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Gradient Calculation Method Applied to the Low-Temperature Geothermal field, SE-Iceland

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ABSTRACT

This 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 partial 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, low-temperature geothermal manifestations, as well as to study the site selection for production/exploration well drilling. 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. 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 and 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 is located in SE-Iceland (Fig. 1), which seems to be a home of low-temperature geothermal field. The study area is about 400 km east of Reykjavik, the capital city of Iceland which lies at 64°42´20´´N – 64°44´20´´N and 15°04´20´´E – 15°06´30´´E. The extinct central volcano of Geitafell is found, but it was active five million years ago (Fridleifsson, 1983a). 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°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.

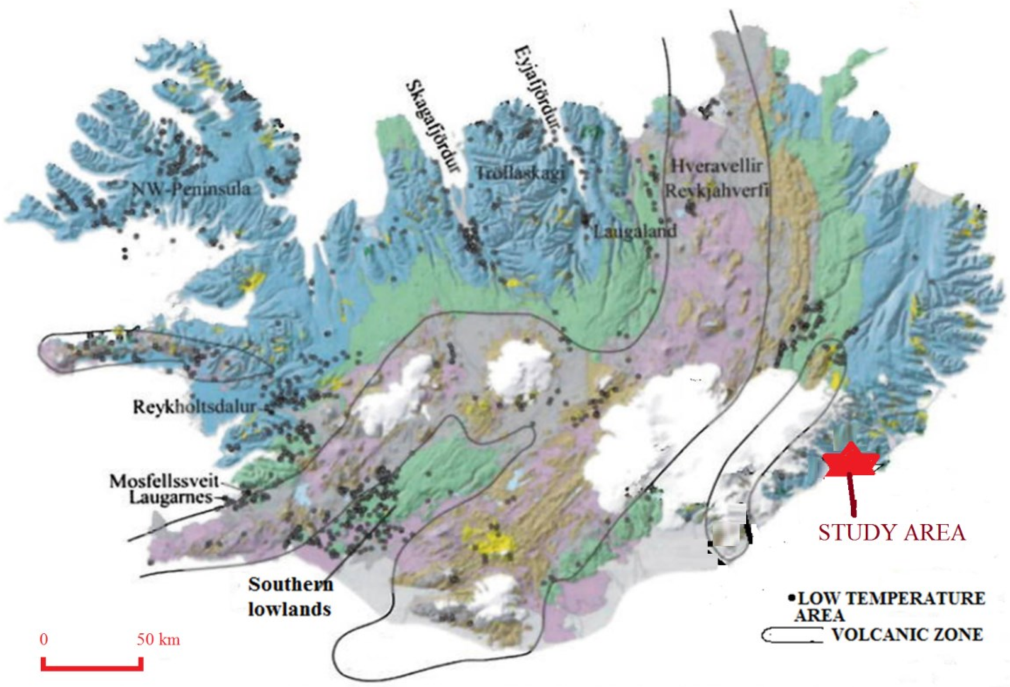

Figure 1: Map showing the location of the study area in SE Iceland.

1.2 Background and Objectives

In order to develop geothermal resources, manpowers, and methods to use the resources in the country, the Geological Survey of Bangladesh (GSB) requested to The Geothermal Training Programme of the United Nations University (UNU-GTP) in Iceland. From this point of view, the authors have been approved to attend the programme in the specialized field of geological exploration. This study is a part of that training course at the UNU-GTP in Iceland. The objective of the study was to provide the exploratory drilling location with the help of gradient calculation method for using the low-temperature geothermal resources and geothermal mapping at Hoffell in SE-Iceland, which is a low-temperature geothermal field. The authors trained how to analyze, interpret and present the data which was gathered to explore such area.

1.3 Previous Work

The geothermal area is mentioned in several reports. The first comprehensive study of the geology of the area appeared in the PhD thesis of Fridleifsson (1983). 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 to acquire better 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 the well confirmed the existence of an 80°C geothermal resources (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. GEO-TECTONIC SETTINGS OF ICELAND

2.1 Geology

Iceland is a young country from the geo-tectonical point of view, which is located on the spreading boundary of the Mid-Atlantic Ridge. 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. 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 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).

2.2 Tectonic Settings

Iceland lies astride the Mid Atlantic Ridge on the diverging North American and Eurasian Plates. 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 which is a constructive plate boundary while the Greenland-Iceland-Faeroes Ridge is thought to be the trail of the Icelandic mantle plume and has been active 60 million years ago (Sigmundsson and Saemundsson, 2008). The mantle plume is seen to be located below Central East Iceland, close to the volcanic rift zone which crosses Iceland from southwest to northeast (Fig. 1) and is divided into two parallel branches in South Iceland (Pálmason and Saemundsson, 1974).

3. GEOTHERMAL ACTIVITIES 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 characterized by high heat flow due to its geological location on a divergent plate boundary. The regional heat flow ranges from 80 to 200 mw/m², 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 and Low-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 (Fig. 2). 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. 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).

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

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 is outside the caldera fault as can be seen on the geological map. The volcano is located northwest of the town Höfn (Fig. 2) and has been deeply carved and eroded by the glaciers of the last glaciation.

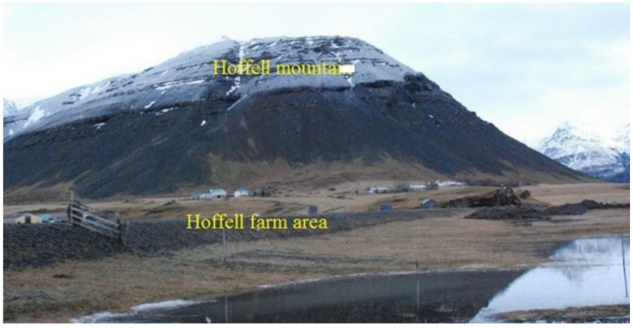

Figure 2: Photograph showing the study area around the Hoffell farm, SE Iceland.

4.1 Geo-Tectonic Settings of the Investigated 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 (Fig. 3). 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).

4.2Stratigraphic Units of the Investigated Area

The research area is separated into seven major stratigraphic units. The stratigraphic divisions are described below (Fridleifsson, 1983a):

Basaltic lava unit-I (B-I): mainly composed of tholeiitic lavas, which is divided into three sub-units.

Rhyolite unit-I (R-I): located within the basaltic lava unit-I, which comprises mixed composition.

Hyaloclastite unit-I (H-I): mainly composed of aphyric basalt clasts, but acid clasts also occurred in some locations. Basic pillow lava is not found within this unit, but pillow fragments occur in many places.

Basaltic lava unit-II (B-II): This unit comprises thick tholeiite, olivine tholeiite, feldspar tholeiite, and feldspar porphyritic basalt flows.

4.3 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 a s 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 (fig. 3). According to Fridleifsson (1983a), the intrusive rocks of this volcanic area have been divided into 12 phases which are described below:

Intrusive phase-1: regarded as a feeder dyke system to basaltic lava units I and II, rhyolite unit I and hyaloclastite unit II.

Intrusive phase-2: the Geitafell central volcano, as well as contemporaneous gabbros, constitutes the phase.

Intrusive phase-3: consists of Feldsparphyric dykes, which are common in this phase and are slightly younger than the Geitafell gabbro and apparently related to the same intrusive episode.

Intrusive phase-4: consists of acid veins crosscut, the pegmatite veins in the gabbro and brecciate the gabbro near the southern end.

Intrusive phase-5: consists of a doleritic cone-sheet swarm, the sheets being 0.5-1.5 m thick.

Intrusive phase-6: A Feldsparphyric dolerite sheet swarm is dominant in this phase.

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.

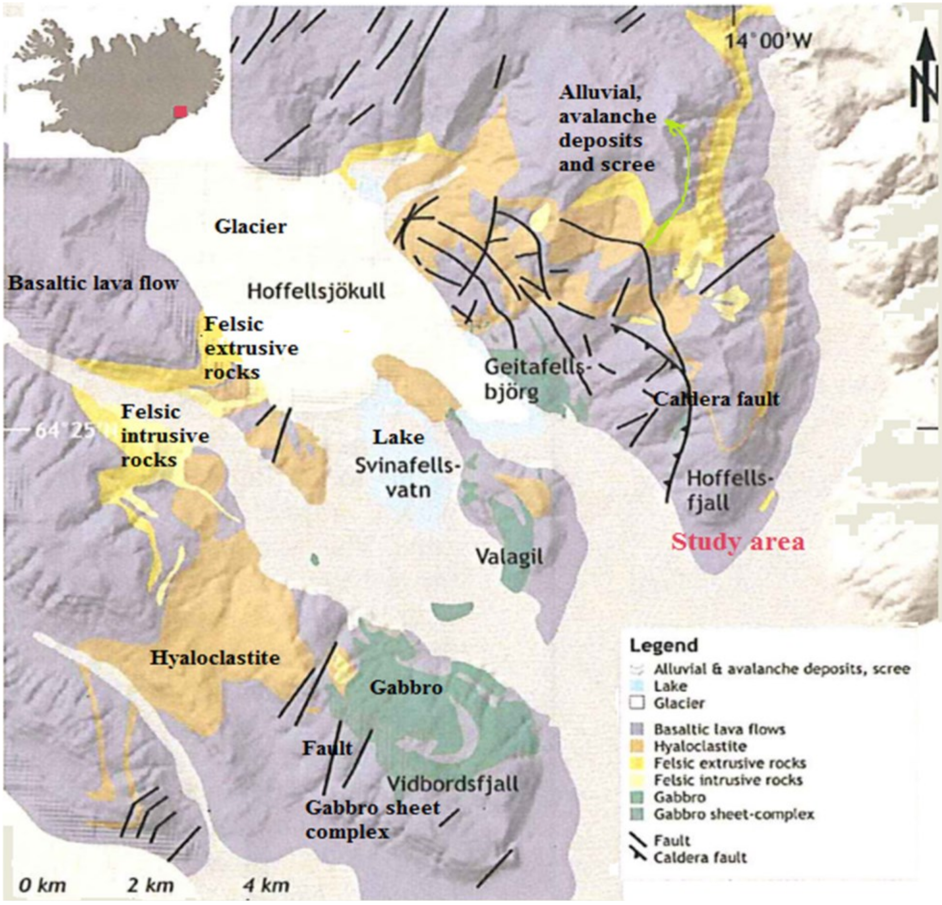

Figure 3: Geological map of the study area (modified from Fridleifsson, 1983a)

Intrusive phase-8: A fine grained basaltic sheet swarm forms this phase and most common in Efstafellsnes, Efstafell area.

Intrusive phase-9: The dykes of this phase are thicker than the sheets which 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.

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.

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.

5. MINERALOGICAL EVOLUTIONS AND TECTONICS OF THE GEITAFELL AREA

The mineralogical distribution within the Geitafell hydrothermal system is represented by the five mineralogical zones. 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, episode, 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. (Fridleifsson, 1983b).

5.1Intrusive Phases

The study area is mainly composed of tholeiitic lavas and dykes but sheets and faults are also found. 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. 2 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 is directly related to the low-temperature geothermal field.

5. 3 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 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).

6. GEOTHERMAL MAPPING

A geothermal or temperature gradient is a physical property that describes the direction and the rate of 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 (Fig. 4) must also be known as a baseline for recognizing thermal anomalies (Saemundsson 2007).

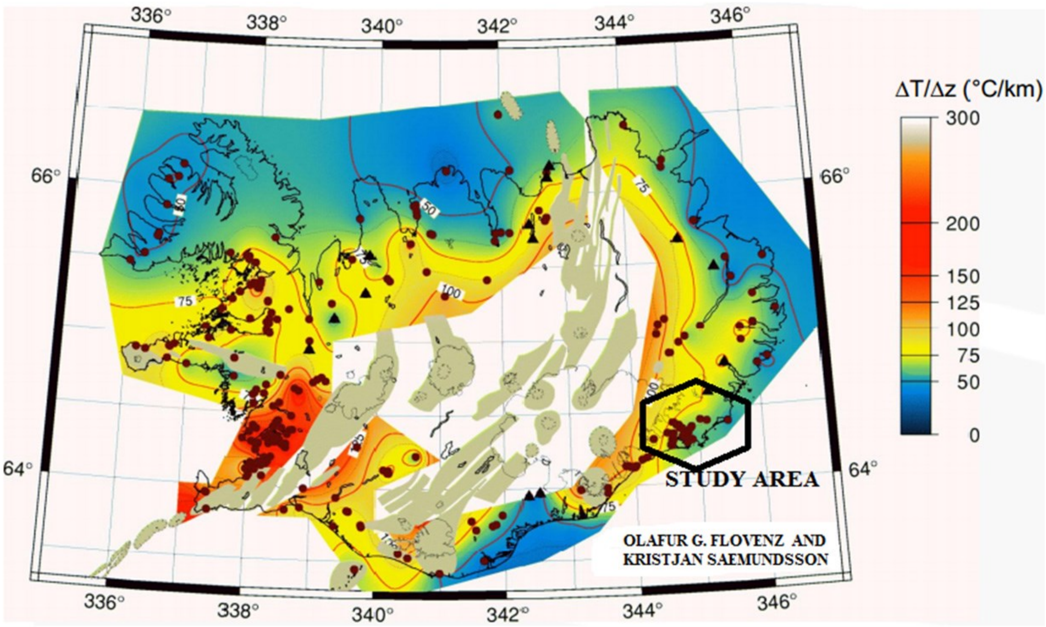

Figure 4: Geothermal gradient map of Iceland showing the regional gradient 40-60°C/km in the study area (Flóvenz and Saemundsson, 1993)

6.1 Gradient Calculation

The gradient calculation was conducted based on Equation 1 as well as with the help of Figure 5, clearly described below. In Figure 4 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 5 where G, T1, T2, D1, D2 are temperature gradient (°C/km), starting temperature of straight line (°C), ending temperature of straight line (°C), starting depth of straight line (m) and ending depth of straight line (m) respectively. With: T1 = 5°C; T2 = 20°C; D1 = 0 m; D2 = 100 m, Equation 1 yields:

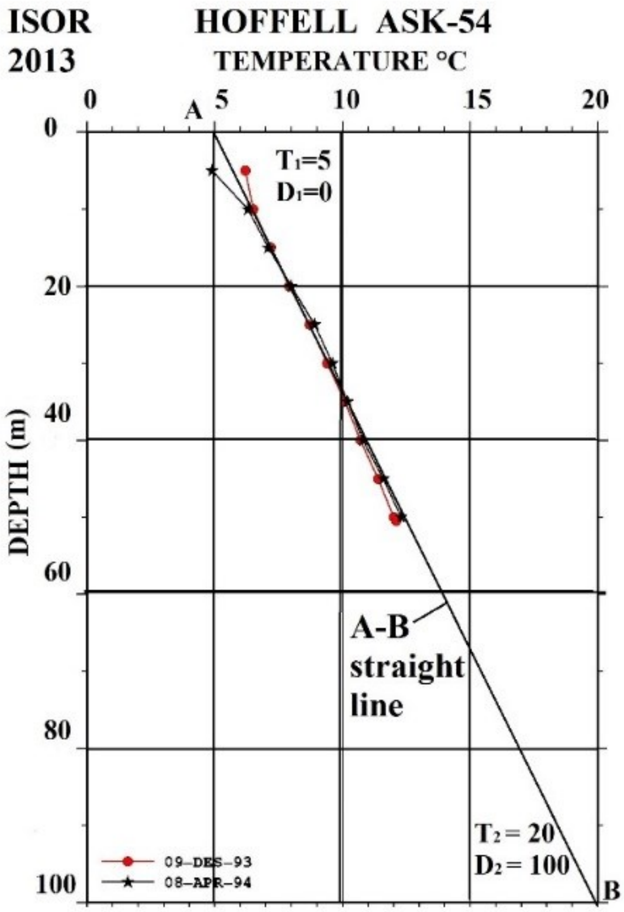

Figure 5: Temperature versus depth relationship.

The temperature gradient of ASK-54 is 150°C/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.

6.2 Geothermal Gradient Map of the Study Area

Figure 6 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°C/km (Well ASK-29). The contour lines were drawn with respect to certain temperature intervals, creating the geothermal gradient map in Figure 7A. 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 (Fig. 7 Map B). Three different temperature zones are shown in the two maps. The red colour-bounded zones represent the highest temperature gradient, >200°C/km (Figure 7). Figure 7 also 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.

7. 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. Televiewer 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. The wells within the area of maximum temperature have been demarcated (Wells ASK- 29, ASK-50, ASK-57, ASK-82 and ASK-86). Only in Wells ASK-29 and ASK-85 insufficient data was collected with televiewer.

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. 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.

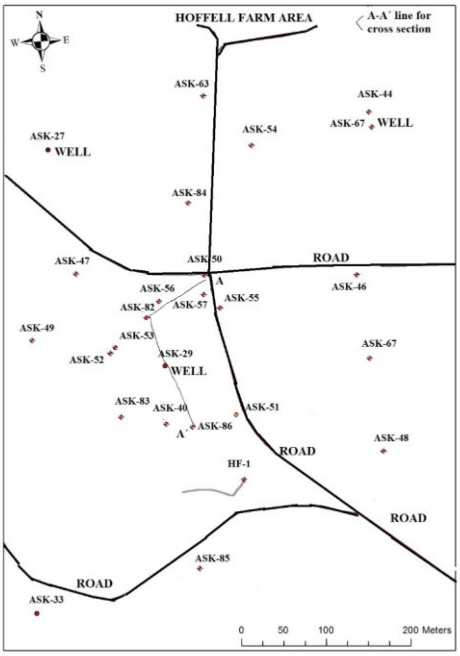

Figure 6: Map showing the location of different wells and roads in the study area.

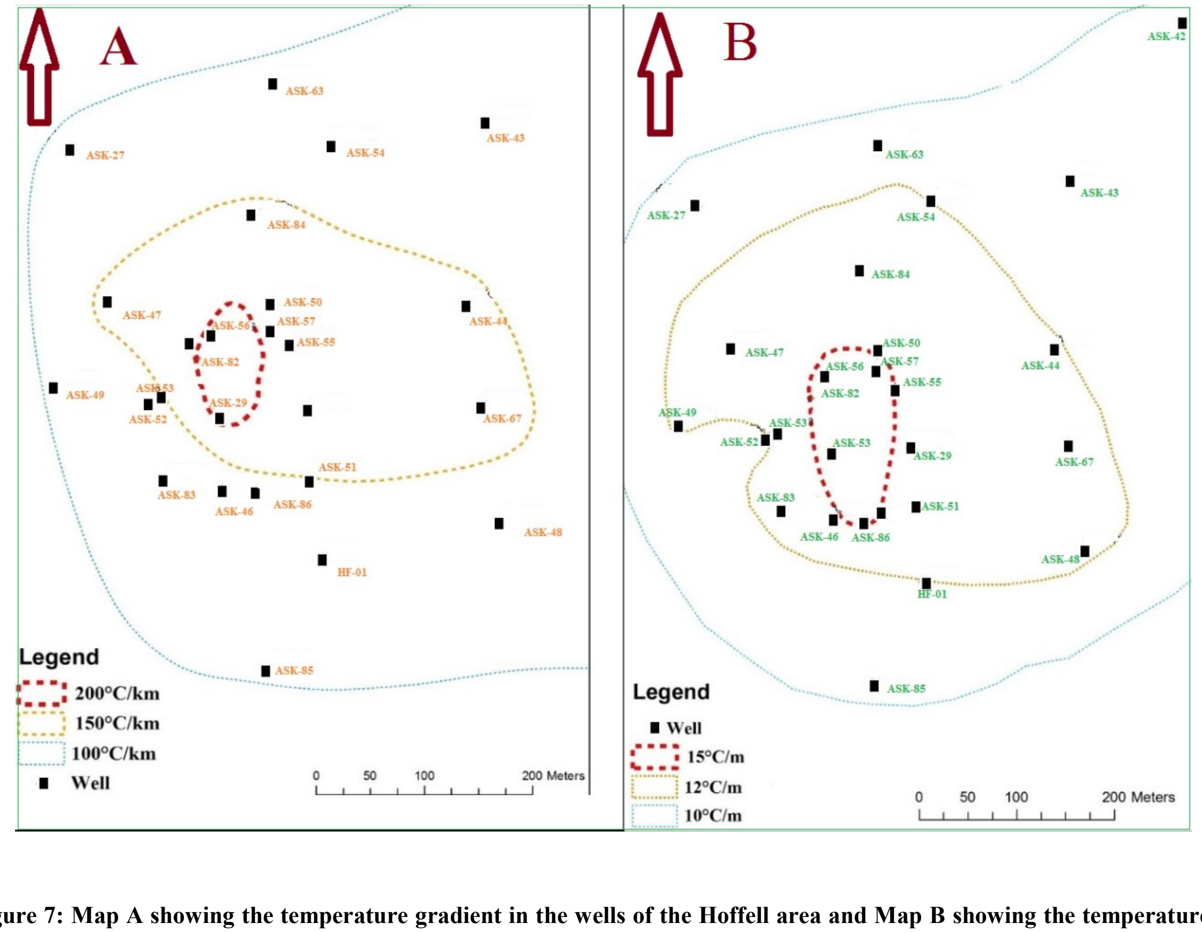

Figure 7: Map A showing the temperature gradient in the wells of the Hoffell area and Map B showing the temperature in the wells of the Hoffell area at 50 m depth, SE Iceland.

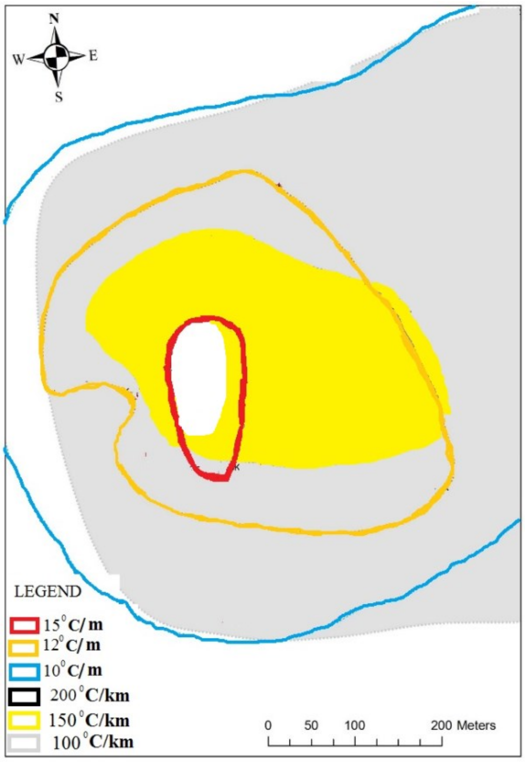

Figure 8: Comparison between temperature and gradient maps of the Hoffell area, SE Iceland.

In the Well ASK-50, the temperature gradient was 150°C/km. This well was also in the high temperature region. From the televiewer data, the vein was at 74 m depth, where an open fracture was 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.

In the Well ASK-57, he temperature gradient of this well was 169°C/km. The well ASK-50 is about 50 m north of this well and shows 160°C/km. Well ASK-55 is 55 m southeast of Well ASK-57 and shows 173°C/km. So ASK-57 is in a comparatively high temperature region. From the televiewer data (Figure 21), a vein was at 458.14 m depth, which showed 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°E. Five partially open fractures were also found with a dip direction of N45°E. This is a deep well with a deep feed zone.

In the Well ASK-82, the temperature gradient of this well was 210°C/km which is in the highest temperature gradient. From the televiewer data, 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°E. A feed zone was observed at a shallow depth.

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

8. CONCLUSIONS AND RECOMMENDATIONS

The study area is in the south-eastern part of the Geitafell central volcano in southeast Iceland. It is feasible 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. 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, 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.

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