and their dip direction (Árnadóttir, 2013)

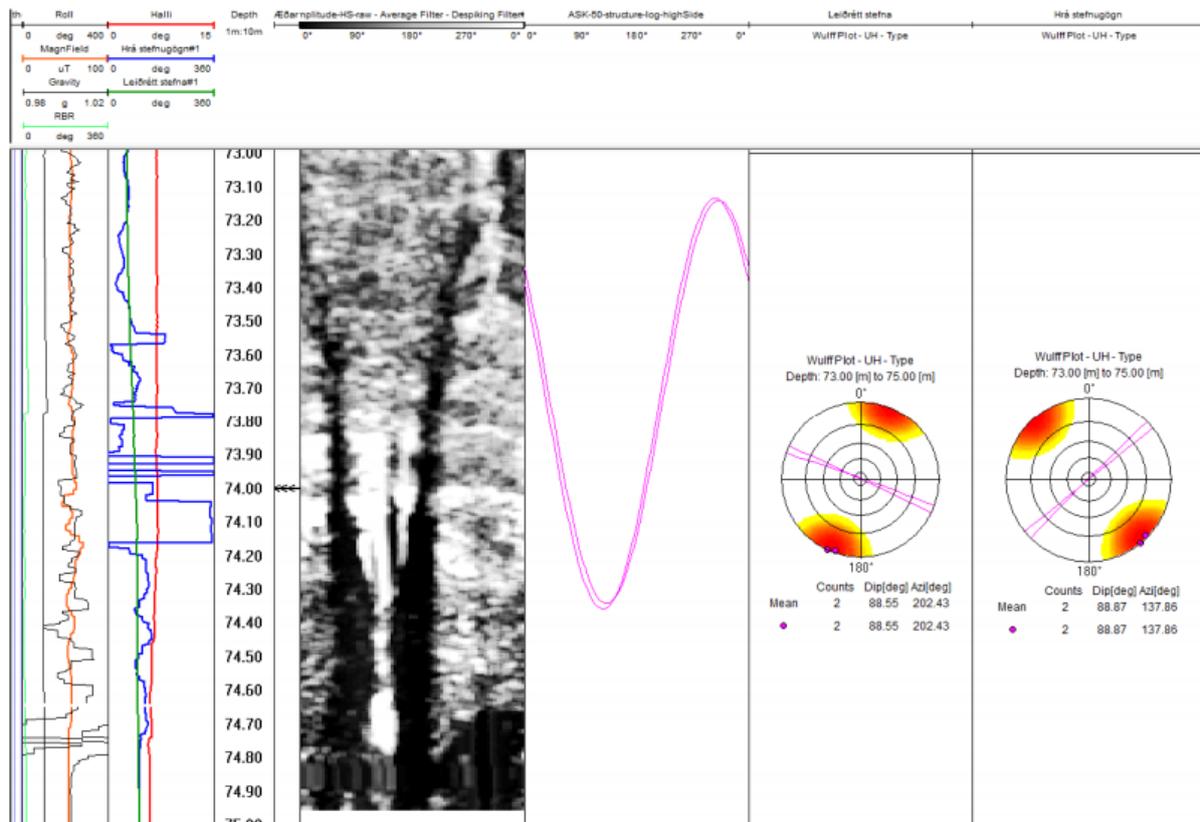


FIGURE 21: Televiewer measurement data of Well ASK-57 showing veins, open fractures and their dip direction (Árnadóttir, 2013)

Well ASK-57. The temperature gradient of this well is $169^{\circ}\text{C}/\text{km}$. Well ASK-50 is about 50 m north of this well and shows $160^{\circ}\text{C}/\text{km}$. Well ASK-55 is 55 m southeast of Well ASK-57 and shows $173^{\circ}\text{C}/\text{km}$. So ASK-57 is in a comparatively high temperature region. From the televiewer data (Figure 21), a vein is at 458.14 m depth, which shows a large open fracture. Here the measuring device was set at 465 m. Four major open fractures were counted with an average dip direction 43° , almost west. 5 minor fractures were observed and their dip angles are $S\ 33^{\circ}\text{E}$. Five partially open fractures were also found with a dip direction of $N45^{\circ}\text{E}$. This is a deep well with a deep feed zone.

Well ASK-82. The temperature gradient of this well is $210^{\circ}\text{C}/\text{km}$ which is in the highest temperature gradient. From the televiewer data (Figure 22), the vein is at 180 m depth, which shows a large open fracture. This is an artesian type well in the middle part of the study area. Two major open fractures were found with a dip direction of almost 30°S , so it is difficult to identify if it is a contact or joint or fault. 18 partially open fractures were also observed and their dip direction is $S37^{\circ}\text{E}$. A feed zone was observed at a shallow depth.

Well ASK-86. The temperature gradient of this well is $180^{\circ}\text{C}/\text{km}$. From the televiewer data (Figure 23), the vein is at 485 m depth, and shows a large open fracture. Here the measuring device was set at 486.35 m. Four major open fractures ($S73^{\circ}\text{E}$) and seven partially open fractures were also found with a dip direction of almost 39°S (Figure 23). A feed zone was also found at greater depth (Figure 24). This is a deep well.

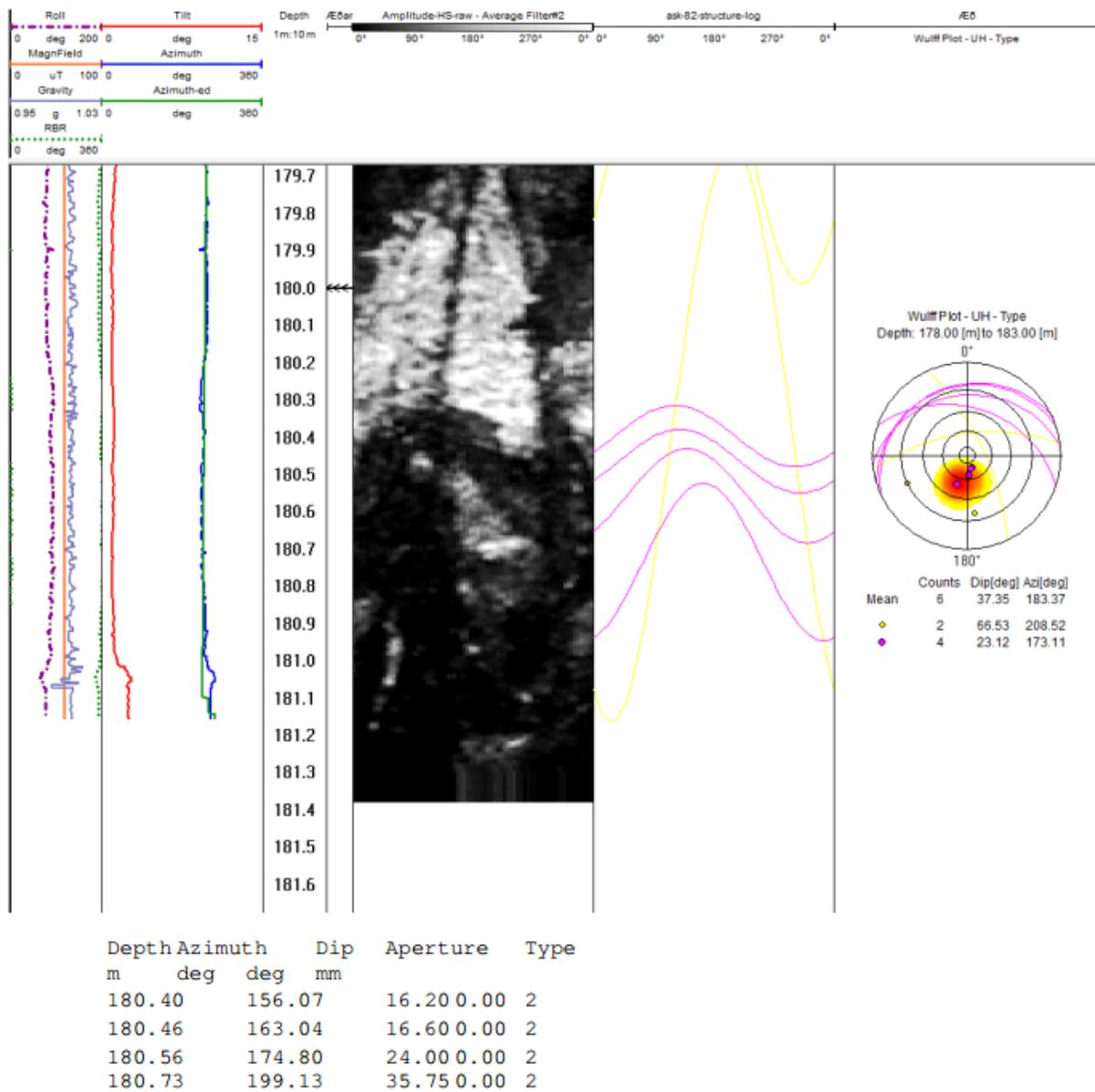
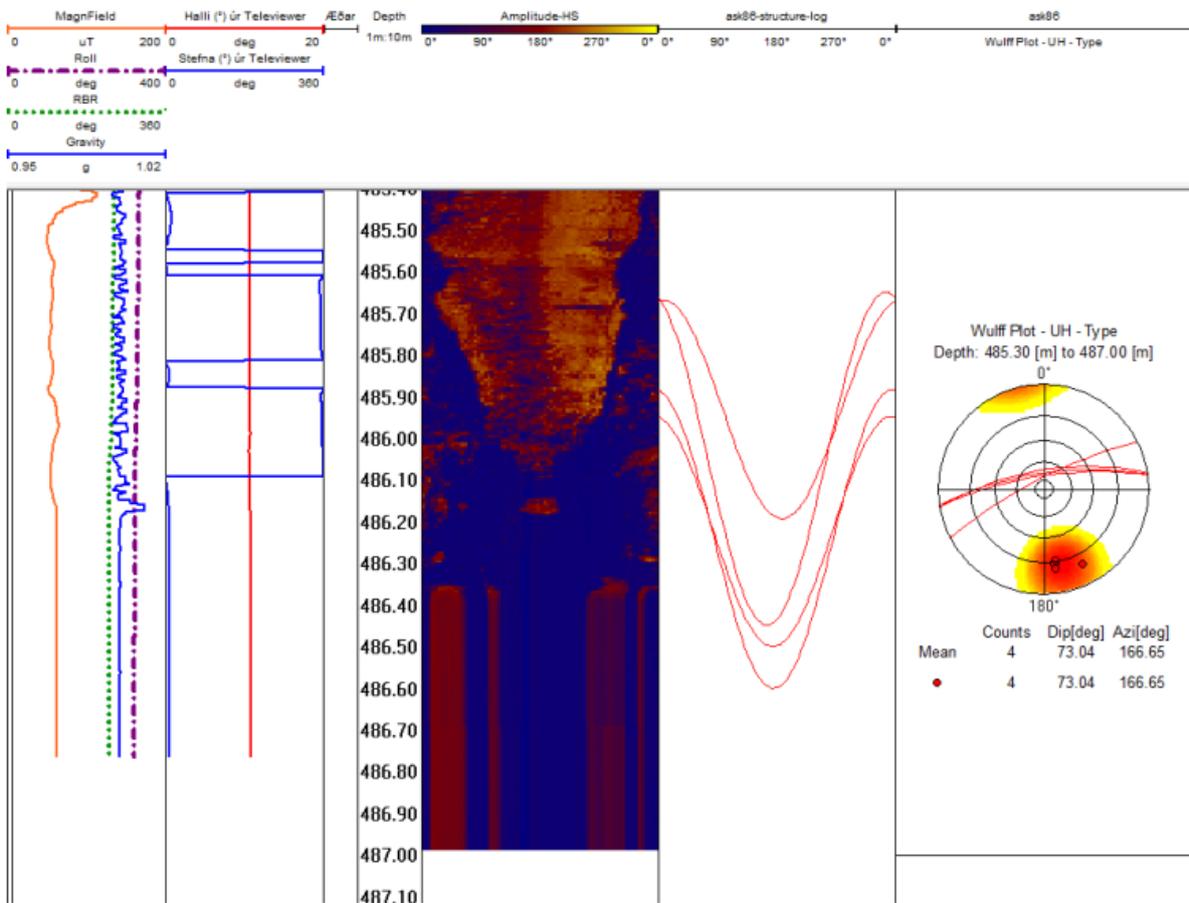


FIGURE 22: Televiewer measurement data of Well ASK-82 showing veins, open fractures and their dip direction (Árnadóttir, 2013)

Figure 24 shows a cross-section from Well ASK-86 to Well ASK-50, showing the feed zones registered in the wells on the cross-section.



Depth	Azimuth	Dip	Aperture	Type
m	deg	deg	mm	
485.93	171.71	71.63	0.00	1
486.05	152.68	76.98	0.00	1
486.22	170.61	68.63	0.00	1

FIGURE 23: Televiewer measurement data of Well ASK-86 showing veins, open fractures and their dip direction (Árnadóttir, 2013)

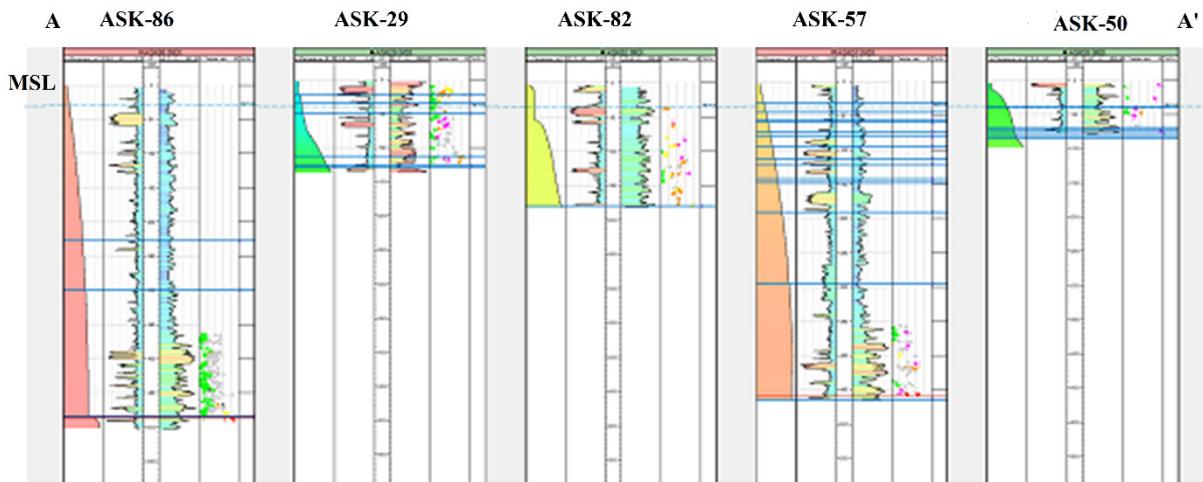


FIGURE 24: Cross-section from Well ASK-86 to Well ASK-50 (location see Figure 15); blue lines indicate feed zones (modified from Árnadóttir, 2013)

9. CONCLUSIONS AND RECOMMENDATIONS

The study area is in the south-eastern part of the Geitafell central volcano in southeast Iceland. It is important on account of the low-temperature geothermal field in an area where the regional gradient is 40-60°C/km. The area was mainly studied with respect to the temperature gradient but also for geological information. The volcanic complex is deeply eroded due to glacial erosion. The stratigraphy is mainly composed of tholeiitic rocks of which 60% are basaltic lavas and 30% hyaloclastites. The general characteristics of the dilation tectonics involved are open fractures and graben at the surface and normal faulting at depth. During the study period, 23 wells were investigated and their temperature gradients measured to establish the subsurface temperature of the area. In this area, heat flow gradually increases from the N-S striking centre to the eastern side.

From the measured temperature gradient of different wells, as well as the televiewer data, it is clear that Wells ASK-29, ASK-56, ASK-82, ASK-57 and their adjoining area show the highest temperature zone. This data also illustrates several veins at specific depths or open fractures striking NNE-SSW and W-E WSW-ENE. The highest zone showed more than a 200°C/km gradient. Even though there are no surface manifestations, it is clear that the subsurface temperatures are abnormal in this region. Based on these results, in case of further drilling, I would propose to site the wells in the eastern part of the zone with the highest temperatures,

The surveyed area is a large region which is geologically controlled by the structures from the Geitafell central volcano. It is probably the most important area in SE-Iceland with respect to geothermal energy and its potential use. Therefore, it is proposed that further geological exploration and geophysical surveys should be carried out to get a clearer picture of the geothermal and geological conditions, as well as the tectonic framework, in an area of great importance to the communities in that quarter of Iceland.

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