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Comparison of Geological and Thermal Structure of Three High-Temperature Geothermal Areas in the Neo-Volcanic Zone of NE-Iceland

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ABSTRACT

The northern part of the neo-volcanic zone (NVZ) in NE-Iceland consist of four volcanic systems, which are arranged in a right stepping en enchelon formation with a north-south direction. The volcanic systems are dominated by up to 80-90 km long fissure swarms extending from a central volcano, but volcanic eruptions, silicic rocks and high-temperature geothermal systems are focused at the central volcanoes, where calderas can form.

Landsvirkjun has explored and developed three high-temperature geothermal areas in NE-Iceland; Theistareykir geothermal area within Theistareykir volcanic system and Krafla and Námafjall geothermal areas within Krafla volcanic system. In this paper similarities and differences in the geological and thermal structure of these three geothermal areas will be highlighted.

Krafla high-temperature geothermal area is centred in the eastern part of Krafla caldera, which is intersected by Krafla fissure swarm. Námafjall high-temperature geothermal area is located in the southern part of Krafla fissure swarm and may represent a parasitic volcanic centre within the Krafla volcanic system partially fed by lateral fissure eruptions from Krafla central volcano. Theistareykir high-temperature geothermal area is in the eastern part of Theistareykir fissure swarm and is located within a central volcano, which is dominated by basaltic volcanic shields and table mountains.

The high temperature geothermal areas at these three locations have been active during changing glacial and post-glacial climatic conditions. Comparison of alteration with current temperature state in the geothermal systems indicate that the high-temperature geothermal areas have previously been much larger than they are today, which may possibly tie to changing pressure conditions during glacial loading of the crust. On the other hand, areas of subsequent temperature reversal in the geothermal reservoirs are closely tied to the main zone of deformation within the fissure swarms.

1. INTRODUCTION

Iceland is located on a divergent plate boundary between the North American and Eurasian plate. Spreading at the plate boundary is accommodated within rift zones composed of fissure swarms with faults, open fractures, eruptive fissures and central volcanoes. The northern part of the neo-volcanic zone in NE-Iceland consist of four volcanic systems, Askja, Fremrinámar, Krafla and Theistareykir, which are arranged in a left stepping en enchelon formation with a north-south direction (Figure 1). The volcanic systems are dominated by up to 80-90 km long fissure swarms extending from a central volcano, but volcanic eruptions, silicic rocks and high-temperature geothermal systems are focused at the central volcanoes, where calderas can form.

The thermal history of geothermal systems in Iceland are affected by repeated rifting events, where extension and opening of fissures changes permeability in the geothermal systems, while volcanic eruptions are a source of renewal of energy to the geothermal system. The thermal history of geothermal systems in Iceland is also affected by changing climatic conditions, whereby glacial loading and unloading have occurred during glacial and interglacial times respectively.

Landsvirkjun has explored and developed three high-temperature geothermal areas in NE-Iceland; Krafla and Námafjall within Krafla volcanic system and Þeistareykir within Þeistareykir volcanic system. Exploration of these three geothermal areas have revealed similarities between thermal structure and geological setting. These three geothermal areas are represented by large resistivity anomalies, but a combination glacial unloading and high permeability in fissure swarms have changed the thermal conditions and cooled parts of the reservoir.

2. THEISTAREYKIR

Exploration of Theistareykir geothermal area started more than 40 years ago but exploration has been carried out in stages. Surface exploration was initiated in early 1970’s (Grönvold and Karlsdóttir 1975) and culminated with the completion of a major geothermal assessment in 1984 (Gíslason et al. 1984, Ármannsson et al. 1986, Darling and Ármannsson 1989). Exploration drilling commenced in 2002 and by 2008 six wells had been drilled. With results from the first exploration drilling phase the conceptual model of the field was updated and the potential of the system was estimated with Monte Carlo method. Subsequent, preparations for developing the geothermal field got underway. Power plant construction commenced in 2015 and at the same time, a second drilling phase to develop the field was launched. By December 2017, Theistareykir power plant was inaugurated and by April 2018, installed capacity reached 90 MW_e. A total of 18 exploration and production wells have been drilled to gather steam for the power plant.

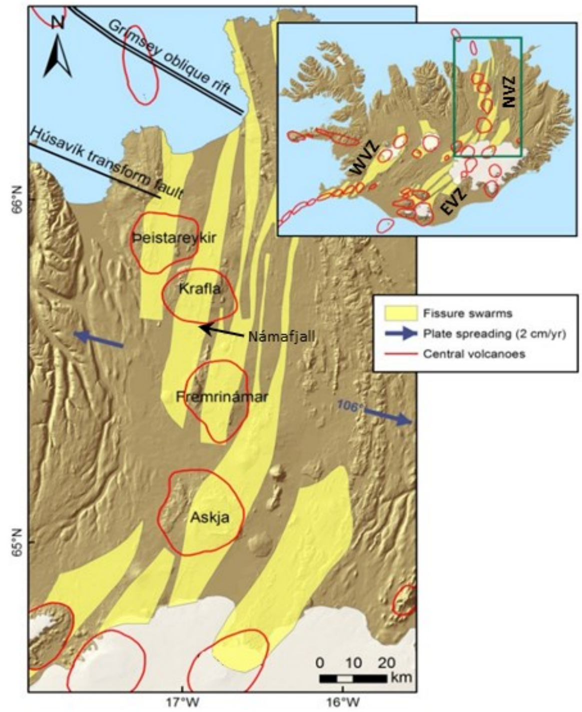

Figure 1: Map of Iceland showing active volcanic systems in northern part of NVZ in Iceland according to Einarsson and Saemundsson (1987). Námafjall geothermal area is located south of Krafla (black arrow). Modified from Hjartardóttir et al. (2012).

2.1. Geological setting

Theistareykir geothermal area is located within Theistareykir central volcano. A 10 km wide fissure swarm transect the volcano, but the fissure swarm extends 55 km from Lake Mývatn from in the south to Öxarfjörður in the north. North of Theistareykir central volcano Húsavík transform fault merges with Theistareykir fissure swarm. The geology at Theistareykir is characterised hyaloclastite table mountains and ridges, while the youngest volcanic formations are large volume basaltic lava shields most of which erupted at the end of the last glacial episode. The latest eruption of Theistareykja lava shield occurred approx. 2500 years BP (Figure 2).

Extension in NVZ is accommodated by the fissure swarms, but at Theistareykir centre of subsidence extension is in the centre of the fissure swarm just west of Bæjarfjall mountain south of the geothermal area, while north of Bæjarfjall mountain the centre of subsidence jumps towards the western edge of the fissure swarm (Figure 2). The geothermal area is E-W trending and altered ground is observed both towards the western and eastern edge of the fissure swarm. However, active surface manifestations are centred north and northwest of Bæjarfjall mountain and cover an estimated area of 11 km^2 (Gíslason et al., 1984).

2.2. Thermal structure

The geothermal area at Theistareykir is based on TEM and MT surveys estimated to cover a much larger area of approximately 45 km^2 in size and can be divided into an eastern and western sector (Figure 2, 3). According to the resistivity survey the conductive clay cap is peaking and reaching the surface north of Bæjarfjall mountain, while to the west in the fissure swarm beneath Storihver in the Theistareykja lava flow the conductive clay is at 200 m depth and is very smooth and planar. Both the eastern and western sector of the geothermal reservoir has been explored with drilling. Drilling has revealed that alteration is corresponding with the depth to the conductive clay cap identified in resistivity surveys. In the eastern sector, temperature is in equilibrium with alteration and reservoir temperatures of 280-350°C. However, in the western sector, alteration is less intense with depth and is indicating that maximum temperatures have reached 230-280°C at 1000-2000 m depth below surface in this part of the reservoir. Since then, the western reservoir has cooled down and temperatures are within 175°C.

3. KRAFLA

Krafla geothermal power plant, located in the caldera of Krafla central volcano, has been in operation for more than 40 years with production commencing in 1978. Initially only 7 MW_e was produced due to the impact on the geothermal reservoir from the volcanic eruptions “Krafla Fires”, which began 1975 and lasted until 1984. Production reached 30 MW_e the same year the Krafla Fires ceased. The second turbine was installed in 1999 with installed capacity reaching 60 MW_e. A total of 46 exploration and production wells have been drilled in the field, but up to 20 wells are currently used for production.

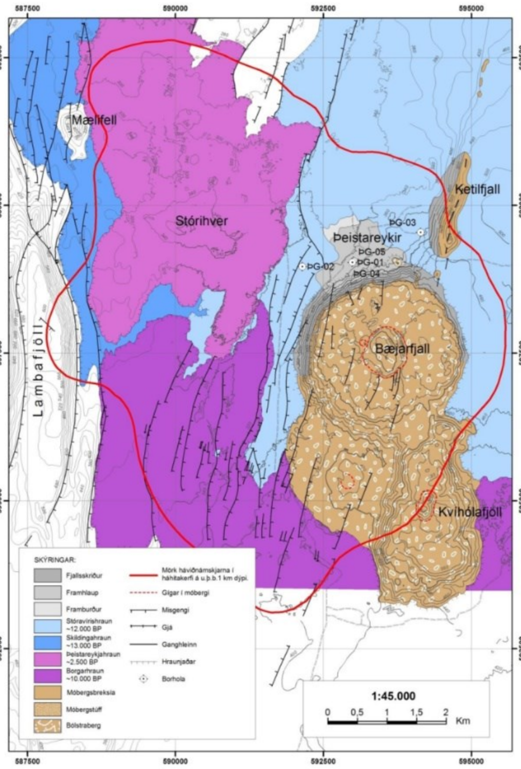

Figure 2: Geological map within Theistareykir central volcano (Sæmundsson, 2007). Outline of resistivity anomaly at 500 m.b.sl. according to TEM survey (Karlsdóttir et al., 2006).

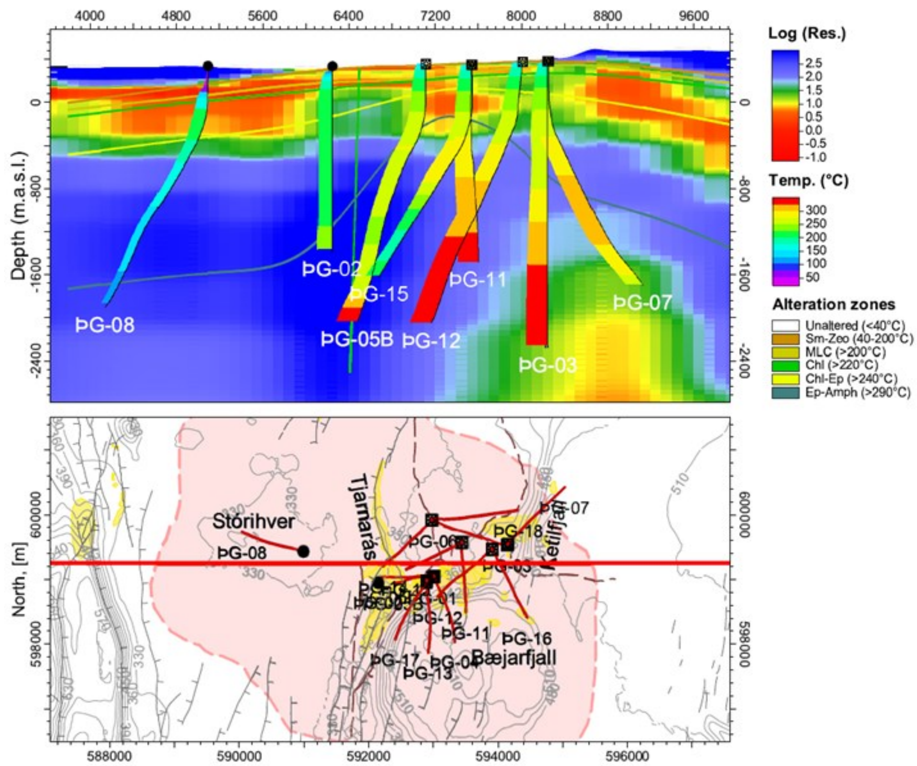

Figure 3: E-W cross section of Theistareykir geothermal system showing 3D TEM-MT resistivity (blue-red colour background)(Karlsdóttir et al., 2012b; Yu et al. 2008 a,b), alteration zonation (lines) and formation temperature (blue-red colour along well trajectory). Below is structural map showing location of cross section (red line) and outline of resistivity anomaly at 500 m.b.sl. according to TEM survey (red stippled line) (Karlsdóttir et al., 2006).

3.1. Geological setting

The Krafla central volcano, located within the NVZ in NE-Iceland (Figure 1), has been active for at least 300,000 years (Sæmundsson, 1991). The volcano is approximately 20 km in diameter and within it is an eroded and partly filled caldera 8x10 km in diameter. A N5-15°E oriented and 90 km long rifting fissure swarm extends through Krafla volcano, while a prominent NW-SE elongated geothermal area covering ca. 10 km^2 is present within the center and at the southern edge of the caldera structure (Sæmundsson, 1991, 2008). The geothermal area appears to be closely coupled to an inferred underlying magma chamber, since seismic studies during the Krafla Fires 1975-84 indicate a S-wave shadow delineating a NW-SE elongated magma domain at 3-7 km depth (Einarsson, 1978). At the southern margin of the caldera there are two smaller areas with surface manifestations; Hvíthólar at the intersection between the caldera and the fissure swarm and at Sandabotnaskarð, which is at the southeastern part of the caldera.

The geology at Krafla is characterized by basaltic lavas from fissure eruptions and hyaloclastite ridges, while minor volumes of subglacial rhyolitic ridges are found mainly at or outside the margins of the caldera (Sæmundsson 1991, 2008; Jónasson, 1994). Volcanic activity has been centered either at the eastern or western part of the fissure swarm respectively, but in the past 3000 years volcanic fissure eruptions and extension have been confined to the eastern part of the fissure swarm (Sæmundsson, 1984, 1991).

3.2. Thermal structure

The geothermal area at Krafla is based on TEM and MT surveys estimated to cover an area of approximately 48 km^2 in size and can be divided into an eastern and western sector (Arnarson and Magnússon, 2001). A WNW-ESE cross section along the southern caldera margin from Sandabotnaskarð through Hvíthólar and to the centre of the fissure swarm is shown in Figure 5. According to the resistivity survey the conductive clay cap is thick and at 300-400 m depth in the east at Sandabotnaskarð. To the west of Hvíthólar field within the fissure swarm the character of the conductive clay cap changes, but it is at 100 m depth and is very smooth and planar. Both the field at Sandabotnaskarð and the field west of Hvíthólar within the fissure swarm have been explored with drilling. Drilling has revealed that alteration is corresponding with the depth to the conductive clay cap identified in resistivity surveys. At Sandabotnaskarð to the east, temperature is in equilibrium with alteration and reservoir temperatures of 260-350°C. However, in the fissure swarm to the west of Hvíthólar, alteration is less intense with depth and is indicating that maximum temperatures have reached 230-280°C at 600-1400 m depth below surface in this part of the reservoir. Since then, the reservoir in the fissure swarm west of Hvíthólar has cooled down and today temperatures are within 175°C.

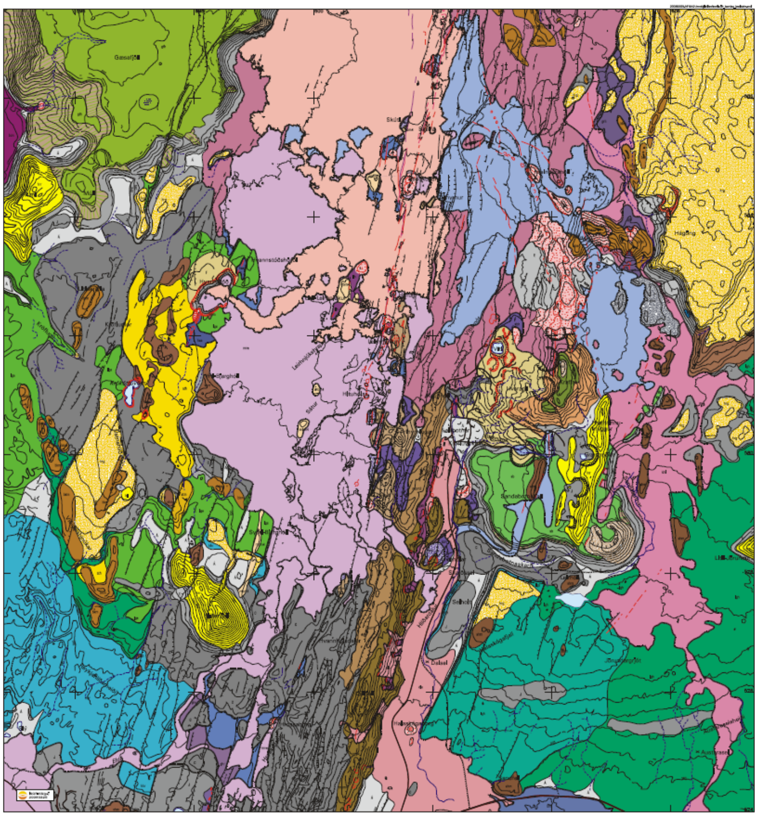

Figure 4: Geological map of Krafla central volcano (Sæmundsson, 2008). Holocene lavas (purple and pink colours) and hyaloclastite ridges (brown colours) have filled the caldera. Yellow colours represent rhyolitic or mixed rhyolite/basalt deposits. Map scale is 1:25000. The width of the map is equivalent to ~12 km

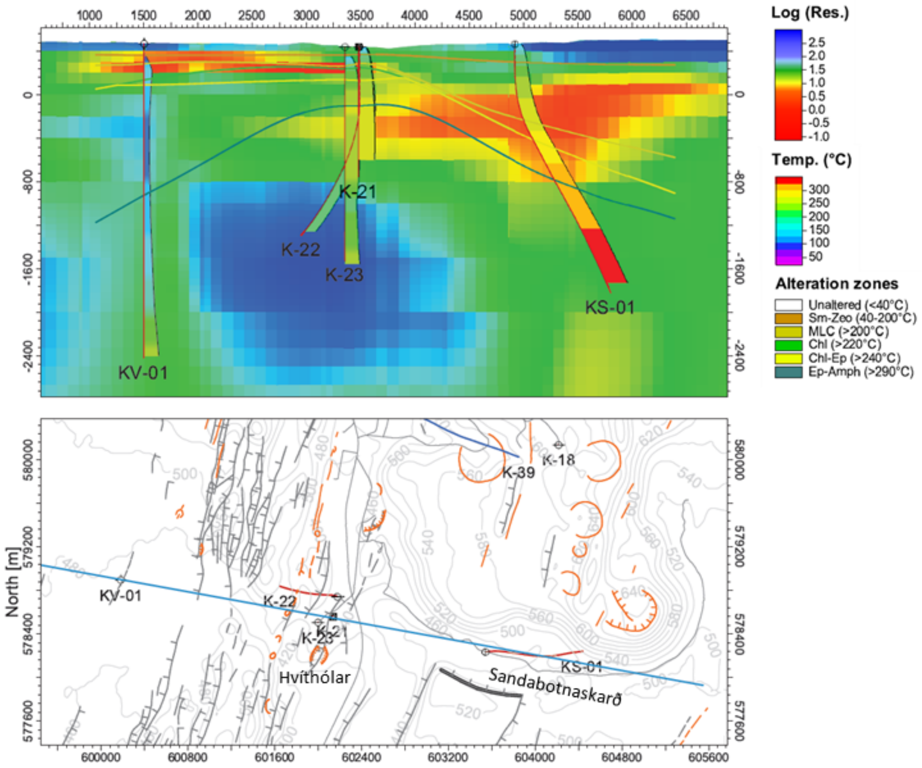

Figure 5: E-W cross section at southern part of Krafla geothermal system showing 1D TEM-MT resistivity (blue-red colour background)(Árnason and Magnússon, 2001), alteration zonation (lines) and formation temperature (blue-red colour along well trajectory). Below is structural map with faults (grey hatched lines) and craters (orange lines) including location of cross section (blue line).

4. NÁMAFJALL

Bjarnarflag geothermal power plant is located at Námafjall in the southern part of the Krafla fissure swarm (Figure 1). Geothermal exploration of the area was initiated in the 1960s and exploration drilling commenced in 1963 to gather steam for a prospective diatomite factory and by 1969 a 3 MW_e power plant at Bjarnarflag was inaugurated. The geothermal system has been explored further as part of plans to develop the field. A total of 15 exploration and productions wells have been drilled in the field, but out of those are only 5 wells more than 1000-2500 m in length.

4.1. Geological setting

Námafjall geothermal area is located in the southern part of Krafla fissure swarm and may represent a parasitic volcanic centre within the Krafla volcanic system partially fed by lateral fissure eruptions from Krafla central volcano. The geology at Námafjall is characterised by hyaloclastite ridges, lava flows and crater rows from fissure eruptions (Figure 6). Fissure eruptions from Krafla volcano have extended to the south and affected the Námafjall area with extension in the fissure swarm (Figure 6) and on some occasions with eruptions through fissures (e.g. Mývatn Fires 1724-1729). The area with active geothermal manifestations covers 5 km^2, and alteration is pervasive in the eastern part of the field at Námafjall mountain (Figure 7).

4.2. Thermal structure

The geothermal system at Námafjall is estimated to cover an area of approximately 20 km^2 in size according to TEM and MT surveys (Karlsdóttir, 2001). A NW-SE cross section at Námafjall is shown in Figure 7. According to the resistivity survey the conductive clay cap is peaking and reaching the surface just west of Námafjall mountain, but the conductive clay cap remains thick as it is dipping towards the NW beneath the fissure swarm west of Krummaskarð, where extension has been centred. Both the fields beneath Námafjall mountain and at Krummaskarð have been explored with drilling. Drilling has revealed that alteration is overall corresponding with the depth to the conductive clay cap identified from the resistivity survey. At Námafjall mountain to the east, temperature is in equilibrium with alteration and reservoir temperatures of 280-350°C. In the fissure swarm to the west of Krummaskarð temperature is in equilibrium with alteration at shallow depth, but deep in the reservoir west of the eruptive fissure that formed during the Mývatn Fires (1724-1729) a sharp temperature reversal to temperatures below 200°C is observed (Figure 7).

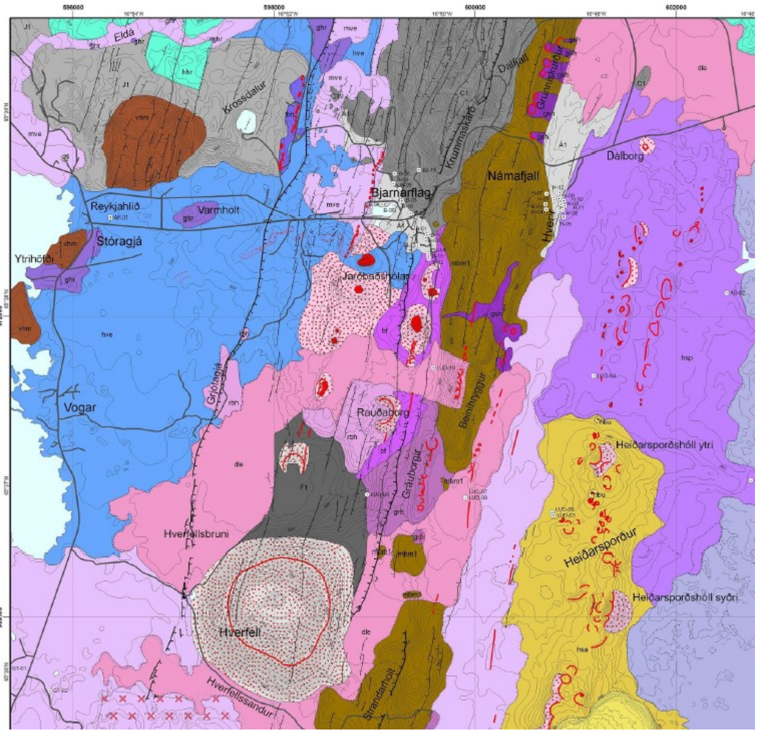

Figure 6: Geological map of Námafjall area within southern part of Krafla fissure swarm (Sæmundsson, 2010).

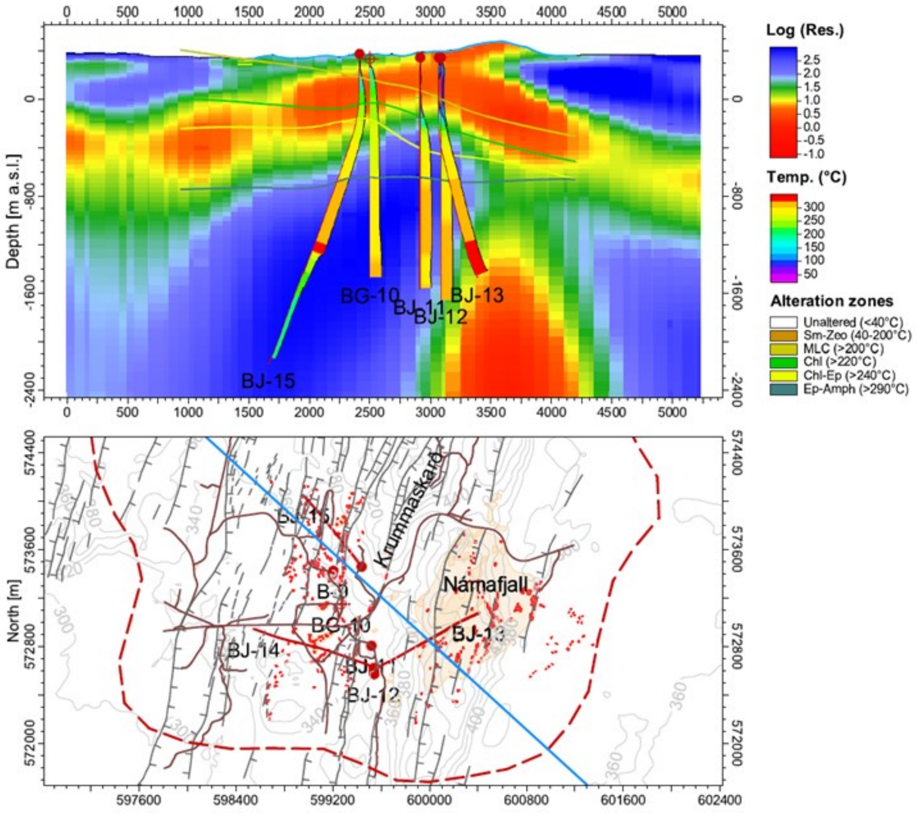

Figure 7: NW-SE cross section of Námafjall geothermal system showing 3D TEM-MT resistivity (blue-red colour background)(Karlsdóttir et al., 2012a), alteration zonation (lines) and formation temperature (blue-red colour along well trajectory). Below is structural map showing location of cross section (blue line), outline of resistivity anomaly at 600 m.b.sl. according to TEM survey, geothermal manifestations (red spots) and altered ground (beige coloured area)(Karlsdóttir, 2001).

5. RESISTIVITY, ALTERATION AND TEMPERATURE STRUCTURE OF THREE GEOTHERMAL AREAS IN NE-ICELAND - COMPARISON

Comparison of resistivity structure and current temperature of the three geothermal areas at Theistareykir, Krafla and Námafjall reveal both similarities and differences.

Within the part the geothermal areas, where the fissure swarm is located and were extension has been focused during the Holocene, the geothermal reservoirs have cooled severely in all three geothermal areas that are compared here. Extension during rifting episodes opens big fissures allowing easy access for cold groundwater to infiltrate the reservoir and cause cooling. At the same time alteration and extend of the conductive clay cap indicates that there previously existed high-temperature geothermal systems with temperatures at 230-280°C within the fissure swarms.

The shape of the conductive clay cap and the intensity of alteration with depth have many similar features at Theistareykir and Krafla, while it is different at Námafjall, which could point towards that timing and cause of cooling is not the same at Námafjall compared to at Theistareykir and Krafla geothermal areas.

At Theistareykir and Krafla geothermal areas the conductive clay cap within the fissure swarm has a distinctive smooth and planar surface. A possible explanation for this feature could be that the geothermal systems in these two areas were at a thermal maximum during the Last Glacial Period, when the areas were covered with a thick glacier and that alteration reached to surface of the ground beneath the glacier during this time resulting in a planar surface of the conductive clay cap. Volcanic eruptions during the Holocene have subsequently covered the altered ground in these areas with 100-200 m thick unaltered lava, which now forms the cold groundwater zone characterized by high resistivity above the conductive clay cap. At the same time temperature dependent alteration minerals indicate that during the thermal maximum temperature was between 230-280°C in an >1000-1200m thick interval below the clay cap in the fissure swarm at Theistareykir and Krafla. This suggests that during the thermal maximum there existed a convection zone with fairly constant temperatures and lower thermal gradient, which probably was controlled by the higher fracture permeability within the fissure swarm.

At Námafjall geothermal area the conductive clay cap does not exhibit a smooth and planar surface within the fissure swarm rather it is gradually dipping downwards towards the west away from the main up-flow zone beneath Námafjall mountain. This could either imply that the thermal anomaly has never been as intense at Námafjall as compared to Krafla and Theistareykir resulting in that alteration have never reached surface or it implies that the thermal maximum of the geothermal system did not occur during the Last Glacial Period, rather the timing of it is more recent. Additionally, the cooling within the fissure swarm at Námafjall geothermal area does not appear to extend from surface to depth like at Theistareykir and Krafla, rather it occurs at >1500 m depth in the reservoir suggesting that cooling is a result of lateral inflow into the geothermal reservoir from the north along Krafla fissure swarm. Latest volcanic eruptions at Námafjall are characterised by small volume fissure eruptions through lateral flow of magma from Krafla central volcano, the main site of the eruptions. Thus, it is tentatively proposed that fracturing associated with lateral magma movement may be linked with subsequent cooling at deeper levels within the fissure swarm at the geothermal area at Námafjall, while strong outflow maintains high temperatures at shallow levels.

6. CONCLUSIONS

Resistivity surveys are used to delineate the extend of geothermal areas, but the caveat of this method is that it is mostly dependent on the clay alteration in the subsurface and thus it maps the extend of the geothermal area, when it was at a thermal maximum. In this paper three high temperature geothermal areas in NE-Iceland have been compared, which are characterised by conductive clay caps extending across a fissure swarm, but where drilling has revealed that the geothermal reservoir has cooled significantly. Comparison of the geological setting, the shape of the conductive clay cap and subsurface alteration and temperature from wells are used to deduce variation in timing of the thermal maximum at these three areas while at the same time highlighting that fissure swarms are susceptible to significant cooling through higher fracture permeability from repeated rifting events, but this allows groundwater to infiltrate and cool the geothermal reservoir.

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